Advanced Gas Turbine Combustion Management

Towards Real-time Monitored Combustors with Extended Operation Range

(Gestion avancée de la combustion dans les turbines à gaz: vers des brûleurs plus flexibles et plus sûrs)

Dr. Fabrice Louis Michel Giuliani

Habilitation Memorandum (venia docendi)

Supervision: Pr. F. Heitmeir (TU Graz, Austria),

Pr. G. Lavergne (ISAE, France)

Version: February 9, 2010

Institute for
Thermal Turbomachinery
and Machine Dynamics

Combustion
Division

So it is with physics and engineering. Physics is the church, and engineering the most devout sinner. Physics is the domain of beauty, law, order, awe, and mystery of the purest sort; engineering is partial observance of the laws, and puttering with machines which never work quite as they should work: engineering, like acts of sin, is the process of proceeding boldly into complex and often forbidden matters about which one does not know enough - the laws remain to be elucidated - but the experience of the past and hunger for the taste of new experience attract one forward.

Norman Mailer, Of a Fire on the Moon, 1970

Online version

Hyperlinks available on the online version of this habilitation[1] allow to display instantaneously the related articles and documents.

For the first connection, a login and password will be asked. Please proceed as follow:

```
Login:     StudenT
Password:  Skriptum
```

Please look out that the capitals letters are correctly tipped.

Version en ligne

Des liens hypertexte permettent d'afficher rapidement nombre d'articles et de documents en relation avec la version PDF en ligne de ce mémoire[1].

Afin d'y accéder, un nom d'utilisateur et un mot de passe vous seront demandés lors de votre première connexion. Veuillez procéder comme suit:

```
Login:     StudenT
Password:  Skriptum
```

Attention de bien respecter les lettres capitales.

[1] http://ttm.tugraz.at/hidden/AV/HABILITATION/labilapapa_main.pdf

Aknowledgements

This memorandum for the habilitation (venia docendi), or "mémoire en vue de l'obtention de l'habilitation à diriger les recherches" (HdR) compiles the milestones and achievements on combustion management collected by the author since 1996. Due to its formal and scientific nature, the human dimension of the project will disappear to face facts and crude rational vision of science. But please allow me for a few lines to afford a narrative structure, and present the people that played a major role during the progress of the work, during the ups and downs, during the 99 % of consumed time and effort spent in an incredible galaxy of more or less useful things this memorandum will not even mention a word about.

Professor Heitmeir is head of the Institute for Thermal Turbomachinery and Machine Dynamics, and Dean of the Faculty of Mechanical Engineering at the TU Graz. He opened the position I now occupy and gave the impulse to get things running. He managed to keep the boat floating during all this time, and allowed me a great scientific freedom. I am really thankful for this. I also wish to thank Professeur Lavergne from ISAE-ONERA and Professor Weyer from TU Bochum-DLR for the role they played at different seasons of the habilitation process. And also Jeroen van Beeck (VKI), Pierre Gajan (ONERA) and Christoph Hassa (DLR) for their role of mentor, and for their friendship.

I thank the members of the habilitation commission: MM...

This work would not have been possible without the assistance and hard work of my team, the Combustion Division. We are a small group, we have our characters and imperfections, we are limited in terms of material and money, we endure breakdowns of various things supposed to work and we have had difficult partners in some projects. But when things start to work - and yes it happens sometimes - we are a great group! Thank to all of you for this: Andreas Lang, Thomas Leitgeb, Stefan Köberl, Christoph Hennig and Johannes Fritzer. Thanks to the stagiaires, assistants and Diploma Students that help us a great deal.

Thanks also to all the people of the TTM institute for the help, for the discussions, and for the coffee breaks! Thanks to the staff of Gebäude und Technik for the infrastructures and security in the laboratory. My employer, the TU Graz, as well as funding entities such as the EU, the FWF, the State of Styria, the ÖAD and the ÖFG are gratefully acknowledged.

Special thanks to Daniela Winkler, Olaf Diers, Umesh Bhayaraju, Prof. Jakob Woisetschläger, Bianca-Tamara Puntigam, Bernhard Wagner, Cornelia Santner, Audrey Camps and Barbara Fuchs.

Thanks to my big Family, and particularly to my small one. I owe this work to you.

Pour Genia. Pour Milo. Pour l'à venir.

Contents

List of Figures 13

Nomenclature 13

I Formal part 19

Résumé en français 21

La thématique "Gestion avancée de la combustion" . . . 21

Travaux de recherche . . . 22

L'Unité Combustion à l'Université Technique de Graz . . . 23

Summary 25

The incentive of "Advanced combustion management" . . . 25

Research . . . 26

1 Curriculum Vitae 29

2 Publication list 33

3 Teaching, training and supervision 41

3.1 Teaching, and related educational institutions . . . 41

3.2 Mentoring and supervision . . . 42

3.2.1 Trainees . . . 42

3.2.2 Lecture assistants . . . 43

3.2.3 Diploma students . . . 44

3.2.4 PhDs . . . 44

4 Project management 47

4.1 Industrial and European projects . . . 47

4.2 Educational projects, and academic exchanges . . . 48

4.3 Organisation of events . . . 49

II Scientific & technical project 51

5 Advanced Gas turbine Combustion Management 53

5.1 Audit on the GT sector . . . 53
5.1.1 Economical aspects and environmental challenges . . . 55
5.1.1.1 Environment . . . 55
5.1.1.2 Natural resources, and replacement fuels . . . 56
5.1.1.3 Moral, Ethics, and Decision-Making . . . 57
5.1.2 Supporting the development of GT combustion technology . . . 58
5.2 Industry: State-of-the-art on GT Technology . . . 59
5.2.1 Gas turbine technology . . . 59
5.2.1.1 Gas turbine basics . . . 59
5.2.1.2 One application: the turbofan . . . 60
5.2.1.3 Trends for turbofan technologies . . . 61
5.2.2 Definition of the requirements . . . 62
5.2.2.1 Specifications of a GT combustor . . . 62
5.2.2.2 Target emissions to be reduced . . . 64
5.2.2.3 Combustor architectures . . . 65
5.3 Research: State-of-the-art on combustion physics . . . 69
5.3.1 Fundamental research approach . . . 69
5.3.2 Known issues, and focus of the research effort . . . 70
5.3.2.1 Combustion instabilities in gas turbines . . . 70
5.3.2.2 Positive aspects of unsteady combustion . . . 71
5.3.2.3 Other topics . . . 71
5.3.3 Flow phenomena taking place in the combustor . . . 72
5.3.3.1 Flow aerodynamics . . . 73
5.3.3.2 Atomisation . . . 73
5.3.3.3 Transport / evaporation . . . 74
5.3.3.4 Combustion . . . 74
5.4 Methodology . . . 75

6 The GT Combustion Division at TU Graz **77**
6.1 The TU Graz . . . 77
6.1.1 Graz University of Technology . . . 77
6.1.2 TTM . . . 78
6.1.3 The region of Graz and gas turbine technology . . . 78
6.2 The Combustion Division . . . 79
6.2.1 Personnel . . . 80
6.2.2 Lectures . . . 82
6.2.3 Specific equipment . . . 83
6.2.3.1 Power equipments . . . 83
6.2.3.2 Specific AV burner designs . . . 85
6.2.3.3 Other burners . . . 88
6.2.3.4 Computational power and specific softwares . . . 89
6.3 Research proposals, accepted projects and budget management . . . 91

6.3.1 Important project milestones . . . 92
6.3.2 Budget repartition . . . 93

III Research and Development 95

7 Selected papers 97

8 Progress in measurement techniques 99
8.1 Advanced image-based diagnostic techniques . . . 99
8.1.1 Rainbow thermometry . . . 99
8.1.1.1 From refractometry to thermometry . . . 99
8.1.1.2 The research on rainbow thermometry at the VKI in 1996 . . . 100
8.1.1.3 A step towards global rainbow thermometry . . . 101
8.1.1.4 Project follow-up . . . 103
8.1.2 Advanced spray visualisation techniques . . . 105
8.1.2.1 Phase-locked Mie scattering visualisations . . . 105
8.1.2.2 Particle and pattern image sizing . . . 106
8.2 Line-of-sight laser-based measurement techniques . . . 113
8.2.1 Incentive of the TOSCA project . . . 113
8.2.2 Fraunhofer diffraction (MALVERN) . . . 114
8.2.3 Hydrocarbon vapour concentration based on infra-red extinction (IRA) . . . 114
8.2.3.1 Measurement principles . . . 115
8.2.3.2 Time-resolved approach . . . 115
8.2.3.3 Further developments within ECCOMET and ALFA-BIRD . . . 116
8.2.4 Laser vibrometry . . . 117
8.2.4.1 A lightweight method for flame stability monitoring . . . 117
8.2.4.2 Measurement technique . . . 118
8.2.4.3 Processing technique . . . 119
8.2.4.4 Further developments . . . 122

9 Progresses on atomisation process and particle transport 125
9.1 Injection jet aerodynamics in presence of a forced flow modulation . . . 125
9.2 Liquid fuel particle transport in a modulated air flow . . . 126
9.2.1 Measurements on atomisation process with pulsed air entry . . . 126
9.2.2 Air-blast atomisation model . . . 128
9.3 BBO-Model and IN-PULSE code structure . . . 136
9.3.1 IN-PULSE for the validation of the atomisation model . . . 136
9.3.2 Effect of combined unsteady atomisation and transport on the spray in the far field . . 139
9.3.3 Results . . . 141
9.3.3.1 About the physics of two-phase flow with pulse air . . . 141
9.3.3.2 About the best strategy towards injection control . . . 141
9.3.4 Model discussion, and project follow-up . . . 142

10 Progresses on the physics of pulsed flames **145**
10.1 Observations with supporting measurement techniques . . . 145
10.1.1 Jet and flame dynamics with PIV . . . 145
10.1.2 Flame dynamics with schlieren technique . . . 146
10.2 Flame dynamics description using laser vibrometry . . . 146
10.3 Project follow-up . . . 146

IV Works in progress, and perspectives of research **153**

11 Perspectives **155**
11.1 Development of the Combustion Unit . . . 155
11.1.1 Experimental facilities . . . 155
11.1.1.1 Test rigs under development . . . 155
11.1.1.2 Power systems under construction . . . 157
11.1.2 Education and dissemination . . . 158
11.1.2.1 Lectures . . . 158
11.1.2.2 Dissemination 2010 . . . 158
11.2 Combustion management activities . . . 158
11.2.1 Advanced sensing and acting techniques . . . 158
11.2.2 Combustor with enlarged operation range . . . 159
11.2.3 Future fuels . . . 159
11.2.4 Unsteady combustion . . . 159
11.2.5 Ignition . . . 160
11.3 Future of the Combustion Division . . . 160
11.3.1 Status quo: AV as an academic entity . . . 161
11.3.2 Major developments: AV as a joint academic-industrial entity . . . 161
11.4 Conclusion . . . 161

Bibliography **173**

List of Figures

2.1 Publication statistics, status quo January 2010 . . . 33

3.1 Trained people statistics, status quo January 2010 . . . 42

5.1 Statistics on electricity generation and air transport . . . 54
5.2 Propulsion gas turbine . . . 60
5.3 Technical and external constraints for GT combustor design . . . 62
5.4 ICAO-CAEP target emission levels . . . 66
5.5 Low-emission concepts: an overview . . . 67
5.6 Basic GT combustor . . . 68
5.7 Airblast atomiser . . . 68

6.1 The GT Combustion Division at TU Graz . . . 78
6.2 TTM educational spectrum . . . 79
6.3 Combustion Division highlights . . . 80
6.4 Combustion unit key personnel, contract status 2008, and main work repartition . . . 81
6.5 Thermal air heater . . . 84
6.6 HTP test rig . . . 85
6.7 Wagner atmospheric burner . . . 86
6.8 Lang pressurised burner . . . 87
6.9 Lang burner aerodynamics . . . 88
6.10 The Kawanabe diffusion burner . . . 89
6.11 The NEWAC sector . . . 90
6.12 The ALFA-BIRD injector . . . 91
6.13 Combustion Division's budget 2005-2011 . . . 94

8.1 The monochromatic rainbow pattern . . . 100
8.2 Determination of refractive index and droplet temperature . . . 101
8.3 Rainbow image, dimensioned . . . 102
8.4 Rainbow samples . . . 103
8.5 Rainbow image processing . . . 104
8.6 Mie scattering visualisation technique . . . 106
8.7 Setup at DLR for background lighting technique . . . 106

8.8 Spray image processing . . . 107
8.9 Liquid ligament segmentation . . . 108
8.10 Samples of atomisation images using the background lighting technique . . . 108
8.11 Prefilm length appearing on the surface of the prefilmer before film breakup . . . 110
8.12 Particle image sizing process . . . 111
8.13 Sensing strategies for combustion stability monitoring . . . 113
8.14 Particle size measurements with a MALVERN instrument . . . 114
8.15 Instrumentation for IR extinction measurements. . . . 116
8.16 IR sensor frequency response . . . 116
8.17 Principle of laser vibrometry . . . 118
8.18 Sensitivity of laser vibrometry . . . 119
8.19 DLV arrangement, measurement and phase-averaging process . . . 120
8.20 DLV signal processing . . . 121
8.21 Fluctuating density mapping process . . . 122

9.1 Pulsed velocity flowfield in free-jet configuration at 100 Hz . . . 127
9.2 Velocity profiles in cylindrical coordinates . . . 128
9.3 Phase-averaged swirl number. . . . 129
9.4 3-D streamlines placed in the injection mixing layer . . . 130
9.5 3D analysis of the airblast aerodynamics . . . 131
9.6 Pulse airblast spray dynamics. . . . 132
9.7 Phase-averaged spray visualisations and vortices from 100 to 400 Hz air excitation . . . 133
9.8 Phase-averaged evolution of the particle size in a pulsed spray . . . 134
9.9 PDA Measurements on the flat prefilmer. Top left: particle velocities. Top right: D32 measurements. Left: injector and resulting spray, with coordinate system. . . . 135
9.10 PDF fits compared with PDA measurement, and $D32$ comparison . . . 135
9.11 Time and space response of droplets introduced in a pulsed air flow field . . . 137
9.12 Possible inlet conditions for the introduction of the atomised phase: steady state (left), constant kerosene flow with modulated PDF (middle), and pulsed kerosene flow (right) . . . 138
9.13 Comparison between PDA measurement and simulation. Particle size distribution, volume distribution and velocity per droplet size measured 15 mm down the injector are shown . . . 138
9.14 SMD correlation at intermediate pressure conditions . . . 139
9.15 Method for reconstructing the phase-averaged droplet size distribution . . . 140
9.16 Role on the atomisation and transportation processes in pulse spray . . . 141
9.17 Combining a spray modulated by a 10 % air pulsation with a kerosene pulsation for four different phase-shifts. Probe at 15 mm. . . . 143

10.1 Jet dynamics observed with with PIV . . . 147
10.2 Recurrent mushroom-shaped flame . . . 148
10.3 Density fluctuation maps using laser vibrometry . . . 149
10.4 LV measurements, confined flame at 1 and 2 bar . . . 150

11.1 Fuel spray test rig. . . . 156

11.2 New designs for two-phase flow investigation to be tested in 2011 157
11.3 A competence on propulsion technologies at the TU Graz 162

Nomenclature

	Latin letters	
a, b	Gamma distribution parameters	
D32	Mean Sauter diameter	[μm]
P	Pressure	[Pa or bar]
P’	Acoustic pressure	[Pa or bar]
Q	Heat release energy	[J]
Q	Mass flow rate	[kg/s]
Q’	Unsteady heat release (cyclic)	[J]
R	Rayleigh criterion	
S	Specific entropy	[J/K/kg]
T	Temperature	[K or ^{o}C]
V	Specific volume	[m^3/kg]

Abbreviations

ABB Asean Brown Bovery

ACARE Advisory Council for Aeronautics in Europe

ALFA-BIRD Alternative Fuels and Biofuels for Aircraft Development, FP7, Collaborative Project, Contract No. 213266

ALR Air to Liquid Ratio, by mass

ANR Agence Nationale de la Recherche

APU Auxiliary Power Unit

ASME American Society of Mechanical Engineers

AT Institute for Propulsion Technology (Antriebstechnik), DLR

AV Combustion Division (Arbeitsgruppe Verbrennung), TTM, TU Graz

BK Combustion Chamber Division (Brennkammer), AT, DLR

CAEP Committee on Aviation Environmental Protection

CC Combustion Chamber

CFD Colourful Fluid Dynamics

CSTC (Belgian National Office for Construction Sciences and Techniques

DA Master's Thesis (Diplomarbeit)

DAC Double Annular Combustor

DGA Direction Generale de l'Armement (French fonds for defence)

DLR German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt)

DMAE Department for Aerodynamics and Energetics Modelling, ONERA

EA Department for Environmental and Applied Fluid Dynamics, VKI

EC European Community

ECCOMET Efficient and Clean Combustion Experts Training

EFRE Europäischer Fonds für regionale Entwicklung - European Regional Development Fund

ENAC French Civil Aviation University (École Nationale d'Aviation Civile)

ENSICA National Higher School of Aeronautical Constructions (École Nationale Supérieure d'Ingénieurs de Constructions Aéronautiques)

FAR Fuel to Air Ratio, by mass

FWF Austrian Research Funding Agency (Fonds zur Förderung der Wissenschaftlichen Forschung)

GHG Greenhouse Gas

GRT Global Rainbow Thermometry

GT Gas Turbine

GuT TU Graz's Facilities and Housing Department (Gebäude & Technik)

HPC High Pressure Compressor

ICAO International Civil Aviation Organisation

LDA Laser Doppler Anemometry

LN Log-normal distribution

LOPOCOTEP LOw POllutants COmbustor TEchnology Programme, EU FP5

LPC Low Pressure Compressor

LPP Lean Premixed Prevaporised, Low-NOx technology

LPT Low Pressure Turbine

LTO Landing and Take-Off cycle, as defined by the ICAO

MH Division for Multiphase-Heterogeneous Flows, DMAE, ONERA

MoPAA Measurement of Prefilming Airblast Atomisation, joint ONERA-DLR study, Annex II

MTU Motoren- und Turbinen-Union, aka MTU Aeroengines

NEWAC New Aeroengine Core Concepts, European Project, FP6, Integrated Project, Contract No. 030876

NGV Nozzle Guide Vane

ONERA The French Aerospace Lab (Office National d'Études et de Recherches Aérospatiales)

OPR Operating Pressure Ratio

OTDF Overall Temperature Distribution Factor

PDA Phase Doppler Anemometry

PDE Pulse Detonation Engine

PDF Probability density function

PEA Projet d'étude amont (Ground research project)

PIV Particle Image Velocimetry

ppm Parts per million (for concentrations, ratio in moles)

R&D Research and Development

RANS Reynolds-Averaged Navier Stokes

RQL Rich-burn/Quick-mix/Lean-burn combustor

RR Rosin-Rammler aka Weibull distribution

RTDF Radial Temperature Distribution Factor

SAC Single Annular Combustor

SAFRAN French conglomerate result of a merger between SNECMA and SAGEM

SFC Specific Fuel Consumption [kg/daN/h]

SNECMA Société Nationale d'Etude et de Construction de Moteurs d'Aviation (propulsion and aerospace equipment, SAFRAN division)

SUPAERO National Higher School of Aeronautics and Space (École Nationale Supérieure de l'Aéronautique et de l'Espace)

TAPS Twin Annular Premixing Swirler

TE Turbine Entry

TM Turbomeca, French helicopter engine manufacturer, part of SAFRAN

TOSCA Technology for Oscillating and Steady-State Combustion Analysis

TTM Institute for Thermal Turbomachinery and Machine Dynamics, TU Graz

TU Graz Graz University of Technology

UHC Unburned Hydrocarbon

VKI Kon Karman Institute for Fluid Dynamics

ZID TU Graz's Central Information Service (Zentralinformationsdienst)

Greek symbols

α	vapour absorption coefficient	[-]
Δ	variation	
Γ	Gamma distribution	
λ	wavelength	[m or nm]
λ_2	second invariant criterion for vortex identification	
ω	rotational speed	[2π rad/s]
ϕ	Equivalence ratio	
ϕ	angle, or phase-shift	[rad]
ρ	Density	[kg/m^3]
θ	angle	[degrees or radian]

Subscripts

kero kerosene

Part I

Formal part

Résumé

La thématique "Gestion avancée de la combustion"

Jusque dans les années 1980, la turbine à gaz, que ce soit en propulsion ou bien au sol, était perçue comme une machine entièrement mécanique, requièrant les techniques les plus poussées en matière de matériaux, d'usinage et d'assemblage. La confiance dans la robustesse de technologies éprouvées et la méfiance relative vis-à-vis de contrôles et d'asservissements potentiellement défaillants a limité, voire retardé, l'introduction de l'assistance électronique dans les turbomachines. Par la suite, au cours des années 90 et ce sous la double impulsion de la prise de conscience en matière d'environnement et de la relance économique dans les secteurs de l'énergie et des transports, de nouvelles voies ont été envisagées afin d'améliorer le rendement des machines, de les rendre plus propres, moins bruyantes, plus flexibles, plus sûres, plus simples à entretenir, et moins chères à la production.

Dans ce contexte, les chambres de combustion sont appelées à fonctionner à de plus forts taux de compression et de température d'entrée. Le profilage et le dessin Low-NOx de la machine complète conduisent à des tubes à flamme relativement compacts, où la densité d'énergie développée par la combustion est très élevée. Pour les taux de compression les plus forts, une gestion des flux de chaleur est nécessaire, notamment pour refroidir l'air primaire avant son admission en chambre afin d'éviter des problèmes d'auto-allumage et de pouvoir exercer un refroidissement efficace du tube à flamme (projet NEWAC). A ces très forts niveaux de puissance (l'ordre de grandeur actuel est la dizaine de mégawatts par brûleur), et dans un milieu extrêmement confiné, il est primordial d'entretenir une combustion stable et ce sur une plage de fonctionnement la plus large possible - surtout en régime maigre. Hors, le problème lié aux instabilités de combustion a retardé la mise en application de techniques prometteuses à faible émissions telle que l'injecteur type LPP (lean premixed prevaporised).

La gestion avancée de la combustion a pour but d'assurer constamment une combustion stable et robuste tout en optimisant des paramètres tels que consommation spécifique et taux d'émissions. Ceci concerne toute la plage de fonctionnement de la turbine à gaz, en modes stationnaires et transitoires. Il s'agit de recenser et de tester différentes stratégies permettant d'agir de manière efficace et rapide sur ces paramètres. Le panel de techniques prises en compte va du choix du foyer (qu'il faut par exemple rendre compatible à plusieurs carburants comme dans le cas de l'utilisation de bio-carburants du projet ALFA-BIRD) à des techniques de contrôle en boucle fermée (surveillance et action sur la flamme, pour la forcer à rester stable ou bien pour élargir le domaine de fonctionnement). En outre, des concepts innovants sont étudiés tels que l'utilisation de certains aspects instationnaires de la combustion (par exemple la combustion pulsatoire), ou bien le remplacement de la combustion "classique" (déflagration) par la détonation pulsée (gain de rendement thermique, stratégie étudiée dans le projet NEWAC).

Plus spécifiquement, l'effort est porté sur:

- les aspects de diagnostic de flamme en temps réel
- la description fine de la combustion instationnaire
- la conception de brûleurs et de foyers: un point d'intérêt porte sur des injecteurs et/ou des trous de refroidissement à géométrie variable, pour pouvoir étendre la zone de stabilité de la flamme ou bien l'adapter à des régimes spéciaux de fonctionnement (par exemple suite à une gestion active de la quantité d'air primaire dans le compresseur, stratégie étudiée dans le projet NEWAC)
- l'analyse des régimes transitoires
- l'analyse de stratégies de contrôle de la flamme sur tout le domaine de fonctionnement d'un brûleur, ou comment faire suivre à la flamme une courbe de transition optimisée d'un point de fonctionnement à un autre
- l'exploitation des aspects "positifs" en combustion pulsatoire (tels que le taux d'émissions) et en détonation pulsée (tels que le rendement thermique)

Travaux de recherche

Le présent mémoire décrit comment le projet de recherche sur la gestion avancée de la combustion est mis en place. La finalité de ce projet constitue donc la perspective en matière de recherche et développement de l'Unité Combustion. Après la partie formelle sur le parcours du candidat, les éléments détaillés sont les suivants :

Etat de l'art sur la combustion en turbine à gaz: Expression des besoins. Mise en place d'une structure adéquate de recherche permettant de répondre à ces besoins.

Travaux publiés: Mise au point d'une instrumentation adaptée - notamment à la description de phénomènes instationnaires. L'effort est porté sur la description de la physique de la combustion instationnaire au travers de l'analyse détaillée des phénomènes de transports au sein d'une flamme pulsée.

Travaux en cours: Physique de la combustion instationnaire. Physique de l'atomisation et stratégies de contrôle de la combustion via l'injection (au sein de deux thèses sur un financement FWF). Perspectives de développement de l'unité.

L'ensemble des publications choisies et la description des travaux en cours établissent l'engagement de l'unité de recherche Combustion à la TU Graz dans le présent projet. L'accent est porté sur l'aspect recherche expérimentale. Dans un souci de complémentarité, des techniques de mesures non conventionnelles (c'est-à-dire non commercialisées comme telles) ainsi que quelques résultats complémentaires non publiés sont détaillés dans le mémoire afin d'étendre les informations fournies par les articles. Y sont décrits :

Des diagnostics en ligne de mire pour la mesure de concentration en carburant (absorption par infra-rouge, projets ECCOMET et ALFA-BIRD) ou bien les analyses de fluctuation de densité (vibrométrie laser).

Une description détaillée d'une injection pulsée, commençant par l'aérodynamique de l'injection, et les phénomènes de transports observés sur les particules, ainsi que la dynamique de flamme pulsée.

L'analyse fine des phénomènes d'atomisation avec du kérosène injecté dans des conditions en chambre de haute pression et haute température sur un injecteur aérodynamique (Projets MoPAA, LOPO-COTEP et thèse Bhayaraju).

L'établissement d'un modèle de transport de particules en régime instationnaire nécessaire à toute stratégie basée sur un contrôle de la combustion au travers de l'injection

Des techniques avancées d'imagerie permettant d'une part d'analyser l'indice de réfraction d'un liquide (technique arc-en-ciel) et de l'autre de décrire les phénomènes d'atomisation (particle image sizing, projet FWF3)

Chacune de ces parties s'accompagne d'un résumé des travaux en cours et des orientations choisies.

L'Unité Combustion à l'Université Technique de Graz

L'Unité Combustion a été crée fin 2004, afin de compléter le panel de compétences de l'Institut de Machines Thermiques et d'Analyse Vibratoire (portant essentiellement sur les aspects turbine à gaz et turbine à vapeur). La structure mise en place est adaptée au projet "gestion avancée de la combustion en turbine à gaz". Les ambitions en termes d'enseignement et de recherche et développement qui ont été fixées comme feuille de route sont les suivantes :

Un pôle compétences et transmission du savoir-faire portant sur les nouvelles technologies en matière de rendement, d'émissions, d'injection, d'opérabilité et de stabilité. Au travers du cours de combustion en turbine à gaz et des échanges académiques effectués avec nos partenaires, ce pôle est un phare essentiel permettant d'identifier et de recruter des jeunes talents pour former le personnel de l'équipe. Il s'agit aussi de notre vitrine vers l'extérieur, nous permettant de se faire reconnaître au travers de publications, de participation à des congrès et à des projets, et par la même occasion d'avoir accès à des financement tiers.

Un pôle grands moyens techniques permettant de se coupler sur les machines de haute puissance de l'institut (station de compression de 3MW de puissance électrique) et d'alimenter à terme une chambre annulaire complète de petite et moyenne puissance. Afin de simuler les conditions de température d'entrée, un réchauffeur thermique de 5MW a été construit et mis en service sur le site. Les aspects sécurité du personnel et des installations, ainsi que les activités type bureau d'études et planification d'essais font partie de ce pôle.

Un pôle physique de l'injection et de la combustion instationnaire se basant sur des injecteurs / brûleurs de laboratoire, ainsi que sur des injecteurs industriels montés en configuration simplifiée. L'effort est porté sur la compréhension de la physique de l'atomisation, la robustesse de la combustion en réponse à une perturbation, et le choix des stratégies d'optimisation de la combustion. Les compétences acquises enrichissent notre savoir-faire et nous permettent de proposer notre expertise en matière de conception de brûleurs. L'aspect développement de techniques avancées de mesure et actionneurs de laboratoires ainsi que techniques embarquées de diagnostic et de contrôle de la combustion fait partie de ce pôle. Ce type de matériel s'oriente vers la surveillance et le contrôle actif de la combustion en temps réel afin d'en assurer la stabilité, d'en exploiter les aspects instationnaires si cela est désiré, et d'augmenter l'enveloppe d'opérabilité de la chambre. Ce pôle représente la "niche" spécifique de recherche choisie par le laboratoire pour la période 2004-2010.

Un pôle modèles et simulation permettant d'exploiter les corrélations issues des expériences, et d'optimiser les procédés. L'orientation choisie est l'aspect "utilisateur", plus que l'aspect "développeur". L'implémentation de la chambre au sein de la turbine est analysée au moyen d'un outil de calcul de performances (YPSE-PRO, code commercial historiquement développé à l'institut, GASTURB, commercial). Un code de thermochimie et de thermocinétique permet d'évaluer l'impact de certains choix techniques sur les émissions (CHEMKIN, commercial, et GASEQ, freeware). Un modèle simplifié d'acoustique permet d'estimer/de dimensionner les possibles plages de résonance acoustique susceptibles d'être accrochées par une instabilité dans une chambre de combustion. Un modèle de transport instationnaire permet d'estimer les effets d'une injection irrégulière sur l'alimentation de la flamme (IN-PULSE, code maison). Les analyses d'aérodynamique 2D et 3D sont réalisées sous FLUENT, le plus souvent dans la phase de conception des modules d'essais.

Bien sûr, ces pôles ne sont pas cloisonnés et un grand niveau d'interactivité et de synergie a lieu entre cette structure et les autres unités de notre institut, ainsi que l'Institut de Mécanique des Fluides, l'Institut de Moteurs de Puissance à Combustion Interne et l'Institut des Techniques de la Chaleur de la TU Graz. Nos partenaires industriels principaux sont PIEZOCRYST, MTU, VOLVO AERO et TURBOMECA, et de nombreux projets à caractères scientifiques sont montés avec l'ONERA Centre de Toulouse et le DLR de Cologne.

Summary

The incentive of "Advanced combustion management"

Gas-turbines belong to the category of Hi-Tech systems, involving a very broad palette of technologies such as advanced materials able to sustain extreme strains and temperatures, ultra-precise machining, and advanced combustion techniques. Mostly dedicated to power and propulsion, they must be efficient, robust, cost-effective, flexible, and easy to maintain. The progress in terms of developments over the last fifty years is enormous, the average SFC (Specific Fuel Consumption) for propulsion systems having been reduced by more than the half.

The drivers for gas turbine technology development are a booming market on transports and energy, combined to a fierce competition between the main GT manufacturers. The strong occasional fluctuations on this market are mostly a function of the oil price. Since the 90's, the effort is put on a strong reduction of the emissions because of rising environmental concerns. In Europe, the combined effort of engine manufacturers and researchers is supported by many research programmes funded by the European Community (EC). For aeroengines, the latest technical solutions for a combined high-efficiency and low-emissions system lead to a higher thrust to weight ratio per engine category (regional, middle- and long-range jet engines, fighter jet engine). Today's trends are a lighter and compacter engine core, a greater by-pass ratio, higher high pressure shaft rotational speeds, hence higher operating pressure ratio and temperature inlet conditions into the combustor, smaller combustor size, lean combustion, higher admissible inlet temperature of the turbine with advanced cooling techniques combined to enhanced material properties.

The topic of this study is related to maintaining combustion stability over an extended operational range of interest (for instance in the lean domain), and also the damping of combustion instabilities. The focus is put on the combustion chamber of propulsion gas turbines, where the constraints are the most demanding. At such levels of energy density, significant pressure and heat release oscillations can appear and get enhanced by thermoacoustic couplings. These instabilities are detrimental to the operation, as well as they represent a danger to the system integrity. Although LPP burners (Lean Premixed Prevapourised) are the most promising technology in terms of NOx reduction, their sensitivity to combustion stability problems have prevented or retarded their implementation in modern gas turbines.

The expensive process of trial and error for technically reliable systems used up to the end of the 80's is being progressively replaced by a scientific approach, since for instance advanced numerical methods allow a detailed combustion modelling (unsteady reactive flows, multiphase, small time and space resolution, thermal chemistry modelling complexity, turbulence)... Still, a further effort on the understanding of the physics involved is necessary in order to cover the gap between academic thermoresonators that have been extensively studied and complex industrial systems. The model must be improved to predict the risk of instabilities and select at the conception level the right stability strategies, active or passive.

The philosophy of advanced combustion management is to bring gas turbine combustors a step further, where the overall efficiency improvement results from a better handling of detailed combustion processes, with an enlarged combustion stability range, and reduced emission levels. Combined efforts of engineering and research are required to push further the frontiers of our ability to use fire, and optimise its use on the whole gas turbine operation enveloppe.

More specifically, the capacity of the GT combustion laboratory at TU Graz is adequate to study and develop the following:

- real-time combustion diagnostics, for laboratory or onboard use
- a refined description of the combustion dynamics of GT flames, under steady state conditions, during operation transients, and in presence of a thermoacoustic coupling
- a review and testing of adequate methods that influence the combustion stability, as well as control strategies
- an investigation of the positive aspects of unsteady combustion, in terms of polluant emissions or thermal efficiency

Research

This document describes the involvement of the Combustion Division at TU Graz (under the guidance of the applicant) in the project on advanced combustion management, based on the chosen publications and a description of the works in progress. After the formal part of the habilitation, the following is detailed:

- State-of-the-art on gas turbine combustion. Description of the needs, and consequent structure adaption and research topics of the Combustion Division
- Experiments in combustion based on adapted or developed instrumentation, with a description of the simplified models
- Detailed combustion dynamics, and testing of strategies regarding combustion control

The applicant's articles connected to this memoir are essentially focussing on experimental research. In order to support these articles, some unpublished technical details or complementary results are reported hereby. The topics are:

Dynamics of pulsed air injection with a detailed description of the jet aerodynamics, effect on the transported phase, and resulting flame dynamics.

Physics of atomisation on kerosene at realistic gas turbine conditions (Projects MoPAA, LOPOCOTEP, and Bhayaraju's PhD Thesis)

A model for particle transport in an unsteady flow to assess a realistic introduction of the liquid phase in the computational domain, and estimate the effectiveness of strategies of combustion control based on a precise actuation of the injection

Line-of-sight, laser-based measurement techniques for time-resolved particle sizing (Fraunhofer diffraction), fuel vapour concentration measurement (infra-red absorption) or density fluctuations in the flame (laser vibrometry)

Advanced imaging techniques used for interferometry (rainbow refractometry), spray dynamics or particle image sizing

The document concludes with the presentation of some works in progress, and discusses the orientations to be taken towards the next decade.

Chapter 1

Curriculum Vitae

The applicant, Fabrice Louis Michel GIULIANI

Ingénieur Diplômé de l'École Supérieure des Sciences et Technologies de l'Ingénieur de Nancy
Post-graduate Diploma Course in Fluid Dynamics completed at the Von Karman Institute
Docteur Diplômé de l'École Nationale Supérieure de l'Aéronautique et de l'Espace
(spécialité: Energétique et Dynamique des Fluides)

Born 02.04.1974 in Nancy, France
French nationality
Married, with children
Military service accomplished

Home address	Office address	
	TU Graz / TTM / AV	Tel +43 (0)316 873 7733
Schützenhofgasse 22	Inffeldgasse 25 A	Fax +43 (0)316 873 107733
A-8010 Graz	A-8010 Graz	E-mail : Fabrice.Giuliani@TUGraz.at

Some links of interest:

Presentation of the TTM Institute	`http://ttm.tugraz.at/`
Combustion Division	`http://ttm.tugraz.at/?seite=research/av/av`
Institute's Staff	`http://ttm.tugraz.at/?seite=home/staff`

Some results:

Activities 2004-2006:	`http://ttm.tugraz.at/down/av/C-MaGine.pdf`
Laser vibrometry for pulsed flame:	`http://ttm.tugraz.at/down/av/poster_TOSCA.pdf`
Power installations:	`http://ttm.tugraz.at/down/av/poster_POWER.pdf`

Education and Training

01/10/1997 - 25/06/1998: Diploma Course, von Karman Institute for Fluid Dynamics

VKI[1], Brussels, Belgium

Graduation June 1998

Post-graduate education in Fluid Dynamics. International environment, *lingua franca* is English

01/10/1999 - 30/09/2002: Ph.D., SUPAERO

France's national engineering school for aeronautics and space[2], Toulouse, France

"Analysis on the Behaviour of an Aeroengine Air-Blast Injection Device with Forced Entries"

Graduated Docteur de l'ENSAE-SUPAERO June 2002 with Excellence (Félicitations du Jury)

01/10/1992 - 27/06/1997: Studies of Mechanical Engineering, ESSTIN (Nancy, France)

Ecole Supérieure des Sciences et Technologies de l'Ingénieur de Nancy[3], Université des Sciences Henri Poincaré, Nancy I

Graduation June 1997

Mechanical engineering, specialisation in fluid dynamics and energetics

ERASMUS exchange student at the University of Strathclyde[4] (Glasgow, Scotland) in 1994-1995

Professional experience, and related institutions

01/10/1997 - 30/07/1999: Research Engineer, VKI (von Karman Institute for Fluid Dynamics, Rhodes St Genèse, Belgium)

Civil servant at the French Embassy in Brussels and research engineer in the Department for Environmental and Applied Fluid Dynamics (EA)

Head of EA department: Pr. Michel Riethmuller

VKI / EA

Chaussée de Waterloo, 72

B 1640 Rhode St Genèse

01/10/1999 - 30/09/2002: Researcher ONERA (the French Aerospace Lab, Toulouse, France) Aerodynamics and Energetics Modeling Department (DMAE), unit multiphase-heterogenous flows (MH)[5]

DGA grant (Délégation Générale pour l'Armement, French Defence)

Assistant lecturer on fluid dynamics in Toulouse's aeronautic engineering schools (ENAC, ENSICA and SUPAERO, Toulouse, France)

Head of the MH division: Dr Pierre Gajan,

ONERA CT / DMAE / MH

BP 4025

F 31055 Toulouse Cedex 4

---

[1] http://www.vki.ac.be/

[2] http://www.isae.fr

[3] http://www.esstin.uhp-nancy.fr/

[4] http://www.strath.ac.uk/

[5] www.onera.fr

01/10/2002 - 30/09/2004: Researcher, DLR (German Aerospace Centre, Cologne, Germany) Department Combustion Physics (Verbrennungsphysik - VP, now Brennkammer - BK), at the Institute of Propulsion Technology (AT)[6]
Head of the BK division: Dr Christoph Hassa
DLR / AT / BK
Porz-Wahnheide
Linder Höhe
D 51147 Köln

Since 01/10/2004: Head of the Combustion Division (Arbeitsgruppe Verbrennung - AV) at the Institute for Thermal Turbomachinery and Machine Dynamics (TTM), at the Graz University of Technology (TU Graz), Austria
Project leader EU programs NEWAC (2006-2010) and ALFA-BIRD (2008-2012), and national research program FWF3
Lecturer on gas turbine combustion
Head of institute: Pr. Franz Heitmeir
TU Graz / TTM / AV
Inffeldgasse 25 A
A 8010 Graz

Languages

French mother tongue

English fluent (First Certificate in English, Cambridge, 1995)

German fluent (BENEDICT language school certificates for ground- and middle level, 2003-2004)

Italian conversational

Miscellaneous

- EU Expert for FP 6 and 7, for propulsion and power. Nr EX2002B070534
- Reviewer
  - for the Turbo-Expo Conference (ASME)
  - for "Aerospace and Technology" (Elsevier)
  - for the "Journal of Sounds and Vibrations" (Elsevier)
  - for "Measurement Science and Technology" (IOP)
  - for "Aerospace Lab" (electronic journal dedicated to scientific advances related to aeronautics and space, edited by the ONERA[7])

[6] http://www.dlr.de/
[7] www.aerospacelab-journal.org

  - as a proposal examiner for the "Global research network programm", Korea Research Fundation

- Conception and management from 2005 to 2007 of the TTM Homepage[8]
- Alumnus ESSTIN (Nancy, F), University of Strathclyde (Glasgow, UK), VKI (Brussels, B) and SUPAERO (Toulouse, F).
- One innovative industrial project for eased transport and storage of a concert bass sound system leading to a patent deposit procedure at the French Patent Office (INPI) in 1996
- First aid training from the red cross 1992
- Running, cycling, squash and volley-ball
- Saxophone and piano, classic and jazz

[8] ttm.tugraz.at

Chapter 2

Publication list

The following lists the issued literature. One section summarises the submitted and planned articles for the academic year 2009-2010. Most of the items are open literature, and copies are available online. Peer reviews are available on demand.

Journals and equivalents

[Gajan et al., 2007] Gajan, P., Strzelecki, A., Platet, B., Lecourt, R., and Giuliani, F. (2007). Experimental investigation of spray behavior downstream of an aeroengine injector with acoustic excitation. *Journal of Propulsion and Power*, 23(2):390–397.

[Giuliani et al., 2002a] Giuliani, F., Diers, O., Gajan, P., and Ledoux, M. (2002a). Characterization of an air-blast injection device with forced periodic entries. In *Proceedings of the IUTAM Symposium on Turbulent Mixing and Combustion, Queen's University at Kingston, Canada, June 3-6, 2001 Pollard and Candel (eds) Kluwer Academic Publ.*, pages 327–336.

[Giuliani et al., 2002b] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2002b). Influence of pulsed entries on a spray generated by an air-blast injection device - an experimental analysis on combustion instability processes in aeroengines. *Proceedings of the Combustion Institute*, 29(1):91–98.

[Giuliani et al., 2009a] Giuliani, F., Hennig, C., Leitgeb, T., and Hassa, C. (2009a). Effect of the initial droplet size distribution of the liquid phase combined with transport phenomena on the resulting airblast spray in

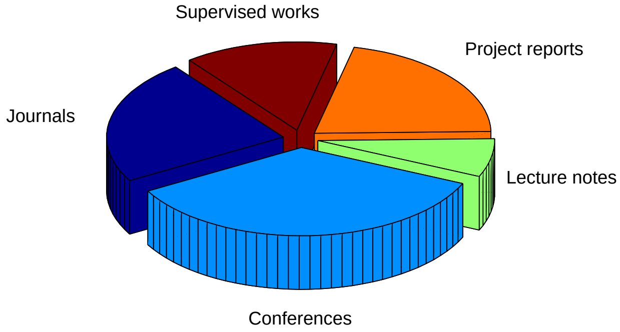


Figure 2.1: *Publication statistics, status quo January 2010*

the far field. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-133.

[Giuliani et al., 2010] Giuliani, F., Leitgeb, T., Lang, A., and Woisetschläger, J. (2010). Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry. *Journal of Engineering for Gas Turbines and Power*, 132. GTP-031603.

[Giuliani et al., 2009b] Giuliani, F., Leitgeb, T., and Woisetschläger, J. (2009b). Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry. In *ASME Turbo Expo, Gas Turbine Technical Congress & Exposition*, Orlando, FL USA. GT2009-59682.

[Giuliani et al., 2006] Giuliani, F., Wagner, B., Woisetschläger, J., and Heitmeir, F. (2006). Laser vibrometry for real-time combustion stability diagnostic. In *ASME Turbo Expo 2006: Power for Land, Sea and Air*. Barcelona, Spain. GT2006-90413.

[Hennig et al., 2009] Hennig, C., Giuliani, F., Freitag, S., and Hassa, C. (2009). Image particle sizing of an air blasted liquid sheet of kerosene at intermediate pressure. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-093.

[Köberl et al., 2010] Köberl, S., Fontaneto, F., Giuliani, F., and Woisetschläger, J. (2010). Frequency resolved interferometric measurement of local density fluctuations for turbulent combustion analysis. *Measurement Science and Technology*. Submitted Sept. 2009.

[Lang et al., 2010] Lang, A., Lecourt, R., and Giuliani, F. (2010). Statistical evaluation of ignition phenomena in turbojet engines. In *ASME Turbo Expo 2010: Power for Land, Sea and Air*, number GT2010-23229, Glasgow, UK. Submitted Nov.09.

[Leitgeb et al., 2009a] Leitgeb, T., Giuliani, F., and Heitmeir, F. (2009a). Design and adaptation of a versatile test facility for turbines and combustion chambers. In *Proceedings of the 8th European Turbomachinery Conference*. Graz, Austria.

[Leitgeb et al., 2009b] Leitgeb, T., Giuliani, F., and Niederhammer, A. (2009b). Computer aided dimensioning and validation of a versatile test facility for combustion chambers and turbines. In *ASME Turbo Expo, Gas Turbine Technical Congress & Exposition*, Orlando, FL USA. GT2009-59592.

International peer-reviewed conference articles and equivalents

[Bhayaraju et al., 2005] Bhayaraju, U., Hassa, C., and Giuliani, F. (2005). A study of planar liquid sheet breakup of prefilming airblast atomisers at high ambient air pressures. In *20th Annual Meeting of the Institute of Atomisation and Spray systems (Europe)*. ILASS 2005 (20th Annual Meeting), Orléans, France.

[Diers et al., 2001] Diers, O., Giuliani, F., Biscos, Y., Gajan, P., and Ledoux, M. (2001). Phasenaufgelöste LDA-Messungen in der Gasströmung einer Luftstromzerstäuberdüse. In *Lasermethoden in der Strömungsmesstechnik*, pages 36.1–36.7. Fachtagung der Deutschen Gesellschaft für Laser-Anemometrie GALA e.V.

[Giuliani et al., 2004] Giuliani, F., Berthoumieu, P., Becker, J., and Hassa, C. (2004). The effect of ambient air pressure on planar liquid sheet disintegration at gas-turbine conditions. In *19th Annual Meeting of the Institute for Liquid Atomization and Spray Systems (ILASS Europe), Nottingham, UK*, pages 68–75.

[Giuliani et al., 2008a] Giuliani, F., Bhayaraju, U., and Hassa, C. (2008a). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine combustor inlet conditions using laser infra-red absorption. In *32nd International Symposium on Combustion*. Montreal, Canada, The Combustion Institute.

[Giuliani et al., 2009] Giuliani, F., Lang, A., Irannezhad, M., and Grönstedt, T. (2009). Effect of a controlled phase-shift on the outlet conditions of a set of pulse detonators. In *19th ISABE Conference*, Montreal, Canada. ISABE-2009-1315.

[Giuliani et al., 2007a] Giuliani, F., Lang, A., Leitgeb, T., , Woisetschläger, J., and Heitmeir, F. (2007a). Time-resolved analysis of density fluctuations in a resonant air-methane flame using dual laser vibrometry for gas turbine combustor qualification tests. In *Proc. of the 18th ISABE conference*. International Symposium on Air Breathing Engines, Beijing, China. ISABE-2007-1187.

[Giuliani et al., 2008b] Giuliani, F., Lang, A., Leitgeb, T., and Woisetschläger, J. (2008b). Phase-defined density fluctuation maps of a resonant air-methane premixed flame using laser vibrometry. In *32nd International Symposium on Combustion*. Montreal, Canada, The Combustion Institute.

[Giuliani et al., 2007b] Giuliani, F., Schricker, A., Lang, A., Leitgeb, T., and Heitmeir, F. (2007b). High-temperature resistant pressure transducer for monitoring of gas turbine combustion stability. In *Proc. of the 18th ISABE conference*. International Symposium on Air Breathing Engines, Beijing, China. ISABE-2007-1111.

[Lang et al., 2008] Lang, A., Leitgeb, T., Woisetschläger, J., Strzelecki, A., Gajan, P., and Giuliani, F. (2008). Analysis of a pulsed flame at intermediate pressure. In *ISFV13 - 13th International Symposium on Flow Visualization / FLUVISU12 - 12th French Congress on Visualization in Fluid Mechanics*, Nice, France.

[Lundbladh et al., 2009] Lundbladh, A., Donnerhack, S., Streifinger, H., Giuliani, F., and Grönstedt, T. (2009). Future innovative cores for commercial engines. In *19th ISABE Conference*, Montreal, Canada. ISABE-2009-1277.

Other conference articles

[Atthassit et al., 2001] Atthassit, A., Biscos, Y., Giuliani, F., and Lavergne, G. (2001). Mesure de la température des gouttes en évaporation et en combustion par la technique arc-en-ciel. In *Recueil des actes du 9^{e} congrès francophone de visualisation et de traitement d'images en mécanique des fluides, FLUVISU*, pages 79–84. Rouen, France.

[Giuliani, 2009] Giuliani, F. (2009). Advanced monitoring of gas turbine combustion stability using laser vibrometry. In *4th EVI-GTI International Gas Turbine Instrumentation Conference*. Norrköping, Sweden.

[Giuliani et al., 2007a] Giuliani, F., Bhayaraju, U., and Hassa, C. (2007a). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine conditions using laser infra-red absorption. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 2001a] Giuliani, F., Gajan, P., Biscos, Y., Diers, O., and Ledoux, M. (2001a). Analyse de l'écoulement diphasique généré par un injecteur de type aérodynamique en régime pulsatoire forcé. *Recueil des actes du 9^e congrès francophone de visualisation et de traitement d'images en mécanique des fluides, FLUVISU, Rouen, France*.

[Giuliani et al., 2005] Giuliani, F., Gajan, P., and Diers, O. (2005). A physical model on air-blast atomisation with modulated air inlet flow. In *Trends in Numerical and Physical Modeling for Industrial Multiphase Flows*. Cargèse, France.

[Giuliani et al., 2001b] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2001b). Analyse en moyenne de phase du champ de vitesse de l'air issu d'un injecteur aérodynamique en régime pulsatoire forcé. In *Recueil des actes du 15^e Congrès Français de Mécanique*, Nancy, France.

[Giuliani et al., 2007b] Giuliani, F., Lang, A., Leitgeb, T., Woisetschläger, J., and Heitmeir, F. (2007b). Using dual laser vibrometry to monitor the stability of gas turbine combustion. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 1998] Giuliani, F., van Beeck, J., and Riethmuller, M. (1998). Thermométrie par arc-en-ciel: technique d'acquisition de donnée à l'aide d'un laser Nd:YAG et traitement de signaux 2D. In *Recueil des actes du 6e Congrès Francophone de Vélocimétrie Laser*, pages B.3.1 – B.3.7, Saint-Louis, France. Association francophone de vélocimètrie laser.

[Köberl et al., 2009] Köberl, S., Giuliani, F., and Woisetschläger, J. (2009). Energy spectra measurements for the density fluctuation in a jet flame using dual laser vibrometry. In *Proc. of the 4th ECM*. European Combustion Meeting, Vienna, Austria, The Combustion Institute.

Lecture notes

[Giuliani, 2007] Giuliani, F. (2007). *Gas Turbine Combustion*. LV319.004. TU Graz lecture notes, second edition.

[Giuliani and Lang, 2007] Giuliani, F. and Lang, A. (2007). *Tutorials and exercises on gas turbine combustion*. UE319.005. TU Graz lecture notes, first edition.

[Giuliani et al., 2008] Giuliani, F., Marn, A., Sanz, W., and Woisetschläger, J. (2008). *Laborübung: Maschinendynamik*. LUE319.044. TU Graz tutorial notes, second edition.

[Van Beeck et al., 1999] Van Beeck, J., Giuliani, F., and Riethmuller, M. (1999). Rainbow interferometry: principles & developments. In *Optical Diagnostics of Particles and Droplets*, volume VKI LS 1999-01, Rhode-St-Genèse, Belgium. von Karman Institute. VKI RP 1999-27.

Supervised PhDs (completed)

[Bhayaraju, 2007] Bhayaraju, U. (2007). *Analysis of Liquid Sheet Breakup and Characterisation of Plane Prefilming and Nonprefilming Airblast Atomisers*. PhD thesis, Technische Universität Darmstadt, Fachbereich Maschinenbau.

[Wagner, 2009] Wagner, B. (2009). *Fuel vapor concentration measurements on droplets by Infrared Extinction*. PhD thesis, ISAE-Institut Supérieur de l'Aéronautique et de l'Espace. No en attente.

Supervised Diploma Theses (completed)

[Köberl, 2008] Köberl, S. (2008). Variable Core Geometrien - Literaturrecherche, Auswertung und Vergleich der Strategien. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften.

[Lang, 2007] Lang, A. (2007). Konstruktion eines Brennkammer-Prüfstandes und Messungen unter mittlerem Druck. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften. Clickable version.

[Lechner, 2008] Lechner, A. (2008). Management der instationären Verbrennung in Gasturbinen. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften.

[Leitgeb, 2007] Leitgeb, T. (2007). Brennkammerprüfstand: Anbindung eines Lufterhitzers und Monitoring der Betriebsdaten. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften. Clickable version.

[Niederhammer, 2009] Niederhammer, A. (2009). Aufbau und inbetriebnahme des luftsystems für einen brennkammerprüfstand. Master's thesis, TU Graz.

[Wagner, 2005] Wagner, B. (2005). Anpassung von Messmethoden an die stationäre und instationäre Verbrennung. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften. Clickable version.

Project reports

[Gajan and Giuliani, 2001] Gajan, P. and Giuliani, F. (2001). Caractérisation d'un système d'injection de turbomachine en régime pulsatoire forcé. *Rapport ONERA RF 3/06107 DMAE*.

[Giuliani, 1997] Giuliani, F. (1997). Experimental study on rainbow interferometry using a pulse laser. Technical Report VKI SR 1997-14, von Karman Institute.

[Giuliani, 1998] Giuliani, F. (1998). Rainbow thermometry: droplet temperature measurement in a spray using a Nd:YAG laser. Technical Report VKI PR 98-11, von Karman Institute.

[Giuliani, 2002] Giuliani, F. (2002). *Analysis on the Behaviour of an Aeroengine Air-Blast Injection Device with Forced Entries*. PhD thesis, ENSAE No 346, Toulouse, France.

[Giuliani et al., 2004] Giuliani, F., Becker, J., and Hassa, C. (2004). Investigation of vapour phase, LOPOCOTEP deliverable 4.15. In *EU FP6 - GROWTH Project*. DLR-IB-325-04-04.

[Giuliani et al., 1999] Giuliani, F., Corieri, P., Buchlin, J.-M., and Olivari, D. (1999). Influence du vent sur un toit de maison: Mesure expérimentale de coefficients de pression en soufflerie. Technical Report VKI EAR 9812, VKI-CSTC Contract Report 1999-25.

[Giuliani et al., 2000] Giuliani, F., Diers, O., Gajan, P., and Biscos, Y. (2000). Caractérisation d'un système d'injection de turbomachine en régime pulsatoire forcé. *Rapport ONERA RF 4/05103-01F DMAE*.

[Giuliani and Hassa, 2003] Giuliani, F. and Hassa, C. (2003). Measurement of Prefilming Airblast Atomisation: Droplet Size Measurement. Internal report DLR-IB-325-11-03, Institute of Propulsion Technology, DLR Cologne, Germany.

[Giuliani and Lang, 2009] Giuliani, F. and Lang, A. (2009). WP2.3 - 2.3.3. Final Assessments for Innovative Combustion. Technical Report TUG-DEL-2.3.3.B, EU IP NEWAC - FP6-030876.

[Grönstedt et al., 2008] Grönstedt, T., Lei, X., Giuliani, F., and Köberl, S. (2008). WP2.3 - 2.3.2. Variable core cycle. Technical Report CHALMERS-DEL-2.3.2.A, EU IP NEWAC - FP6-030876.

[Grönstedt et al., 2009] Grönstedt, T., Lei, X., Leitgeb, T., and Giuliani, F. (2009). WP2.3 - 2.3.2. Final Assessments for Variable Core Cycle. Technical Report CHALMERS-DEL-2.3.2.B, EU IP NEWAC - FP6-030876.

[Lang et al., 2008] Lang, A., Giuliani, F., Lei, X., and Grönstedt, T. (2008). WP2.3 - 2.3.3. Basic configuration for innovative combustion. Technical Report TUG-DEL-2.3.3.A, EU IP NEWAC - FP6-030876.

The previous list concerns referenced academic reports, contract reports, or technical reports.

Press articles, and other medias

[Giuliani, 2006] Giuliani, F. (2006). Auf dem Weg zu umweltfreundlicheren, effizienteren und zuverlässigeren Gasturbinen. Forschungsjournal der Technischen Universität Graz, WS 05-06, p.34. Clickable version.

[Giuliani, 2007] Giuliani, F. (2007). Ce que la recherche peut faire pour vous, et inversement. Collectif Sauvons la Recherche. Clickable version.

[Griesser, 2009] Griesser, D. (2009). Die unglaubliche Reise im Energiespar-Flieger. Der Standard.

[Knaus, 2008] Knaus, G. (2008). Maschinenbau. Warum nicht? Factory Woman.

[Senarclens de Grancy, 2006] Senarclens de Grancy, A. (2006). Traumberuf Forscher? TUG Print, p.9. Clickable version.

[Tzivanopoulos, 2007] Tzivanopoulos, K. (2007). Eintauchen in die Welt der Technik. Kleine Zeitung. Clickable version.

[Wahlmüller, 2007] Wahlmüller, C. (2007). Forschungsgeld ist für renommierte Labors reserviert. ECONOMY, Unabhängige Zeitung für Forschung, Technologie und Wirtschaft.

Ongoing and submitted publications during 2009-2010

[Giuliani and Hennig, 2010] Giuliani, F. and Hennig, C. (2010). Evaluation of active control strategies regarding airblast atomisation. In *23rd European Conference on Liquid Atomization and Spray Systems - ILASS*, Brno, Czech Republic. Submitted Jan. 10.

[Giuliani and Lang, 2010] Giuliani, F. and Lang, A. (2010). Pulse detonation as an option for future innovative gas turbine combustion technologies: a concept assessment. In *27th Congress of the International Council of the Aeronautical Sciences - ICAS*. Submitted.

[Köberl et al., 2010] Köberl, S., Fontaneto, F., Heimel, M., Giuliani, F., and Woisetschläger, J. (2010). Measurement of local density fluctuations for combustion diagnostics of different flames using dual laser vibrometry. In *AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*.

Chapter 3

Teaching, training and supervision

3.1 Teaching, and related educational institutions

1999 - 2002 (3 years) part-time lecturer at ENAC, École Nationale d'Aviation Civile[1], 7 av. Edouard Belin, F 31055 Toulouse
Tutorials and exercises on incompressible and compressible flows.

1999 - 2002 (2 years) part-time lecturer at ENSICA, École Nationale Supérieure d'Ingénieurs de Constructions Aéronautiques[2], 1 place Emile Blouin, F 31056 Toulouse
Tutorials and exercises on boundary layers

1999 - 2002 (2 years) part-time lecturer at SUPAERO, École Nationale Supérieure de l'Aéronautique et de l'Espace[2], 10 av. E. Belin - BP 4032, F 31055 Toulouse Cedex 4
Tutorials and laboratory workshops on instrumentation and techniques for detailed multiphase flow measurements

Since 2004, Lecturer at TU Graz, Graz University of Technology[3], Faculty for Mechanical Engineering and Economics, Institute for Thermal Turbomachinery and Machine Dynamics, Inffeldgasse 25A, A 8010 Graz
Head of the Combustion Division.
Lecture on Gas turbine combustion, exercises and Workshops
Tutorials and laboratory workshops on machine dynamics
Tutorials and laboratory workshops on flow measurements in gas turbines
Expertise on mechanical engineering projects (construction exercises)

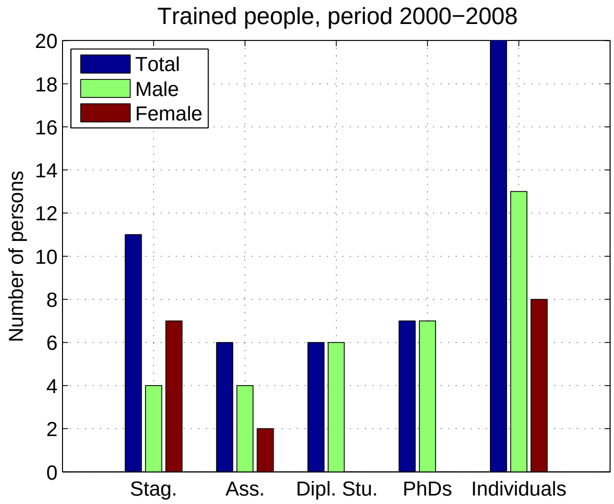


Figure 3.1: *Trained people statistics, status quo January 2010*

3.2 Mentoring and supervision

3.2.1 Trainees

07-08/2000: Gregory Ortet, student (Maîtrise) at the Université Paul Sabatier (entered then Supaero in 2001, promotion 2003), 2-months summer training at ONERA
« Phase-locked spray visualisation measurements »

09/00-02/2001: Olaf Diers [4], ONERA-DLR 6 months exchange in the frame of the MOPAA programme at ONERA
« Conditioned LDA measurement and pulse jet aerodynamics analysis»
The successful exchange with Olaf boosted the applicant's PhD and sealed his next research position at DLR Cologne.

10/2003-03/2004: Christoph Hennig[5], student at the Stuttgart University of Technology, 6-month technical training at DLR
« Semi-automatic statistical analysis of large number of air-blast visualisations for particle image sizing and atomisation pattern sizing »
Christoph Hennig finished in between his studies at TU Stuttgart and joined the Combustion Division in 2008 for a PhD at TU Graz

05-07/2004: Anne Hines, student at Virginia Tech, USA, for an IASTE Student Exchange Programm, 3-months summer training at DLR
« Advanced image processing for visualisation analysis of flat liquid sheet atomisation »

07/2005-09/2005: Cornelia Santner[6], student at TU Graz for a 3-months summer trainee
« Inventaire, dismounting and planification of the CLEAN air-system reorganisation for the combustion

[1] http://www.enac.fr/
[2] http://www.isae.fr
[3] http://www.tugraz.at/
[4] Olaf.DiersDLR.de
[5] christoph.hennig@tugraz.at
[6] Cornelia.Santner@tugraz.at

laboratory needs »
Cornelia Santner finished in between her studies and joined the institute's Turbine Division in 2008 for a PhD at TU Graz

07-08/2006 and 07-08/2007: Barbara Fuchs[7], for a one-month summer training at TU Graz, in the frame of a governmental program supporting parity in the technical field (FIT-T3[8])
Summer 2006: « Literature research for the combustion lecture, and support in the laboratory » Summer 2007: « The Institute for Propulsion Technologies at TU Graz in 2060 ». Techno-artistic vision promoting the development of the branch aeronautics and aerospace at TU Graz.

07-08/2007: Natascha Scheikl, also in the frame of a FIT-T3 programm
« Preparation of exercises using GASEQ for detailed combustion chemistry, and revision of the unit's leaflet »

06-08/2008: Audrey Camps[9], student at SUPAERO, in the frame of a summer training abroad
« Development of a H2-feeded ignition lance for soft ignition of the "small" combustion test rig, in view of ignition without detonation at intermediate pressure conditions » [Camps, 2008]

07-08/2008: Sarah Dober and Lisa Pucher for the FIT programme 2008. Documentation of test rig checklists and security procedures

07-08/2009: Damaris Legenstein for the FIT programme 2009. Set-up of a literature database using JabRef, and other works.

07-09/2009: Slavey Tanov as a summer trainee, working on laboratory constructive details (portable air heater and laboratory ventilation.

3.2.2 Lecture assistants

Summer-Semester 2006-2007 and Winter Semester 2007-2008: Andreas Lang, assistant position under the applicant's supervision on the combustion lecture, methodology for dimensioning the cooling on a flame tube, and supervision of the tutorials.

Winter-Semester 2007-2008, repeated 2008-2009: Barbara Fuchs, assistant position under the applicant's supervision on an E-Learning project concerning the combustion lecture in 2007-2008. More infos on the Teach-Center of the TU Graz here[10]. 2008-2009 assistant in charge of the graphics and corrections of this document.

Summer-Semester 2007-2008: Harald Scheer, assistant position under the applicant's supervision taking care of the combustion lecture notes in German.

---

[7] bar.fuchs@edu.uni-graz.at
[8] http://www.fit.tugraz.at/
[9] audrey.camps@hotmail.fr
[10] to access the E-Learning homepage on Gas Turbine Combustion, please click the address
http://tugtc.tugraz.at/wbtmaster/courses/319004_panel5.htm
and click *Login*, click *Extern*, type in *AVGuest* as login name and *combustion* as password (please pay attention to the caps: the login is case sensitive).

Winter-Semester 2009-2010: Slavey Tanov, assistant position under the applicant's supervision on laboratory details..

3.2.3 Diploma students

01/2005-12/2005: Bernhard Wagner[11], student at TU Graz
« Conditioning of measurement techniques for steady-state and unsteady flame diagnostic [Wagner, 2005]»
Bernhard Wagner joined then the ONERA to start a PhD in the frame of the ECCOMET project under the applicant's co-supervision.

06/2006-03/2007: Andreas Lang[12], student at TU Graz
« Design, construction and testing of a air-CH4 combustion test rig at intermediate pressure [Lang, 2007]»
Andreas Lang joined the NEWAC project in April 2007 for a PhD under the applicant's supervision.

06/2006-04/2007: Thomas Leitgeb[13], student at TU Graz
« Combustion test rig: static analysis, design and construction of the air piping of the thermal air heater, and automated monitoring of the operation conditions [Leitgeb, 2007]» Thomas Leitgeb joined the NEWAC project in June 2007 for a PhD under the applicant's supervision.

05-12/2007: Stefan Köberl[14], student at TU Graz
« Parametric analysis of different variable technology core concepts for advanced propulsion gas turbines [Köberl, 2008, Grönstedt et al., 2008]»
Stefan Köberl joined a FWF project in January 2008 for a PhD under the applicant's co-supervision.

05/2007-03/2008: Andreas Lechner, student at TU Graz
« Advanced management of unsteady combustion for propulsion systems: literature survey on detonation-based combustors, and spray test rig for experimental analysis of unsteady injection [Lechner, 2008]»

10/2008-04/2009: Andreas Niederhammer[15], student at TU Graz (DA ongoing)
« Final construction of the HPT air distribution system. Qualification tests and documentation on the operation envelope»

3.2.4 PhDs

02/2003-08/2007: Umesh Bhayaraju[16] at DLR Cologne, student at TU Darmstadt, PhD responsible: Prof Cameron Tropea, Darmstadt, supervisors: Christoph Hassa and Fabrice Giuliani, DLR. « Analysis of

[11] bernhard.wagner@onecert.fr
[12] Andreas.Lang@tugraz.at
[13] thomas.leitgeb@tugraz.at
[14] stefan.koeberl@tugraz.at
[15] niederh@sbox.tugraz.at
[16] ucb20@cam.ac.uk

Liquid Sheet Breakup and Characterisation of Plane Prefilming and Nonprefilming Airblast Atomisers [Bhayaraju, 2007]», clickable version[17]

Graduated doctor in Darmstadt on the 30.08.2007. Took since then a post-doctoral position at the Dept. of Engineering, Cambridge University.

10/2006-12/2009: Bernhard Wagner, now student at ISAE, Toulouse « Measurement of fuel vapour concentration in a kerosene spray by means of the Infra-Red extinction technique »

PhD director: Pierre Gajan, co-supervisors: Alain Strzelecki and Fabrice Giuliani, in the frame of the ECCOMET project.

04/2007-today: Andreas Lang, TU Graz

« Experimental analysis of unsteady combustion processes for innovative propulsion systems »

PhD theme strongly coupled to the NEWAC project on pulse-detonation based combustion processes, and combustion instabilities in low-NOx burners. PhD director: Pr. Franz Heitmeir, supervisor: Fabrice Giuliani.

Andreas Lang performed a short duration mobility training in the frame of ECCOMET in 2009, on kerosene ignition.

07/2007-today: Thomas Leitgeb, TU Graz

« Advanced combustion monitoring for gas turbines »

PhD theme related to both NEWAC and FWF3 projects. PhD director: Pr. Franz Heitmeir, supervisor: Fabrice Giuliani. Thomas Leitgeb will also perform a short mobility training in the frame of ECCOMET in 2009, on the code AVBP.

01/2008-today: Stefan Köberl, TU Graz

« Analysis of flame-flame interaction in gas turbine burners »

PhD theme, fundamental research orientation, financed by the FWF. PhD director and supervisor: Pr. Jakob Woisetschläger, co-supervisor: Fabrice Giuliani.

07/2008-today: Christoph Hennig, TU Graz

« Evaluation of active control strategies regarding airblast atomisation, a combined numerical-experimental approach »

PhD theme, fundamental research orientation, financed by the FWF. PhD director: Pr. Franz Heitmeir, supervisor: Fabrice Giuliani.

08/2009-today: Johannes Fritzer, TU Graz

« Analysis of the injection, atomisation and vapourisation of replacement fuels »

PhD theme related to the ALFA-BIRD project. PhD director: Pr. Franz Heitmeir, supervisor: Fabrice Giuliani.

[17] http://elib.tu-darmstadt.de/diss/000886/Dissertation_Final_Print_Ready_CV_5.pdf

Chapter 4

Project management, networking and organisation of events

4.1 Industrial and European projects

1998-1999 Efficiency of a dry cooling tower using forced draft under strong wind conditions mounted on a combined cycle power plant (St Ghislain, Belgium[1]) for HAMON-THERMAL SA (Brussels, Belgium). Dimensioning of a model aerocondenser to be tested in the L1B large wind tunnel facility at VKI.

1998-1999 Static pressure repartition on a house roof by strong wind, as a function of the incidence angle for the CSTC in Limelette [Giuliani et al., 1999]
Tests over a multi-pressure taps model in the large wind tunnel facility L1B of the VKI

1999-2002 DGA - Project: PEA TITAN and ETNA with SNECMA MOTEURS and TURBOMECA (Group Labinal, today both Group SAFRAN)
Methods for conditioned measurement techniques, strongly related to the PhD thesis [Giuliani et al., 2002b]. Participation in the meantime on a transverse project at ONERA on combustion instabilities, involving several departments.

EU Cluster LECT (EU FP4 BRITE EURAM/LECT III, contract BRPR950122, Low Emission Combustor Technology)
LECT co-ordinated 10 different European Research programmes, related to the aircraft engine low NOx emission reduction technology. Participation to the start of the EU and ICLEAC project (EU FP5 Reference G4RD-CT-2000-00215, Instability Control of Low emission Gas Engine), on low-emission combustors and the problematic of combustion instabilities.

2002 EU Project MOLECULES (EU FP5, Reference G4RD-CT-2000-00402, Modelling of low emissions combustors using large eddy simulation)
Acoustic characterisation of a test bench for jets in crossflow

[1] http://www.electrabel.com/assets/content/whoarewe/mmv_generation_CCGT_en_DF2BF599BE1141A79A4E6AC20810885C.pdf

2002-2004 EU Project PRECCINSTA (EU FP5 Reference ENK5-CT-2000-00060, PREdiction and Control of Combustion INStabilities in Tubular and Annular gas turbines combustion systems)
Planning of the high-pressure set-up to be built at DLR Köln, and experiments at atmospheric conditions

2002-2004 EU Project LOPOCOTEP (EU FP5, Reference GRD1-CT2000-25062, GROWTH program, Low Pollutant Combustor Programme)
Analysis of air-blasted kerosene vaporisation based on infrared light extinction [Becker, 2003, Giuliani et al., 2004a].

2006-2010 EU project NEWAC (ONGOING) (EU FP6, reference AERO-1.4-30876, NEW Aero Engine Core concepts)
Research on innovative combustion concepts involving primary air management, pulse detonation, and stability of a TURBOMECA LPP system. Giuliani project leader TU Graz.

2008-2011 FWF project on flame-flame interaction (ONGOING), co-supervision of a PhD thesis

2008-2011 FWF project on airblast injection control (FWF3, ONGOING), project leader and PhD supervisor

2008-2012 EU Project ALFA-BIRD, ONGOING, on the analysis of bio-fuel atomisation and vaporisation. Giuliani project leader TU Graz.

4.2 Educational projects, and academic exchanges

2002-2004 DLR-ONERA common programme MOPAA on the analysis of kerosene air-blast atomisation at isothermal conditions and intermediate pressure [Giuliani and Hassa, 2003].

2006-2007 Academic exchange programme ÖAD-AMADEE with the ONERA, Centre de Toulouse.
Exchange of know-how, instruments and common research published from 2006 to 2007.

2006-ONGOING Projekt FIT "Frauen in die Technik" The Combustion Division takes part to a program sponsored by the Austrian Ministry of Women the on promotion of parity in technical sciences. Female stagiaires that did not get their A-grade yet come for a summer-training at our place.

Marie-Curie ECCOMET Mobility Programme, ONGOING Three students from TU Graz participate to the ECCOMET projet from Cerfacs, which is strongly connected to the AMADÉE exchange. The research themes are the development of IRA technique (Bernhard Wagner, PhD at ONERA Toulouse since 2006), the training on the CERFACS code AVBP (René Pecnik in 2006, Thomas Leitgeb's training is planned at Cerfacs in 2009), and the analysis of kerosene ignition (Andreas Lang, training at ONERA Fauga-Mauzac planned 2009).

E-Learning at TU Graz, ONGOING Since 2007, the Combustion Division takes part to a large scale experiment on the use of IT technologies for pedagogic purposes (E-Learning). The lecture is available online, and interactive tutorials - mostly the manipulation of experimental data, or the use of basic simulation codes - are designed to be done online with different set of parameters per student, so that the teacher can compare and comment the results at the end of a tutorial session. The results over the four last years are very encouraging.

ÖFG-sponsored exchange with Ecole Centrale de Paris, ONGOING During the ASME Turbo Expo 2009, it was suggested to perform a common experiment on a flame at Ecole Centrale de Paris, using a technology developed at TU Graz. The first exchange took place in December 2009. A grant proposal for a Franco-Austrian joint study is currently under preparation will be submitted bilaterally at the FWF and ANR (Agence nationale de la recherche) in April 2010.

4.3 Organisation of events

Conferences Organisation of the European Turbomachinery Conference in 2009 in Graz (logistics, and all-rounder)

Workshops

- Organisation of the AMADEE workshops at TU Graz with ONERA members (5 attendants, over 3 days), in 2006 and 2007
- Organisation of the MOPAA workshops at DLR still with ONERA members (5 attendants, over 2 days)
- one NEWAC Management Meeting and one SP2-Workshops are planned for the academic year 2008-2009
- in charge of the "VKI evenings" when the VKI community happens to group in Graz

Journées du Film d'Entreprise Event organiser as member of the Student's Union of the ESSTIN in 1995 (member) and 1996 (responsible), on industrial film communication. This event is part of the short-cut movie festival "Prix de Court" in Nancy. Topic 1996: the image of civil nuclear power, sponsored by EDF, with a presentation of the Cattenom powerplant. Organisation, research of sponsors, TV and radio footage for event advertisement. Debate moderation. 300 visitors at the Palais des Congrès in Nancy, May 1996.

Sports team leader of the Half-Marathon of Brussels (VKI, 1999) and Graz (TU Graz, 2008).

Others Youth leader in summer holidays camps from 1991 to 1997 (France, UK, Canada and Irland) with children from 4 to 15.

Part II

Scientific & technical project

Chapter 5

About Advanced Gas turbine Combustion Management

This chapter discusses the background and the aim of advanced combustion management. The intended field of application is gas turbines.

At first, a review of the expansion of the GT market is done, with focus on the environmental impact. Although land-based gas turbines are mentioned at the beginning, the following highlights mostly aero-engines.

Secondly, we discuss how the GT industry responds to the current needs, and what has been done in terms of environmentally friendly systems. A state-of-the-art of technology is drawn, with the expression of the current needs in terms of research, towards on-demand combustion.

The current needs are a better understanding of the physics of turbulent combustion at elevated pressure and temperature, in oder to define universal design guidelines (or guidelines that go beyond a specific design, facilitating the transmission of know-how from one system to the next), control strategies and advanced simulation models for low-emission burners with an enlarged operation range, in which the combustion achieves the highest possible efficiency (as near as possible to 100 % over the whole operational range), and remains stable (no instabilities). Smooth ignition and emergency reignition also fall in this topic [Camps, 2008, Lang et al., 2010].

5.1 Audit on the GT sector, socio-economic aspects, and fact statement on the environment

GT development for propulsion and power

Figure 5.1 depicts the booming development in the gas turbine sector over the last decade. The presented figures and estimates issued from EuroStat[1] cover the 27 EU member countries from 1996 to 2007. The current trends are a rising demand in electricity production and in mobility.

[1] http://epp.eurostat.ec.europa.eu/

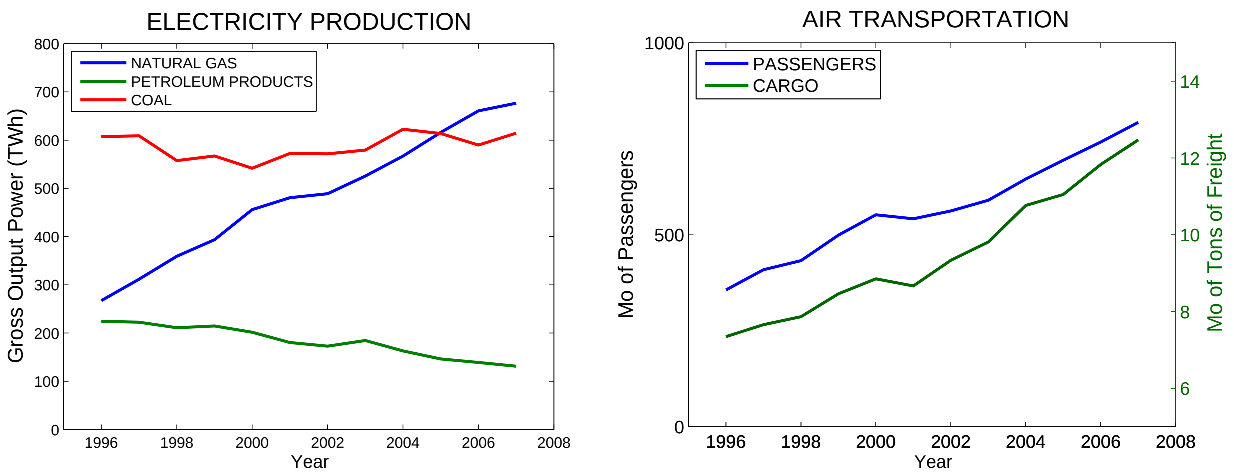


Figure 5.1: *Statistics on electricity generation and air transport for the EU members (EU 27) from 1996 to 2007. Source: Figures and estimates based on EuroStat data*

Land-based gas turbines

Concerning electricity generation in Europe, one sees on the first plot the stagnation of electricity produced from coal, and the reduction of energy produced with oil or diesel. This is mostly due to the maintenance of the current thermal power-plant park using coal boilers, and also due to the non-replacement of obsolete auxiliary Diesel engine power plants to the benefit of gas turbines that are natural gas-fired, available over the whole power range from decentralised to central units. The deregulation on the energy sector at the end of the 80's combined with the opening of the Russian gas market during the 90's enhanced the gas turbine market. Furthermore, natural gas combustion is cleaner due to its high methane contents (highest hydrogen/carbon ratio in the alkane group). Therefore the concerns on environment policies have enhanced natural-gas fired power plants - among which a large number of new combined cycle plants - that now produce more electricity than the coal installations. For instance, the power station of Mellach is at the moment extending using a combined cycle GT-steam (see section 6.1.3 p.78).

According to the IPCC report [Metz et al., 2007], natural gas is forecast to continue to be the fastest-growing primary fossil fuel energy source worldwide, maintaining average growth of 2 % annually and rising to 161 EJ consumption in 2025. The industrial sector is projected to account for nearly 23 % of global natural gas demand in 2030, with a similar amount used to supply new and replacement electric power generation. The share of natural gas used to generate electricity worldwide is projected to increase from 25 % of primary energy in 2004 to 31 % in 2030.

Aeroengines

Aviation fuel currently corresponds to 2-3 % of the total fossil fuels used worldwide. Of this total, the majority ($>$ 80 %) is used by civil aviation. By comparison, the whole transportation sector currently accounts for 20-25 % of all fossil fuel consumption. Thus, the aviation sector consumes 13 % of the fossil fuel used in transportation; it is the second biggest sector after road transportation, which consumes 80 % (IPCC, 1996b).

Concerning air transportation, the market is also in constant expansion (figure 5.1, right). Combined with the development of new technologies such as internet, flying has become a common consumer's habit, helped by the success of the low-cost companies that encourage early booking and reduce their cost by offering spartan flight conditions. The air cargo transportation is also increasing at about the same rate. This trend has survived the 1997 south-asian crisis, the terrorist attacks of September the 11th and the SARS. AIRBUS lately published a forecast report[2] on the further expansion of this market that is expected due to the rash economical development of India and China. MTU reports an expected world-wide long-term growth of about 4 to 5 % p.a. also with a focus on the emerging societies and markets.

How the aeronautical industry reacts to the 2008 financial crisis is not yet clear. Of course if a slow-down in the market is everything but welcome, it is nevertheless an opportunity to reorganise for the coming challenges. The sector was so active up to 2007 that most industries such as AIRBUS worked at their maximum capacity, summing-up delays in the production of machines such as the A380. Now the industry finds itself suddenly taken in the trap between an order book which is full, but no liquidity to perform the work because the banks will not do their job. An alarming signal is the withdrawal of major industry partners in the EU call 2010 (ground-research oriented) - that announced that they pass this occasion and concentrate on the EU Call 2011 (applied research).

5.1.1 Economical aspects and environmental challenges

5.1.1.1 Environment

Global GHG (Greenhouse gas) emissions due to human activities have grown since pre-industrial times, with an increase of 70 % between 1970 and 2004 [Pachauri and Reisinger, 2007]. Hoffert et al. [Hoffert, 2002] reports an augmentation of CO_2 concentration from 275 to 370 ppm over the 20th century. For information, one passenger flying a round trip from Graz to Munich and back (about 640 km) makes a footprint[3] of about 90 kg of CO_2.

The ozone layer depletion achieved about 20 % and 50 % respectively over the northern and southern hemisphere over the 40 last years [ozo, 2006]. Recent storms, hurricanes and floodings achieved the highest intensities ever logged in climate reports: extreme temperature events have changed in frequency and/or intensity over the last 50 years, and there is an observational evidence of enhanced tropical cyclone activity in the north Atlantic since about 1970. The correlation between global activity and global warming is a passionate subject of discussion, with deep political and economical implications. To the facts set out previously, the global warming sceptics oppose a bias due to long term natural cyclic changes, or sudden changes due to solar or volcanic activity, plus the fact that sinks and sources for GHG are not yet well understood nor modelled. Taking this into account, the competent authority on climate change, the IPCC (Intergovernmental Panel on Climate Change[4], a body of the United Nations) stated in 2007 that human activity is *very likely* (probability > 90 %) to have an impact on the climate change [Pachauri and Reisinger, 2007, Foucart, 2007].

According to the IPCC report [Pachauri and Reisinger, 2007], 80 % of the world's energy needs are covered by the use of Hydrocarbons. The energy and transport sectors require respectively 51 % and 26 % of this total energy. The overall energy supply and transports account for 25,9 % and 13,1 % respectively

[2] http://www.airbus.com/en/corporate/gmf/
[3] http://www2.icao.int/public/cfmapps/carbonoffset/carbon_calculator.cfm
[4] http://www.ipcc.ch/

of the total emitted greenhouse gases (GHG). When considering the only CO_2 emissions (56.2 % of the total GHG) based on the use of fossil fuel ressources, these values become 45.1 % and 23 % respectively, the total being estimated to 27.5 Gt CO_2 per year (in 2004). Crossing these numbers with those of IPCC report [Metz et al., 2007], natural gas fired powerplants account for about 6.5 % of the total CO_2 emissions, and air transport for about 2.5 % (in 2004).

The precautionary principle recommends a strong reduction in the GHG emissions combined with a reduced and/or optimised use of the natural ressources. The Kyoto Protocol (1997, [http://unfccc.int, 2005]) was the first international attempt under the guidance of the United Nations to regulate GHG emissions through a weighting of emission-bonus and -malus as a function of the degree of industrial activity of a given country, and emission reduction targets to be met at a given deadline (for instance 2012). It was ratified by 183 parties (status in 2008) and came into force in 2005.

At the time of production of this report, the Copenhagen Conference on Climate Change (7-18/12/2009) ends up on a mixed result. On the one hand, the great world economies such as the USA recognise the problematic of pollutant emissions and its impact on climate and health - which is a breakthrough. On the other hand, they refuse the creation of an authority overruling the country's sovereignty. The main objectives were a limitation in the temperature rise by 2050, combined of course to reduction in CO_2 emissions, a financial support to enhance the development of low-emission technologies in emerging countries, and a system of monitoring and controlling to make sure the objectives are kept.

5.1.1.2 Natural resources, and replacement fuels

GT operation is based on the use of hydrocarbon fuels. The world's natural resources are a limited quantity, and our current rate of consumption is not sustainable on the long term.

Most documents tend to agree that we have or are about to reach the peak oil [Kjärstad and Johnsson, 2008], which is the point in time when the maximum rate of global petroleum extraction is reached, after which the rate of production enters terminal decline. Oil should get harder to extract in the near future, with a dramatic effect on the fuel costs. In order to assess or predict the possible scenarios on hydrocarbon availability as a function of the current and growing economies, the International Energy Agency (under the direction of the Organisation for Economic Co-Operation and Development-OECD) produces and updates yearly a report named "World Energy Outlook" [weo, 2006][5]. The worst case scenario is a collapse of energy ressources by 2030, if no adapted policies are chosen.

The oil companies claim that new extraction technologies such as the use of tar sands may increase the known oil quantities by 35 % [Kjärstad and Johnsson, 2008]. The European Union encourages the development of renewable energies, with the aim to cover 15 % of its needs in terms of energy by 2020. For instance, XTL (Anything-to-Liquid) is an option based on the Fischer-Tropsch process: through partial combustion of carbohydrate (e.g. biomass) or non-liquid hydrocarbon (e.g. natural gas, coal) and catalysis of the between products CO and H_2 one can produce synthetic fuels apt for aviation [Moses and Roets, 2008].

[5] http://www.worldenergyoutlook.org/

5.1.1.3 Moral, Ethics, and Decision-Making

While lecturing on the problematic of hydrocarbon use and environmental impact, the applicant likes to draw a parallel with the problem of getting overweight. For those who face this, it is the kind of problem where one says "Tomorrow I do something" - where tomorrow means actually someday - ignoring the frustration of it and the mid-range risks such as sickness and shorter life expectancy. There is always an excuse: life is tough, other problems are to be treated more urgently, the mind is strong but the flesh is weak.

Our global approach on the problematic of hydrocarbon use and environmental impact is treated much alike, with a lot of passionate debates but also sometimes a lack of seriousness. Politicians make use of passion and populism to facilitate decision making ("Our house is burning, but we look somewhere else", Jacques Chirac, speech at the Earth Summit in Johannesburg, September 2002; "It's important to rescue the frogs", Al Gore, *An Inconvenient Truth*, 2006). However, dramatisation and demonisation can be a double-edged sword used by their detractors.

The following lists a series of ideas and facts that are not purely of technical essence, that should help rationalise the debate, and state decision making on solid grounds.

Fair-trade: The local resources of the developed countries do not cover their energy needs. There is a great energetic dependency focused on the Middle East, the Caribbean Gulf, Russia or Africa. The African reserves are at the moment a source of international tension, such as in Sudan or Gabun at the moment. In Sudan, the government is supported by developed countries to ensure their access to oil concessions although the repeated violation of human rights are known (civil war with ethnic cleansing in Darfur). The primary importers of Sudanese oil are Japan, China, South Korea, Indonesia, and India. Sudan exports oil since 1999 that in between has reached 92.6 % of its export value in 2007 (Source: Ministère des Affaires étrangères[6]). Gabun, a former French colony, is a democracy where the son of the former lifelong-elected president (Omar Bongo, deceased 2009) was "elected" to further direct the country. The arguments of Bongo Junior's opponents were a greater return-on-investment on the country's oil ressources. This election was supported by the French government, and there will be no change concerning the oil exploitation of the oil firm TOTAL.

The question is asked, whether our needs can have priority on our principles - and where shall the limit be set: where does the energy come from, who benefits from the oil concession money, what may be the consequences of an unfair trade?

Food price: In 2008, the barrel of Brent oil has achieved record levels of 145 $ in July before sinking to 42 $ in December (2008 stock exchange crisis, source: Les Echos[7]). The period where the value was above 115 $/barrel provoked a great demand in biofuels, since the prices of ethanol or vegetable-oil blends became price-effective. However, a collateral effect was the rise of food price, affecting particularly the populations of the third-world and emerging countries. The decoupling between the energy and the food market is an important issue. This question was arisen during the preparation of the EU project ALFA-BIRD. For instance it was asked that the option consisting in farming algae for biofuel purpose, was that only saltwater algae are chosen to save precious freshwater. Another argument for algae ist that they do

[6] http://www.diplomatie.gouv.fr/
[7] www.lesechos.fr

not belong to the conventional food chain.

Our generation's footprint: From a humanist point of view, it is a noble commitment to worry for the future generations. The legacy for our descendance is our knowledge, our infrastructure, our level of technology, the wish for a world in harmony and the hope for a long and prosper life. But all this is hopeless in a future world with depleted ressources and irremediably damaged environment. The preparation of the post-fossil fuel era is therefore a matter of great importance.

***bonus Pater familias* common sense:** However, a drastic change in our way to consume energy and its impact on the economy is not realistic. We shall make the best of the situation, involving the minimum of fuel. The optimisation of energy needs is not just based on the efficiency of thermal machines or their low-NOx aspect, but also what we make out of it. The effort shall be harmonised "from well to wing", and the end-user shall be reeducated to make a proper use of the machine (e.g. optimisation of the fuel transport and distribution, tentative to achieve maximal seat occupancy per flight, optimisation of the aircraft security procedures regarding engine extra running-time on the ground and in the air, capacity to switch on and off rapidly to the electrical network at peak consumptions). The motto "do not waste energy" is more than ever an issue.

5.1.2 Why it is important, to further support the development of GT combustion technology

The question is asked, given the aforementioned elements, why shall we take the defense of GT combustion technology? Why shall we train engineers to further develop these technologies, and what is the sense of it?

One can draw a historical parallel between the steps achieved in using fire and our degree of civilisation (capture and maintain of fire at the dawn of Mankind for heat, light in the dark and protection against wild animals, then cooking, pottery, metallurgy, weaponry, from the early thermal machines of Newcomen and Watt to today's standards). Nevertheless, the extensive use of fire implies the notions of security and responsibility, and this also beyond the risk of accidents. The modern Prometheus is challenged by the depletion of the world's natural fuel resources, and by a probable impact on the environment.

The "western civilisation" is based on a 300-year-old industrial tradition, a democratic policy and a free-trade economy, ensuring in principle the fundamental liberties of the individuals, peace and prosperity. Modern geopolitics and socio-economics gave birth to a supranational economy, where production and finances are strongly decentralised and stateless. This phenomenon, called globalisation, is also sustained by low-cost and largely available energy resources. The world's energy consumption based on fossil fuel is currently estimated to be a rough 10 TW [Hoffert, 2002].

Despite its inequities and harshness, despite the risks involved, the western civilisation provides the mankind with its primary needs: food, warmth, and shelter. It also offers him the possibility to choose his own life. The western civilisation has overcome great challenges, with technical achievements never reached before in known history. Man, despite its weak condition and mortality, is able through development of technology bound with social progress to push forward most of all frontiers. Aeronautics allow us not only to fly, but also to move fast, go far away and safely. Electricity provides us not only the basic domestic services but also much more for leisures and cocooning, two "everyday life" notions that were pure luxury only one century ago. The culture has never been so multidisciplinary, and the lifelength so long. To this progress, Rousseauists [Rousseau, 1778] oppose the lost of innocence and the corruption of the mind through materialism and decline of spiritualism. Philosophy, ethics, the lessons learned from industrial mistakes and the precautionary principle facing the unknown set the guardrails of this development.

To summarise: we cannot restrict the production of gas turbines for propulsion and power to a *numerus closus* contingent without a negative impact on the economy. We shall not waste on the meantime the ressources we need. Due to a force majeure risk, we have an obligation of development for existing systems as well as retrofits on old ones to minimise the environmental impact. We have also a moral obligation of changing our own education, mentality and bad habits in direction of finding a more sustainable way of life. We shall also not fall in the trap of excessive regulation that would kill our liberties and creativity. We have to stay alert and inventive. We shall make better gas turbines, as well as a better use of them.

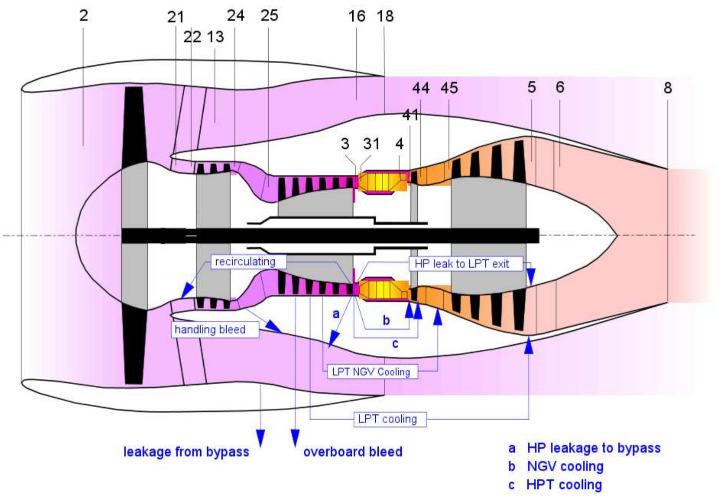
5.2 Industry: State-of-the-art on GT technology

5.2.1 Gas turbine technology

5.2.1.1 Gas turbine basics

Gas turbines are powerful and elegant engines designed to provide thrust or/and torque. The history of gas turbines is very recent, since the first effective demonstrators for propulsion and power appeared in the late 1930’s (4MW power gas turbine from ABB as a in Neuchâtel, Switzerland, in 1939, and the first jet-powered flight in Germany of a HE178 airplane with 3.7 kN thrust in the same year). Ever since then, gas turbines established themselves as The Standard in the fields of aeronautics because of their high thrust-to-weight ratio compared to other propulsion systems and their capability to reach or even exceed the sound barrier. The same holds in the power generation sector where their gross output surpassed the most powerful diesel engines, due to their relative design simplicity (the only moving part is the rotor). The largest power gas turbine in 2008 is the SGT5-8000H from SIEMENS, achieving a gross power output of 340 MW. The overall efficiencies of modern standard gas turbines achieve about 40 % for propulsion and power, where the latter can be extended to 60 % when coupling an industrial GT to a steam turbine (achieving 530 MW in the case of the SGT5-8000H with combined cycle).

The thermodynamics of conventional gas turbines can be described in a first approximation by the Brayton cycle: the fresh air undergoes a reversible adiabatic compression in the compressor stage, then combustion takes place at constant pressure and rises the temperature of the medium and the resulting hot gases expand in the turbine. For power generation the turbine stage is dimensioned to transmit the necessary work to the compressor, and the extra torque is used to run the generator. Aeorengines often rely on a multi-spool architecture, allowing to keep the fan at low rotational speed, and to achieve high pressure ratios using a high-pressure and high-rotational speed spool. In which case the high pressure turbine is dimensioned to run the high pressure compressor, and the low pressure turbine is dimensioned to rotate both fan and low-pressure compressor. The propulsive effect results from the combination of the by-passed air ejected by the fan and of the hot gas ejection into the ambient.



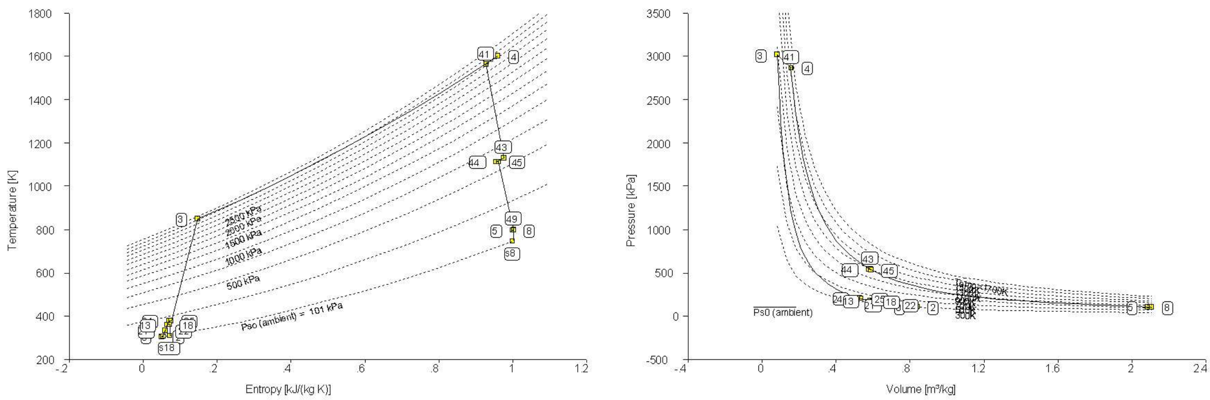


Figure 5.2: *Propulsion system and thermodynamics. Left: turbofan model, two-spool with booster. Bottom: $T-S$ and $P-V$ thermodynamic diagrams. Performance calculation performed at take-off conditions using GASTURB [Kurzke, 2006]*

5.2.1.2 One application: the turbofan

The optimisation of the baseline thermodynamic principle leads to a "turbofan" layout adding a cold bypass flow to the hot core flow. This is representing almost all todays' aeroengines in service in civil aviation. The optimisation process leads also to a high by-pass ratio. Most of the intake air flows through the by-pass, where the fan acts as a propeller. The combination of these two processes (fan+jet) produces thrust more efficiently than other jet designs, and presents other advantages such as jet noise reduction.

Figure 5.2 represents a turbofan similar in many aspects to the CFM56-5B3 that flies on the AIRBUS A321 (take-off thrust 145 kN, bypass ratio 5.4). This figure was generated using the software GASTURB [Kurzke, 2006] for gas turbine optimisation and cycle analysis. The stations of interest for the thermodynamic diagrams follow:

- station 2 is the air inlet condition (defines the total air mass flow entering the nacelle's hub),
- station 21 is the air condition after the fan at the mass flow split between engine core and bypass,
- station 22 is the booster inlet condition (compressor stage mounted on the low-speed shaft, on which the fan is also mounted, composing the low-pressure compressor stage LPC),
- station 25 is the high pressure compressor (HPC) inlet condition, measured at the end of the compressor's intermediate duct

- station 3 is the inlet condition in the combustor pressure casing, taken at the diffusor's inlet
- station 31 is the combustor inlet condition,
- station 41 for high pressure turbine inlet condition,
- station 45 for the low-pressure turbine inlet condition, taken at the end of the turbine transition duct
- station 6 for the hot nozzle inlet condition,
- station 8 is the nozzle outlet condition.

For combustion investigations, the stations of interest usually cover the domain from value 3 to 41.

A refined thermodynamic cycle of a real two-spool engine is presented in figure 5.2. It describes the state variables such as temperature T, pressure P, specific volume V and entropy S of the air passing through the machine, at the stations described before. The shown operation point is take-off. As in any thermal machine, it is important that the delta between the highest and the lowest cycle temperature is set to the highest possible value. Due to material reasons, the entry temperature of the burnt gases into the turbine (TET) at take-off (full-load, in figure 5.2 about 1600 K) is therefore often the limiting factor. Advanced materials, thermal barriers and cooling techniques allow to set the admissible TET well above the melting temperature of the walls and rotating parts.

5.2.1.3 Trends for turbofan technologies

Table 5.1 reports that some GT with advanced cooling techniques can undergo up to 2000 K TET. In order to augment the overall efficiency, the pressure ratio is relatively high (about 30 in many current systems, can go up to 50) resulting in a higher T_3 temperature hence in an even higher T_{41} temperature for a similar fuel burn. The work corresponding to the cycle loop surface on the $P-V$ diagram surface in figure 5.2 is required for the entrainment of the large fan.

To augment the machine efficiency, one idea is to augment the OPR (30 and more) while heat addition at large pressure levels generates less entropy than at lower pressure, at the cost of a more complicated engine core architecture (larger compressor and turbine components, up to three spools - low pressure, intermediate pressure and high pressure spool). The combustion chamber (CC) becomes more compact.

Table 5.1: *Some extreme (P,T) parameters in current GT technologies at maximum Take-Off conditions. The limiting factor is the maximum bearable material temperature without cooling: 1250 K. Source: MTU*

Parameters \ Application	Regional & middle range engines	Long range engines	Trend
Overall Pressure Ratio OPR	30 - 35	38-50	↗
Bypass Ration BPR	4 - 6	7 - 10	↗
HPT Turbine Entry Temperature TET	1750 - 1850 K	up to 2000 K	↗
LPT Turbine Entry Temperature T45	1150 - 1250 K	up to 1350 K	-

The inlet air temperature can reach 800 K and more in absence of intercooling. The air split in the combustor involves less cooling because of a better compromise between injection aerodynamics and wall heat management. The density of thermal power in the main combustion zone achieves orders of magnitude up to the MW per liter.

A novel concept involving a gear box between the fan and the low-pressure spool allows the construction of two-spool aeroengines with high OPR, where the high rotation velocity of the LPC/LPT is reduced to sub-stall rotation velocity of the fan with the help of a gear box. This offers a simpler construction than a three-spool engine (also lighter provided the gearbox weight is smaller than the added weight of a third spool), and each rotating component can run at its maximum efficiency. This concept was used so far on the HONEYWELL TFE731-60 aeroengine flying with the Dassault Falcon 900, a business jet. It is currently being validated on a PW1000G aeroengine designed for the MITSUBISHI regional airjet MRJ, with 12 % less fuel burn than the reference conventional engine for this category. PRATT & WITHNEY announced recently their intention to adopt this technology on larger engines (Flug Revue 2/2007).

5.2.2 Definition of the requirements

5.2.2.1 Specifications of a GT combustor

State-of-the-art GT technology, plus external factors such as discussed before show how numerous the constraints are for the combustion engineer who has to design a new system. The many parameters are summarised in figure 5.3. The combustor is a complex system, it results from a multitude of compromises, and requires an extensive and expansive trial-and-error session before being validated. The main problem is that precise combustion research often requires full-scale experiments, since many parameters such as thermochemistry at given (P,T) conditions have to be simulated at scales specific to the flow.

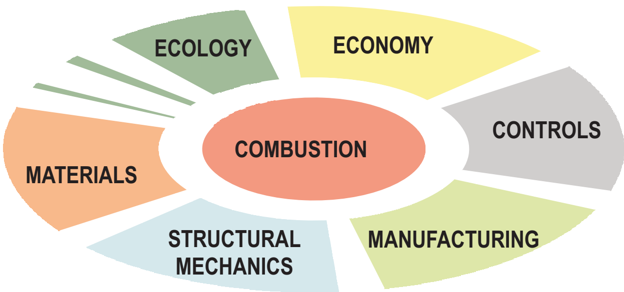


Figure 5.3: *Technical and external constraints for GT combustor design*

The eleven specifications for combustor design that follow were prescribed by Lefebvre [Lefebvre, 1999b] more than 30 years ago. They are still up-to-date. These are the baseline rules for advanced combustion management.

High combustion efficiency : Combustion efficiency ($>$ 99.9 % at design point) achieves quasi 100 % on all modern combustors at cruise. Combustors with efficiencies of less than 90 % anywhere else on the operation enveloppe are unlikely to be tolerated [Walsh and Fletcher, 2004].

Reliable and smooth ignition (no detonation), especially at low temperature. Ignition is usually performed with help of high-energy spakplugs. Ignition difficulties at cold start are similar to the ones met with internal combustion engine, with the risk to spray too much kerosene before the flame starts, and the resulting risk of detonation. Civil aeroengine combustors are also designed to ignite at windmilling condition in case of emergency, where the pilot manages to keep up the required speed with the still active engines, or speeds up in a descent manoeuver to recover the minimum air inlet velocity necessary to maintain the fan in rotation (windmilling), compress the air, and achieve the right T_{31} for auto-ignition. Ignition at extremely cold temperatures for helicopters that landed at high altitudes in the mountains, as well as emergency re-ignition for combat airplanes at high altitudes (10-20 km) where the air is extremely thin are also important issues of R&D.

Wide stability limit (over the whole operation range): Stability is here meant in the sense of flammability, or pushing the flame blow out limits well beyond the engine's operation.

No combustion instability: where stability means steady-state flame, and instability is often of aero-thermo-acoustic origin.

Low pressure loss between compressor and turbine: The pressure loss of the liner varies from 3 to 5 %. If losses in the diffusor are to be minimised, a minimal value is required to maintain turbulence in the liner (jet swirls and cooling jets).

Cooling air: The reduction of the amount of combustion chamber cooling air (currently about 1/3 of the main air) has an influence on the overall efficiency, since turbulent mixing is a highly entropy-generating process. Less cooling air tends also to a lower overall pressure loss. However, augmenting the pressure ratio for future designs result also in augmenting the T_3 temperature, which acts against the cooling effectiveness.

Deliver the ideal gas temperature at the turbine inlet: Temperatures up to 2500 K are achieved in the primary zone at full load, cooled down to 2000 K in the dilution zone before reaching the turbine's first guide vanes. Temperature gradients, as well as unsteady temperature fluctuations, augment the fatigue of the parts at turbine entry. The Overall Temperature Distribution Factor (OTDF, see equation 5.1) is the ratio of the difference between peak and mean temperature right before the plane of the HP turbine Nozzle Guide Vane (NGV). OTDF should be controlled to be less than 50 %. The Radial Temperature Distribution Factor (RTDF) is analogous to OTDF but uses circumferentially averaged temperature values. RTDF should be controlled to be less than 20 % [Walsh and Fletcher, 2004].

$$\text{OTDF or RTDF} = \frac{T_{4max} - T_{4mean}}{T_{4mean} - T_{31}} \tag{5.1}$$

Low emissions, no unburned, no soot: The problem on emissions is that they are conflicting with each others. NOx appear at high temperatures and long residence times, at near-stoichiometric conditions. UHCs, soots and CO appear at extreme lean or rich combustion. Since it is not feasible to achieve low levels of NOx, UHCs and CO at once, an acceptable compromise is to be found.

Ease of maintenance: The maintenance shall be performed on time intervals greater than 10 000 hours of operation on power turbines. The parts shall be easily accessible and disposable.

Integration aspect in comparison with the other turbine elements: This is less a problem for industrial GT where notions of size and volume are flexible. For aeroengines, the dimensions and weight of the combustor have to be optimised.

Lifetime - durability: A modern aeroengine is designed to operate up to 50 years.

Multifuel capability: This was meant originally for stationary gas turbines, but can be extended to aviation using biofuels.

For instance, the company MTU sets its objectives as follows: low UHC, no soot, lowest possible NOx emissions, combustion efficient near 100 %, high mechanical integrity, low weight, low cost and low volume design. These parameters are set in view of all constraints of selected architectures, and for all relevant cycle conditions.

5.2.2.2 Target emissions to be reduced

GT combustor designers put a very strong efforts on reducing the impact on the environment of their machine while improving constantly their efficiency (taken separately, the notions efficiency and low-emissions may often be conflicting).

The environmental issues for a combustor mean primarily to reduce the CO_2, NOx and CO emissions, and at a secondary level to reduce noise. The authority on emission regulation and certification for aeroengines, including noise, is the ICAO/CAEP (International Civil Aviation Organisation / Committee on Aviation Environmental Protection) [ica, 1993]. For more information about the impact of these emissions on the environment, please refer to section 5.1.1.1 p.55.

Carbon dioxide, CO_2

The production of CO_2 is specific to the average carbon contents of the fuel (this explains why natural gas is favoured as a "low-emission" fuel since its main composant is methane CH_4, having thus the lowest carbon content in the alkane group). It is also proportional to the specific fuel consumption (TSFC), so that reducing CO_2 emissions means increasing the overall efficiency (see section 5.2.1.2 p.60). In other words, it means saving fuel for doing the same job. This parameter is therefore a major sales argument.

The CO_2 represents 77 % of total anthropogenic GHG emissions in 2004 (74 % in 1990). Radiative forcing of CO_2 predominates over all other radiative forcing agents [Pachauri and Reisinger, 2007]. It results from the continuous increase in atmospheric CO_2 concentration caused by human activities since the preindustrial era. CO_2 emissions represent about 6 % of the exhaust mass flow exhaled by a conventional aeroengine core.

For land-based gas turbines, one strategy for advanced power plant cycles is CO_2 ground sequestration and storage (e.g. the Graz Cycle [Jericha et al., 2004]), where CO_2 is separated from the exhaust gases and injected into the deep ground, where it shall be trapped by airtight layers. A part of it may eventually react with the surrounding because of the high pressure and temperature and remineralise. However, elements such as the CO_2 separation and storage costs, the geologic assessments on ground eligibility, and the cost-effective construction of a demonstrator at industrial size retarded so far the validation of this concept.

Nitrate oxides NOx

The NOx emissions (generic term for nitrate oxides such as NO, NO_2, N_2O, ...) contribute to the GHG formation at ground level and to the ozone layer depletion at high altitude. They represent 7.9 % of the yearly emitted GHG emissions, and are classified third after methane (14.3 %) and CO_2 (77 %). They represent up to 0,01 % of the mass flow of the exhaust gases of a classical GT core (Source: IPCC 1999). They mainly result of the reaction of dissociated air nitrogen in the reaction zone (thermal NOx). The higher the temperature, the longer the residence time, the larger the NOx concentration.

Figure 5.4 shows the limits fixed for NOx emissions at ICAO-LTO cycle (Landing and Take-off cycle, as defined by the ICAO), for several certified engines parameterised over OPR. For instance, one goal of the NEWAC project (see section 4.1 p.47) is to achieve 76 % NOx reduction in comparison with CAEP2, which means limiting the NOx emissions in the [20 to 30 g/kN/cycle] range for an OPR $\in$ [20 to 60]. Note that the admissible NOx level augments with the OPR, since higher combustor temperatures are involved resulting in a larger NOx production.

Modern land-based gas turbines aim at NOx values below 20 ppm, ultra low NOX means below 5 ppm.

UHCs and soots:

Unburned hydrocarbons (UHC) and soots (or smoke) result from a poor combustion respectively at extremely lean and rich combustion. Hence, they degrade the combustion efficiency. Furthermore, they fall in the GHG class. They are normally associated with poor atomisation, inadequate burning rates, the chilling effect of film-cooling air or any combination of these. These emission take place in principle at part load. Typically, liquid-fuelled combustors produce more of these emissions than gas-fuelled GT combustors at similar thermal power.

They provoke health problems when accumulated in confined atmospheres since these are submicronic particles with high aromatic contents.

CO:

CO emissions also results from a poor combustion respectively at extremely lean and rich combustion. It is a potential fuel since it can be further reduced to CO_2, hence degrade the combustion efficiency when produced. It results from inadequate mixing of fuel and air, inadequate burning rates in the primary combustion zone or insufficient residence time because of a too sudden air injection quenching.

It is highly toxic, provoking rapid suffocation when unnoticed because odourless and colourless. Special security measures are to be taken when working with GT combustion in a confined atmosphere.

Note that CO and UHCs have a similar growth rate when operating at extremely rich or lean conditions, whereas NOx appear mostly near stoichiometry. It is therefore not possible to reduce all emissions at once, a compromise has to be found.

5.2.2.3 Combustor architectures

Figure 5.5 is a synthesis of the main designs of combustors found on current systems, summarising the potential of different Low-NOx strategies as seen at the end of the 90's. Gas turbine Low-NOx systems started to be studied about 30 years ago during the 70's (e.g. early works on RQL technology of Pierce et al, 1980,

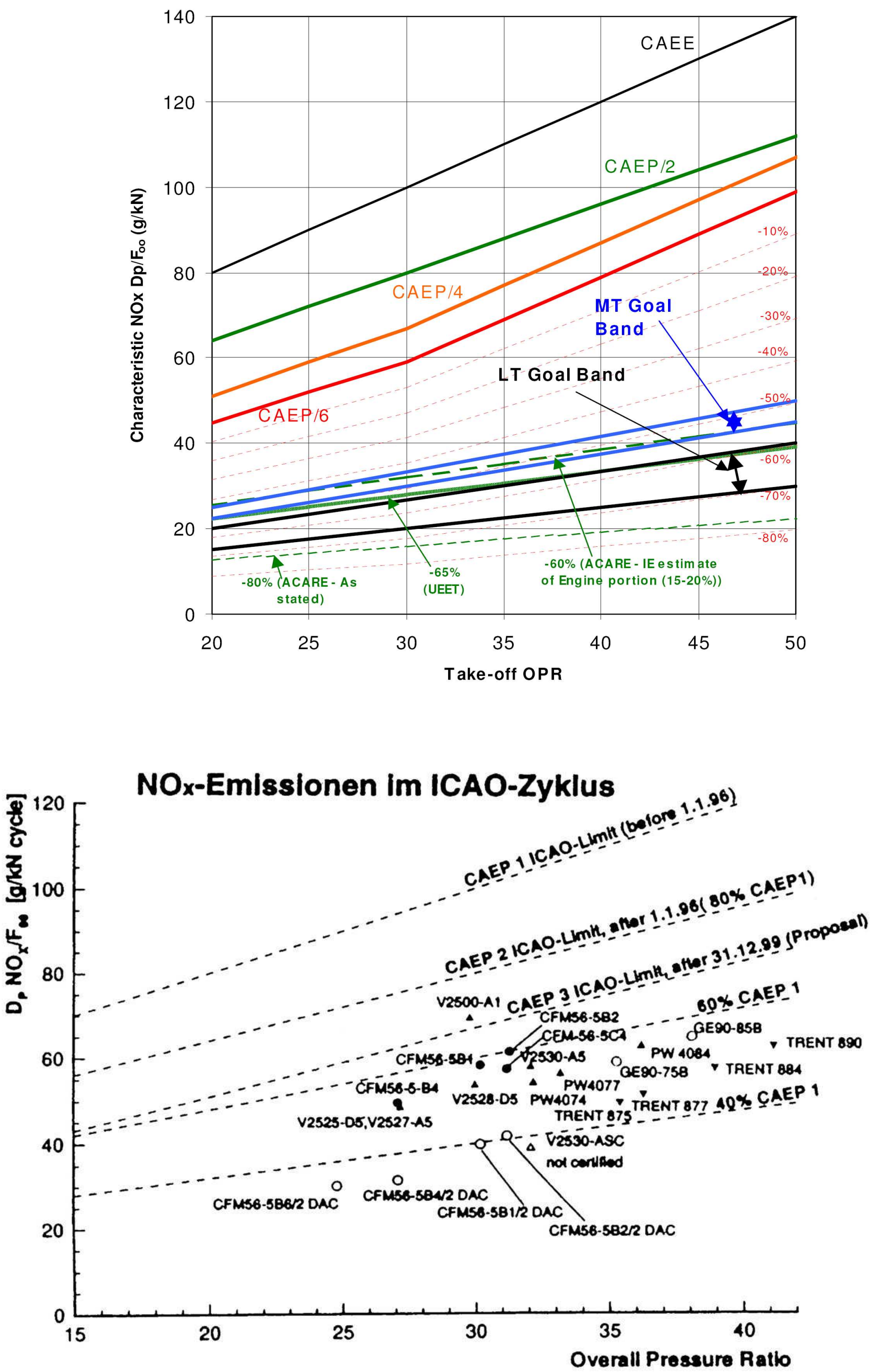


Figure 5.4: *ICAO-CAEP target emission levels [ica, 1993] in the medium and long term, and some existing engines*

as reported in [Smith et al., 1991]). The Research & Development effort was strongly enhanced beginning of the 90's, with the introduction on the market of low-emission burners on ABB, GE and SIEMENS land-based machines, as well as the introduction of double-annular combustors (DAC) on turbofans during that decade. Low-NOx concepts are compared to the conventional combustor, and estimates of NOx reduction are drawn. The colours show the domain of operation of each concept, for instance in the rich and lean domain for the Rich-burn/Quick-mix/Lean-burn (RQL) burner, or lean combustion with the lean premixed prevapourised concept (LPP).

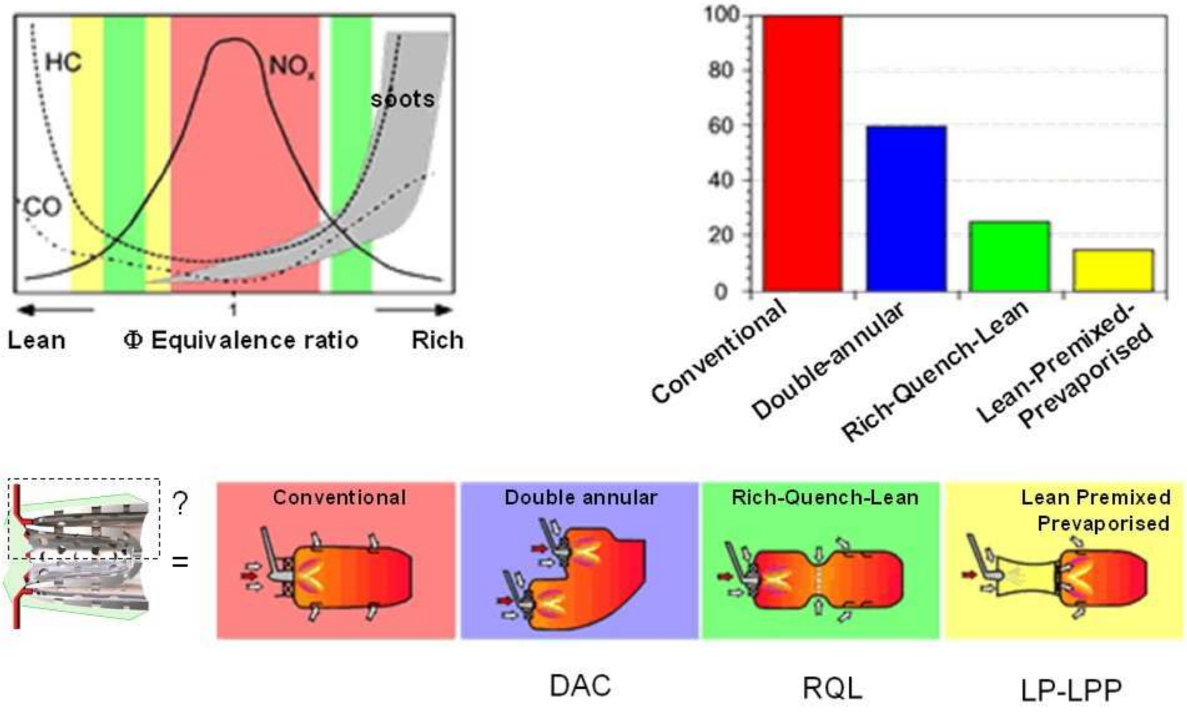


Figure 5.5: *Low-emission concepts: an overview. Figure source: ITS, Universität Karlsruhe (homepage, 2006)*

The conventional combustor

This is the most represented architecture in current civil aviation. The conventional combustor combines an air-blast injection system to an annular combustor geometry, see figures 5.6 and 5.7. It is also known as SAC (Single annular combustor) with near-stoichiometric combustion in the primary zone ($\phi \simeq 0.8$). The injector of the air-blast type became a standard injection system during the 70's (works of Lefebvre, see [Lefebvre, 1989a]) and complemented the pressure nozzle injection, ensuring a refined spray, by taking advantage of the aerodynamic forces of the injection. Figure 5.6, right summarises the aerodynamics of the injection, where fine atomisation takes place in the mixing layer between two swirled flows at the tip of the injector, and the flame stabilises around the internal recirculation zone, a mechanical flameholder is therefore not required. Figure 5.7 details the air-blast technology. In comparison with elder combustor designs comprising can combustors or tuboannular architectures and pressure nozzles for injection, the UHCs are reduced to the status of traces in a SAC geometry, and there is much less black smoke plume at the tail of modern jets. Combustion is steady, and the thermal efficiency is high. The next concepts detail

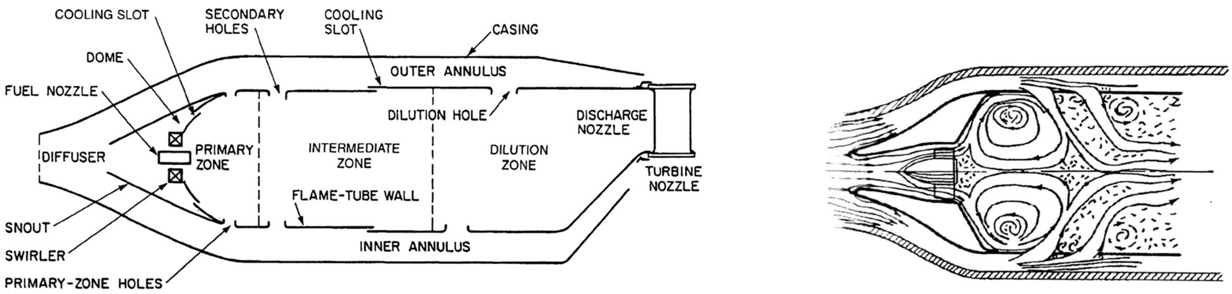


Figure 5.6: *Basic GT combustor*

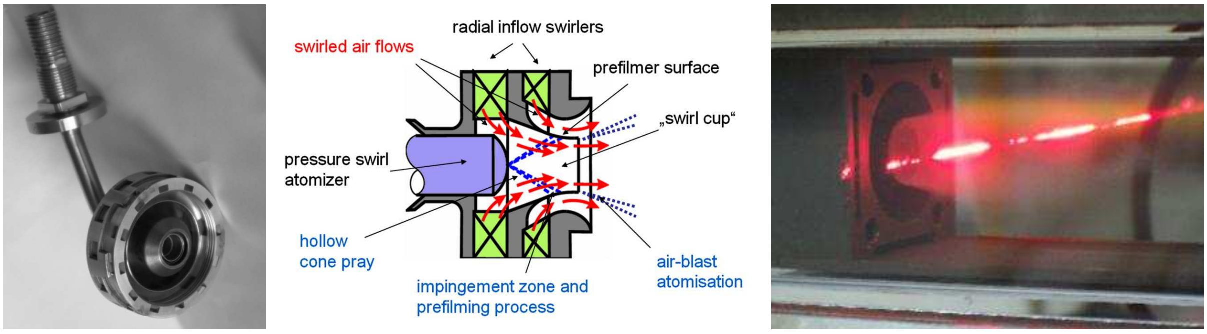


Figure 5.7: *Left: air-blast picture (standard industrial system). Centre: principle of air-blast atomisation. Right: laboratory airblast injector under operation at the DLR Cologne spray test rig, using laser diagnostic methods (here: infrared absorption for fuel vapour measurement [Giuliani et al., 2004a])*

how emissions can be further reduced compared to this reference.

Staged combustion

The idea is to split one flame into several that can be driven separately. As a result one gets more flexibility on their respective power and can optimise the operation. It often consists in a pilot flame burning at near stoichiometric conditions that maintains combustion and ensures part load operation, and a main zone with lean combustion that provides the thermal power at full load. Figure 5.5 shows the DAC concept (Double-Annular Combustor). Reducing and distributing the single burners results in smaller residence time for NOx formation, combined with the operation at lean conditions resulting in up to 40 % NOx reduction compared to a conventional combustor. However, the added complexity of this staging is such that some engine manufacturers are investing to come back to a SAC geometry where the split is placed in the injector itself (TAPS concept: twin annular premixing swirler). The commercial introduction of the CFM56 with first generation DAC was not a commercial success (more expensive, more maintenance costs), but the second generation GE90 and CFM was more successful. This technology is successfully in operation since about 10 years.

Rich-burn/Quick-mix/Lean-burn (RQL)

This is the third low-NOx concept presented in figure 5.5, with target emission reduction more than 50 % than the conventional burner. A rich mixture is injected, and rich combustion takes place in the combustor dome, ensuring the combustion robustness. After that a secondary injection of air takes place, quenches the flame and lean combustion takes place downstream, providing most of the thermal power. The drawback is a higher production of soot in comparison with the conventional burner. RQL technology was successfully commercialised (e.g. the TALON burner flying with the PW6000).

Lean premixed prevapourised (LPP)

The last Low-NOx concept of figure 5.5 is the most promising in terms of NOx emission reduction (more than 70 %). The LPP burner aims to achieve the characteristic of a well-stirred reactor while being fed with liquid fuel, and this at lean operation to minimise NOx production. It consists of a classical air-blast system and of a premixing tube where fuel vaporisation and mixing take place. The lean operation is set at an equivalence ratio such that NOx emissions are strongly reduced, while attention is paid that the thermal efficiency is not too affected (the effect of lower flame temperature is partly compensated by energy savings due to a lower need in cooling air), that the CO and UHC emissions remain low, and that the blow-out limit stays away from operational bandwidth. However, the greater transit time of the reactants between injection nozzle and flame front favorises the couplings between turbulence and acoustic, facilitating the appearance of combustion instabilities. This is the main drawback of this concept that retarded its industrial use.

5.3 Research: State-of-the-art on GT combustion physics

5.3.1 Fundamental research approach

In comparison to the combustion engineer who works at system level, the scientist is trained to work at parameter level. His task is to isolate a given problem, separate the constraints inherent to the whole system, and concentrate on one specific physical aspect of GT combustion. The complex GT environment disappears and leaves place to a test cell with defined boundary conditions. The specific industrial problem is broken, if possible, into a universal model. Of course, the interactions present in a specific industrial problem are missing, and the complexity of a model arises when adding up the parameters to be taken into consideration. In the meantime, the model becomes problem specific and loses its universal aspect. The communication between industry and research is essential for the problem description in the one direction, and on the specifics of the model when delivering the results. The input of the scientist is essential for decision making towards the right compromise between optimisation of a given parameter and standard operation of a GT.

So far, the GT has been a mechanical driven machine, where the quantity of fuel injected dictates the output power. The "old-school type" industry favoured so far the "KISS" factor (Keep it simple and sexy): keeping a conservative approach, pushing forward the technology of each standard components and maintaining the part of electronics for measurement and controls al low as possible. However, given the ambitions discussed previously (e.g. achieve the ACARE[8] targets [aca, 2005] on emission reduction in aeronautics at the horizon 2020), and the complexity and degree of interaction of the phenomena announced in the following (e.g. combustion instabilities), it appears clearly that this principle has achieved its limit. The detailed GT elements, the degree of interaction between the parameters and the modelling tools have achieved such a

[8] http://www.acare4europe.com

level of complexity that each attempt to further develop the system cannot be treated anymore in the good old "quick and dirty" way. Development based on a trial-and-error approach offers limited know-how specific to one system, and a technical solution may not be valid from one system to the next.

The proposal of the scientist is to sustain GT development based on a rational approach: documentation, problem isolation and breakdown into significant non-dimensional parameters, testing, modelling and model validation, synthesis. A. Einstein defines the scientific approach as "the attempt at the posterior reconstruction of existence by the process of conceptualisation" [Einstein, 1940]. The scientist's first mission is to extend our current degree of knowledge on turbulent multiphase combustion at elevated pressure and temperature. For applied research purpose, the scientist's mission is to help the engineer to understand which parameters are of importance, and to size what is their impact and domain of application. This industry-research joint study has been successfully supported by the EU for more than 15 years, in what are called the Framework Programmes[9].

5.3.2 Known issues, and focus of the research effort

5.3.2.1 Combustion instabilities in gas turbines

Combustion instabilities such as the "Rumble" (low frequency noise, in the range of $\simeq$ 100 Hz, see Culick [Culick, 1988]) are due to an aero-thermo-acoustic coupling, involving undesired energy exchanges between the acoustics P' of a cavity (the combustor) and the flame's periodic heat release Q'. Note that the levels of fluctuation amplitudes involved in this coupling, for intensification as well as for damping purpose, are quite small compared to the mean amplitudes, usually in the range of 1 % of the average value.

The Rayleigh criterion, as defined for more than one century [Rayleigh, 1875] remains the reference concept on the condition of existence of an instability, and states that the thermoacoustic coupling is enhanced provided both P' and Q' act in phase over the combustion volume V. Putnam and Dennis [Putnam and Dennis, 1953] defined this condition mathematically with help of the R index in the following equation:

$$R = \int_V \int_\tau P'Q' \; dV \; d\tau \tag{5.2}$$

The condition $R > 0$ will enhance the energy exchange between heat release and acoustic, hence facilitate the amplification of the combustion instability. Its contrary $R < 0$ should have a damping effect, and is the condition to be reached when using active combustion stability control.

If the combustor is shaped so that it performs stable combustion at the main operating points (passive control, with help of resonators for instance [Steele et al., 2000, Macquisten et al., 2006]), combustion may turn unstable during transients. This is critical on broad-operating-range systems. This aspect has encouraged the R&D on active control (see most of the works of A. Dowling at Cambridge University [Evesque et al., 2004]), with successful applications at power gas turbines (note that the solutions presented in the papers [Hermann, 2001, Garay et al., 2006] respectively for Siemens and Alstom are specific to each system - there is no common "universal control system" acknowledged so far). Feasibility and certification of such control strategies remain an open issue for propulsion systems.

A better comprehension of the global dynamics of the combustion in GT combustors is the key towards the development of new technologies for ensuring steady-state and optimised combustion over the whole operational envelope.

[9] http://ec.europa.eu/research/

5.3.2.2 Positive aspects of unsteady combustion

The pulse combustor or pulse jet

The pulse jet, also known as Schmidt tube [Putnam et al., 1986] was the first propulsive application based on aero-thermo-acoustics. Basically it is a piston engine without moving parts where the outgoing and reflected pressure wave plays the role of the piston. It was extensively used by the Germans at the end of the second world war because of the simplicity and low-cost aspect of the resonator (the main components are a tube and a valving system for air and fuel acting at the quarter-wave resonator's frequency - a few hundred Hertz therefore its nickname "Buzzbomb"). The low compression ratio of the thermoacoustic cycle is responsible for a low efficiency, therefore this technology did not survive the competition with rocket or GT propulsion. This object remained an academic resonator, subject to regularly publications [Zheng et al., 2008].

Pulse combustion boilers

Another positive aspect is the gain in efficiency due to combustion at higher pressure than ambiant, resulting in a higher heat release in comparison with a steady-state atmospheric burner. The shorter reaction timescales are also responsible for a significant NOx reduction. Historically, F.H. Reynst used thermoacoustics for heat generation [Reynst and Thring, 1961]. However, annoyances such as noise and vibrations have overcome the potential advantages of this technology.

Near constant-volume combustion:

A last device based on unsteady-state combustion that used to be dedicated to military research and comes now progressively towards civil applications is the Pulse Detonation Engine (PDE) [Wintenberger, 2004]. One can see it as the extension of a Schmidt tube where the standard deflagration flame has been replaced by detonation. The ensemble generates intermittent thrust. For a similar reactant mixture, detonation achieves higher product temperature than deflagration, with a lower entropy generation. Hence, machines with high pressure and temperature combustor inlet conditions could increase their efficiency based on the detonation process, or single-spool machines with intermediate (P, T) conditions at the combustor inlet would achieve an acceptable efficiency because of a simplified architecture. When throttled, the PDE also acts as a pressure gain combustor, so that a smaller compressor is required to achieve similar averaged Turbine Entry (TE) conditions as in a conventional GT cycle. However, the need for research and development is huge given all the technical details to be solved before practical applications in flight. The state-of-the-art noise and emission levels generated by detonation technologies may also be detrimental given the ACARE goals. The Combustion Division did 2007-2009 a feasibility and dimensioning study on this topic, in the frame of the NEWAC project [Giuliani et al., 2009b].

5.3.2.3 Other topics

Advanced ignition

The themes of research regarding ignition focus mostly on low-NOx startup, emergency re-ignition, and helicopter GT startup at high altitudes. For low-NOx start-up, adaptive ignition may replace in the near-future the current high-energy spark-plugs. The Division Group has experienced soft ignition with use of a gas lance, where the idea is to avoid detonation when igniting the main flame. In that case, the flame thermal power is adapted to the operating conditions, and the lance works as a pilot flame. Detonation may happen because of the time gap between two sparks, when the combustor progressively fills up with fuel and that the ignition sequence started with a couple of misfiring sparks. Another low-NOx strategy for optimal ignition is the use of a laser source, where the beam energy is focussed at an optimal position somewhere within the injection domain [Moesl et al., 2009]. An improved ignitability of the fuel-air mixture can be found in the central zone of the combustor, where higher local equivalence ratios prevail and where mixing is favorable for a smooth ignition. This shall be more efficient than a wall-mounted plug. It is also of interest for emergency re-ignition.

Variable core geometry

One last aspect to be discussed is the management of the flame response to low transients (or changes that can be seen as quasi-static, in opposition to high frequency modulations that will be called dynamic transients). One potential technique to ameliorate the GT efficiency is to throttle further the turbine, or control the main air split at compressor level, so that the air mass flow fits the optimum of the compressor or turbine efficiency curves. This strategy results in a better TSFC for instance at cruise at high altitude [Lundbladh and Avellán, 2007]. Technically speaking, the power input (fuel injection), and the GT rotational velocity get decoupled. The question here is to determine how far combustion can adapt such operation changes, and what is to be modified on the conventional combustor geometry so that the flame is maintained over an extended range.

5.3.3 Flow phenomena taking place in the combustor

The phenomena of interest taking place in a combustor are broken down as follows, and are often analysed separately in a first approach:

- Flow dynamics: describes the aerodynamics in the combustor, and is set so that the best compromise is found between flame stabilisation, cooling, TE temperature and turbulence profiles versus pressure loss and thermal efficiency.
- Atomisation: describes the transition from continuous liquid flow to a sparse, polydisperse heterogenous cloud of particles. Atomisation should ideally produce small particles with a narrow-band size deviation (e.g. Sauter mean diameter below 40 μm) at all operation, and at the lowest energy cost as possible (kerosene pumps sizing, injector air pressure loss)
- Transport / evaporation: is strongly correlated with atomisation and aerodynamics. Fuel placement, evaporation efficiency and resulting equivalence ratio are dependant on the transport time lag as well as on the distance to be covered between the injection and the front flame, and all types of couplings with any of the elements of this list. This sets the flame feed conditions, as well as the type of flame (wether it is a diffusion flame, partly or fully premixed flame).
- Combustion: is seen firstly as thermochemical reaction, where the both the oxydant (the fuel) and the oxidiser (oxygen present in the air) react as soon the minimum energetic input necessary to

sustain the reaction is provided (Arrhenius' law). The thermal power released will make the process self-sustainable provided a recirculation heats up the front flame tip by use of the burnt gases' high temperature. A common value for the Fuel to Air Ratio (FAR) in kerosene-fuelled GT at stoechiometry in the primary zone is about 1/15.

The following lists a short overview of the state-of-the-art modelling and measurement techniques for each of these points.

5.3.3.1 Flow aerodynamics

The flow aerodynamics cover primarily the injection dynamics taking place in the primary zone, where the generated turbulence allows to swirl-stabilise the flow. Further down the flow and following the liner's walls, the cooling / dilution jets (jets in cross flow, impinging jets, cooling films) will progressively set the TE conditions. The most dangerous situation for a liner is the presence of a hot spot, where heat is focused on one point in absence of proper cooling, leading sooner or later to a local wreckage. An experienced combustion engineer or researcher is able to prevent these during the design phase by making use of CFD.

Combustor flow dynamics are treated with a fluid dynamics approach, based on solving the Naviers-Stokes equations. Detailed analysis, especially during the design phase, requests usually the use of CFD. The air flow analysis is based on an Eulerian scheme, the transported phase (e.g. kerosene particles) is based on a Lagrangian approach. DNS (Direct numerical simulation) offers the most detailed time- and space-resolved simulation, but is demanding in terms of computational-cost. LES (Large Eddy Simulation) that considers the simulation of large scale turbulence and uses correlations for subgrid turbulence is at the moment the preferred simulation tool [Roux et al., 2005]. Rapid flow simulations are offered using steady RANS (Reynolds-Averaged Navier Stokes), with FLUENT for instance.

Experimental characterisation is usually performed on combustors with simplified geometry (for instance dump combustors), equipped with optical access. Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) are the most commonly used measurement techniques for detailed flow description. If the measurement is not possible at realistic GT, the parameters of similarity are the inlet reference velocity and the swirl number.

5.3.3.2 Atomisation

Pioneer works for ameliorated atomisation and evaporation were done by Lefebvre for both pressure nozzles and airblast sprays [Lefebvre, 1989a, Lefebvre, 1989b, Lefebvre, 1999a]. Basically, a liquid sheet injected at low velocity in a high-velocity and highly turbulent air mixing layer provides a refined spray. The mechanisms on atomisation process have been extensively studied, the larger part at ambient conditions, and broken into sub-categories such as primary [Hong, 2003] and secondary atomisation [Pilch and Erdman, 1987] processes at low ALR (Air to Liquid Ratio by mass), and the more complex "sheet striping" at higher ALR, wich is the process of interest for GT application with the strongest needs in terms of modelling.

Droplet size measurements are performed with PDA or Fraunhofer diffraction (MALVERN). These techniques assume that the droplets in the measurement volume are spherical, and have less bias in diluted sprays.

The DLR has been intensively studying airblast atomisation of kerosene at realistic GT conditions over the 15 last years [Brandt, 1999, Giuliani and Hassa, 2003, Becker, 2005, Bhayaraju, 2007], in order to produce correlations on droplet size and spray characteristics, as well as design guidelines for airblast with and without prefilmers.

Trontin et al. [Trontin et al., 2008] report on the different CFD methods able to simulate the liquid-air interface and the separation mechanisms (level-set, volume of fluids, total variation diminishing, and front tracking). At the moment, available computational power limits the applications of fully detailed atomisation. Specific studies often simulate the injection as the introduction of scalars that represent spherical particles with a specific probability density function of particle size and velocity.

5.3.3.3 Transport / evaporation

The ONERA worked intensively over the last ten years on fundamental two-phase flow modelling, including liquid particle transportation, evaporation, fuel diffusion, and other interactions such as particle-particle or particle-wall. This research effort is done to improve the models to be implemented in the 2-phase flow code CEDRE[10].

Provided the case study is simplified, the complex phenomenon affecting droplet size distribution in a spray and vapour repartition around these droplets can be more precisely analysed. Niazmand et al. [Niazmand et al., 1994] computed 2D velocity and temperature fields inside and outside an isolated droplet, taking into account nonuniform boundary conditions at the interface and Marangoni effect [Dwyer et al., 2000]. Frackowiak et al. [Frackowiak et al., 2005] from ONERA realised a 3D-numerical simulation with an experimental approach for model validation. For model validation they used a monosized acetone droplet piezo-injector. Measurements of vapour concentration around droplets have been performed with Laser Induced Fluorescence (LIF) on monodisperse droplet streams. The 3D direct numerical simulation (DNS) is performed on the system [external flow + droplet], including the droplet's internal dynamics. This computation is very detailed while taking into account 2-way coupling, and nonuniform heat and mass transfers at the droplet interface. The same numerical exercise can not yet be performed on a complete spray because of the limited computational power.

5.3.3.4 Combustion

The flame can be modelled in 1D as a first approximation as an infinitely thin reaction zone, where the heat power input will be added. The level of model complexity augments when this process takes place with a diffusion flame, of a premixed flame, or partially premixed. The coupling with the flow aerodynamics, the heat transfer through diffusion and radiation sum up all the modules required for realistic simulation.

The first approach to combustion is the thermochemical reaction analysis at equilibrium, as in a well-stirred reactor. This will establish the order of magnitudes such as the adiabatic flame temperature as a function of the reactants and inlet conditions, as well as an estimate or trends on the emissions. This approach is the right one for the analysis of premixed flames with gaseous reactants, and a practical tool such as GASEQ[11] is used at the Combustion Division.

[10] http://cedre.onera.fr

[11] http://www.arcl02.dsl.pipex.com/

However, combustion in a GT combustor does not take place at equilibrium, and undergoes unsteady flow effects. For modelling, a CFD tool with a combustion module is required. The flame position depends on the local air flow (velocity of the order of the m/s in the turbulent mixing layer around the central recirculation zone) and fuel placement. Turbulent combustion often requires an auto-adaptive mesh where the flame front requires a finer mesh (the reaction time scales - function of the flame width - are higher than the flow time scales related to the flow turbulence or mean velocity). For advanced simulations, detailed chemokinetic modelling is required, for instance using CHEMKIN[12]. However, combined to the degree of modelling complexity of the flow, the computational costs rapidly explode.

For "affordable" GT combustion CFD, the basic reactions are often simplified to correlations covering the very products of interest for a given type of flame. The complex fuel composition is replaced by a simplified, surrogate mixture, if not a single molecule (e.g. $C_{12}H_{23}$ for kerosene Jet A1, see [Rachner, 1998]). The 2-way coupling of the flow with the flame is detailed by Poinsot et al. [Poinsot and Veynante, 2005]. Approaches of multiphase combustion are modelled by Borghi et al. [Borghi, 1999].

Although a dimensional analysis allows to downscale a specific burner, the operating conditions (especially pressure and temperature) are important since combustion thermokinetics is highly dependent on these two parameters. This is a problem, especially when having optical accesses that can only be effusion-cooled. Often, the full annular combustor is reduced to a single-injector sector to facilitate the observations. As a result, the aerodynamics are specific to a bluff-body-like flametube. The flame-flame interaction is therefore often neglected, which was a motivation for the FWF project [Woisetschläger and Giuliani, 2006] taking place currently at the Combustion Department. The flame front is analysed experimentally with help of LIF to locate the front flame, and/or to describe the appearance/disappearance of intermediate products using simplified fuels (with no aromatics). Raman spectroscopy allows a detailed analysis of the thermochemistry taking place in the flame.

5.4 Methodology

The thematic "Advanced combustion management" aims primarily to identify, inventory and evaluate combustion control strategies able to ameliorate drastically the combustion stability - or make proper use of unsteady combustion.

A complementary objective is the extension the operational enveloppe, adaption to non-conventional fuels, and forcing combustion to follow specific curves from one operation point to the next, where the curve is an optimum between machine output power and pollutant emissions.

With respect to advanced combustion management, two philosophies of research confront each other. The first states that one must understand the physics of turbulent combustion and then think in terms of an adequate strategy. The second is such that one must investigate the influence of a large variety of known Active Control Systems (ACS's) on any relevant controllable combustion parameter (mostly related to the atomisation itself). This trial and error philosophy counts partly on feedback knowledge and mostly on luck to find the required "efficient and economically sustainable device" that will improve the turbomachine. The main problem of the second philosophy is that these actions are specific to a particular device and offer very little flexibility and adaptability from one system to the next.

[12] http://www.ca.sandia.gov/chemkin/index.html

The approach we propose is to consider turbulent combustion from two opposed points of view: where unsteadiness is banned (towards stable combustion) or wished (toward pulse combustion and pulse detonation). What we learn on the one hand can be considered for the opposite application (regarding measurements and controls).
This approach is based firstly on the perturbation of known parameters (e.g. air flow modulation) on simplified configurations, and the analysis of the system's response (e.g. effect on the flame dynamic). The feedback loop on the acquired know-how should help to retain which parameter is a potential control driver, and which is not. These parameters are limited to the injection, cooling and ignition elements. The refined description of perturbated systems necessitates an adapted palette of measurement techniques, time- or phase-resolved.

The focus is put on aeroengine combustor configurations, this means two-phase flows, turbulent, reactive. In order to simplify the problem, the approach will be broken into:

- Flow dynamics due to an acoustic perturbation, and during transients
- Physics of atomisation at realistic GT conditions. Modulation mechanisms of the atomisation
- Physics of ignition, towards adaptive ignition (smooth, start at once)
- Measurement techniques development and/or adaption
- Modelling and simulation: transport, vaporisation, diffusion in an unsteady flow, combustion, 2 way-coupling mechanisms
- Control strategies, evaluation, testing and validation

It would be of course presumptuous to pretend that just one laboratory can size the problem. Significant progresses can only be done in the frame of joint cooperation with scientific and industrial partners. The following chapter discusses the creation of the Combustion Division at TU Graz, that can be seen as a research instrument designed to tackle this problematic. Our ambitions are to educate and train students with up-to-date information on GT combustion, research on advanced combustion management, become visible in the combustion community, and be recognised as a reliable research partner.

Chapter 6

The GT Combustion Division at TU Graz

6.1 The TU Graz

Graz is the second largest city in Austria (290 000 inhabitants "intra-muros") after Vienna, and capital of the federal state of Styria, in the south-east of the country. Situated on a strategic bottleneck along the Mur river opening the road towards the Alps to the north and the plains to the south, Graz grew to an important cultural, industrial and academic city (about 40000 students). Among its rich patrimony, the largest medieval weapon arsenal, the view over the old city centre's roofs classified as a World Heritage Site by the UNESCO and before all its typical *art de vivre* are the greatest attractions of the city of Graz.

Graz and its surroundings are very active in the field of automobile and automotive industry. MAGNA STEYR (vehicle assembly, about 10 000 employees) and AVL (internal combustion engine R&D, about 1850 employees) are two of the largest employers in the region.

6.1.1 Graz University of Technology

The TU Graz (Technische Universität Graz[1], founded 1811) is the second largest educational institution of Graz right after the University of Graz (22 000 students). It is the second technical university in Austria after Vienna. It groups seven faculties (Mechanical Engineering and Economic Sciences; Technical Chemistry, Chemical Process Engineering and Biotechnology; Civil Engineering; Electrical and Information Engineering; Technical Mathematics and Physics; Computer Sciences; Architecture), and 104 institutes.

According to the "TU Graz - Facts and figures 2008" report[2], it counts about 10 250 students (21 % female students, 15 % exchange students). 1 120 of the 1 800 employees belong to the academic staff. The total budget 2008 was 154 MO€.

Buildings and facilities covering 200 000 m^2 are mainly distributed over three campuses ("old", "new", and "Inffeld"), plus some locations such as the observatory situated on the city's heights.

[1] www.tugraz.at/

[2] http://portal.tugraz.at/portal/page/portal/Files/BDR/SB/Facts_2008_en.pdf

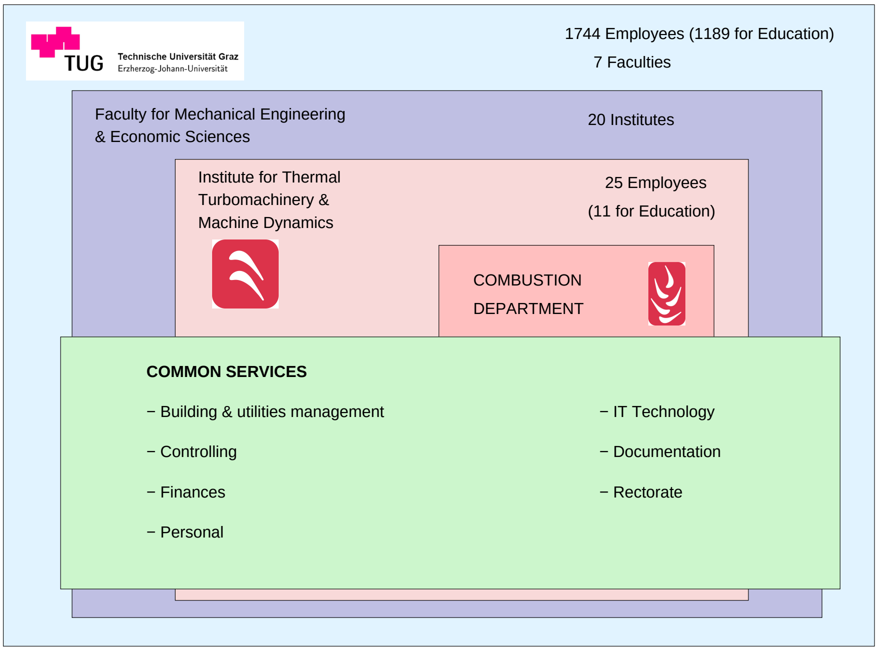


Figure 6.1: *The GT Combustion Division at TU Graz*

6.1.2 TTM

The Institute for Thermal Turbomachinery and Machine Dynamics (TTM[3]) counts about 25 employees under contract (including the 6 Combustion Division members). It is part of the faculty for mechanical engineering and economic sciences (figure 6.1). The institute exists since 1969, and occupies its current grounds since 1986. The first Head of institute was Prof. Jericha, a former ELIN-Engineer, which explains the original orientation towards power machines. Since 2001, Prof. Heitmeir who is a former MTU Engineer, occupies the functions of Head of Institute and Dean of Faculty since 2006. He is at the origin of the new direction towards propulsion systems. He has also initiated the creation of the Combustion Division.

TTM specialises in education and research in the field of compressors, gas and steam turbines and their application in modern power plants, airplanes and vehicles. The results of research serve to improve the design of turbomachines, which leads to higher reliability, longer life time and remarkably higher efficiencies.

Figure 6.2 shows the structure of the institute by specialities, which is also strongly correlated with its lecture spectrum[4] covered by TTM. A strong motto is "Learning by Doing", therefore the institute possesses a large number of educational facilities, and the research test rigs or codes provide realistic data at industrial level, so that the students obtain up-to-date information.

6.1.3 The region of Graz and gas turbine technology

The ELIN in Weiz (today VATech, part of SIEMENS) is a provider of electrical generators. In the past, it has produced gas turbines for power generation. The institute possesses for demonstration purpose a massive ELIN rotor-shaft for recovering energy on a fluid catalytic grabbing process, in an oil refinery. Prof. Jericha, before becoming first Head of institute, was Head of research and development department at ELIN in

[3] www.ttm.tugraz.at/
[4] https://online.tu-graz.ac.at/

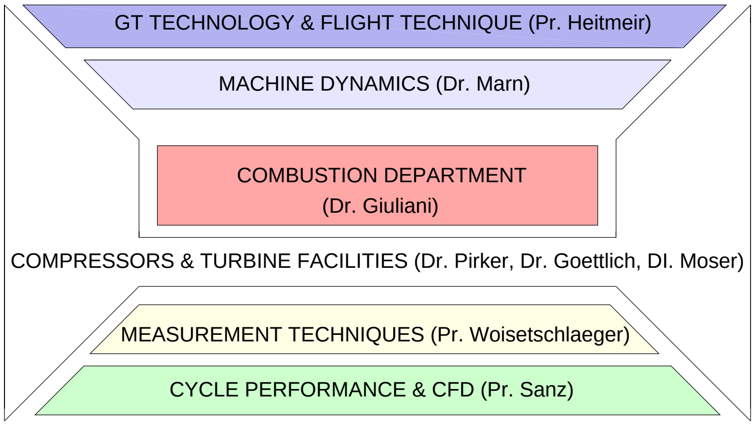


Figure 6.2: *TTM educational spectrum, and interaction between divisions*

steam turbine development. Another division was related to hydropower (the todays' Andritz Hydro Power, Andritz AG) that developed among others water turbines. The need of engineers for large rotating machines was also at the origin of the machine dynamics speciality of the institute.

For a short duration, HITACHI POWER had its headquarters in Graz (2005-2006) for the construction of GT thermal power plants for eastern Europe and the Middle-East markets. For some reason, the management was repatriated after one year to Oberhausen, Germany.

The firm SAPPI, specialised for paper production, commissioned in 2007 its own power station (combined cycle) equipped with a 40 MW gas turbine of type SIEMENS SGT 800.

The nearest large power station of Mellach (coal, oil and natural gas-fired boilers, with a total capacity of 560 MW electrical power, and also designed for heat production) constructs at the moment a new combined cycle power unit equipped with two SIEMENS SG5-4000F, for an extra 832 MW electrical production.

ANTONOV announced 2007 its intention to acquire the old air force domain near Graz airport to host an airplane construction plant there. Other possible locations are near Zeltweg, or in the south of Vienna.

Finally, the institute is in contact with the Austrian Air Force in Zeltweg and Hörsching. In the frame of Austria's recent acquisition of Typhoon combat airplanes, a secondary business finances R&D projects between the Eurofighter consortium and educational institutions such as the TU Graz.

6.2 The Combustion Division

The German name of the Combustion Division is "Arbeitsgruppe Verbrennung", and will be shortened as AV in the following.

The opening of the applicant's current position was announced in March 2004, and he started in October of the same year.

It was the wish of Prof. Heitmeir to create a division, with an educational role on combustion, and with the capacity to perform research (with an emphasis on experimental research [Marn, 2004, Schennach, 2004]) at national and international level. One motivation for this, was the fact that MTU closed down their own R&D combustion facilities in 2003 but may need to further perform combustor research. The financement would be ensured partly by the Professor's chair at TTM, by the TU Graz, and by third-party budgets we would have to seek for.

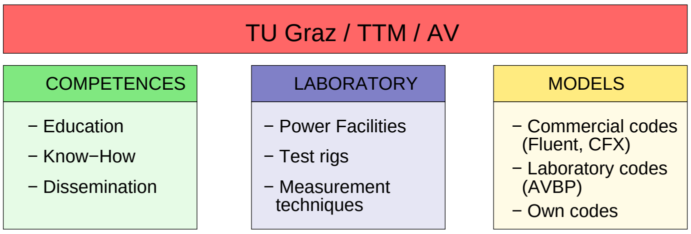


Figure 6.3: *Combustion Division highlights*

The existence of the Combustion Unit is supported by the following interactions with the other sections of the institute (figure 6.2):

GT Combustion $\Longleftrightarrow$

- **GT Technology and flight technique:** The GT combustion lecture details some aspects of the lectures by Profs. Heitmeir, Jericha and Zhuber. Educational test facilities, numerical codes and specific tutorials are provided
- **Machine dynamics:** Acoustics and thermoacoustics are a spin-off of machine dynamics
- **Compressor and turbine facilities:** Power supply
- **Measurement techniques:** Available and applicable to combustion: LDA, PIV, PDPA, Schlieren, Laser Vibrometry
- **Cycle optimisation and CFD:** Air system facility simulated with IpsePRO, gas turbine optimisation using GASTURB, FLUENT used for internal aerodynamics

The applicant was in charge of the development of the Combustion Division, with aims to create it, build up a laboratory and hire staff members. The basic structure of the group was defined 2004 as shown in figure 6.3. The first thing to do was to establish a pole of competence and to attract the attention of the students on the new discipline. A synthesis of the know-how, and strategic choices on the direction of research to be followed were taken: e.g. advanced sensing techniques for combustion instability detection. The frame of this habilitation was defined, and the outcome of the habilitation would depend on the Division's results.

Learning by doing implies facilities. In 2003, Prof. Heitmeir already made arrangements for the construction of a thermal air heater [Schennach, 2004], enabling the institute to perform hot flow research. During the construction of the air heater (delivery and assembly 2005, connections 2006, first fire in 2007, validation tests in 2008) and its connection to the institute's power network, smaller facilities were constructed to train on aspects such as flame ignition, combustion at elevated pressure, spray analysis and adapted instrumentation.

The third column of the AV group, modelling, aims to synthesise the know-how acquired from the experiments through model validation, and extend our capacities towards studies that cannot be analysed experimentally (for a question of approach, of parameter, or of complexity). CFD models such as FLUENT are used to analyse internal flows as for instance in the design phase of a test rig.

6.2.1 Personnel

As the needs of the unit were estimated in 2004, a team of 6 people was foreseen to sustain the structure as defined in figure 6.3. The required personnel was recruited over time, in relation with the start of third-party financed projects. All PhDs employed up to 2009 are former trainees of the applicant. The coming positions concern multi-fuel injection (especially replacement fuels) with focus on the vaporisation, and combustion CFD.

Figure 6.4 shows the current personal of the unit, and a raw distribution of the roles. This structure should remain steady till 2011 and even extend (due to workspace limitations, one more person could join the crew). The work is split between the current AV members as follows:

Fabrice Giuliani: Head of the Combustion Division

- Leader of the Combustion Division group
- prospective task on project financing and people recruitment
- executive and financial management
- co-ordination with other parties such as the Facilities and Housing Department (GuT)
- project representative and contact person for the project's technical issues
- Know-How integration / dissemination
- Lecturer

Andreas Lang: industrial burners

- Engineering 1: NEWAC SP2 on PDE activities
- Engineering 2: NEWAC SP6 on a twin LPP burner with pilot characterisation
- Research: Combustion physics at industrial conditions (NEWAC)
- Important outputs: analysis on the robustness of a LPP burner set to excitation, and guidelines for improving stability. Feasibility analysis on the integration of a PDE-based combustor in a hybrid engine.
- Career opportunities: ECCOMET exchange in 2009 with the ONERA, on the study of ignition systems. Lecturer.

Thomas Leitgeb: combustion control strategies

- Engineering 1: NEWAC SP2 on Variable Geometry Combustor with extended range

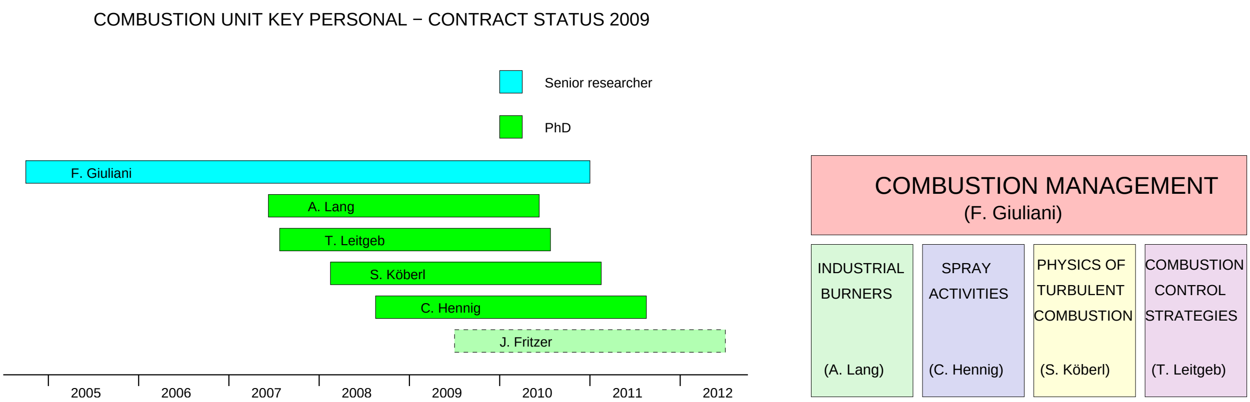


Figure 6.4: *Combustion unit key personnel, contract status 2008, and main work repartition*

- Engineering 2: NEWAC SP6 on the planning, measurements and controls of the air system
- Research: Evaluation of sensing and actuating technologies for combustion control (NEWAC, FWF3)
- Career opportunities: ÖFG exchange with Ecole Centrale de Paris on laser vibrometry measurement on a resonant flame, initiated by a discussion at the ASME 2009 conference with the colleagues of Paris.

Stefan Köberl: combustion fundamental research (main supervisor: Prof. J. Woisetschläger)

- Engineering: NEWAC SP2 on Variable Core Geometry and cycle optimisation
- Research: Combustion physics on model flames (FWF Jakob)
- Important outputs: validation of advanced measurement techniques such as laser vibrometry, analysis of flame-flame interactions, and flame response to a tangential excitation

Christoph Hennig: spray technologies

- Engineering: ALFA-BIRD spray activities
- Research: detailed atomisation processes
- Important outputs: refined understanding of the atomisation process at realistic GT inlet conditions. Guidelines for efficient actuation of the atomisation
- Career opportunities: exchange with the DLR Cologne on spray particle image sizing

Johannes Fritzer: replacement fuels for aeronautics

- Engineering: ALFA-BIRD fuel vaporisation analysis
- Research: instrumentation for fuel vaporisation measurement based on the absorption of line-of-sight laser light
- Important outputs: understanding the role of the cuts in kerosine and replacement fuel on the atomisation, declare whether current injection technologies are valid for these new products, or if technical arrangements are required
- Career opportunities: exchange with the ONERA and the CERFACS in the frame of the EC-COMET programme

6.2.2 Lectures

The specific lecture on gas turbine combustion started 2006. It took about two years to obtain the authorisation from the faculty to introduce a new lecture, and to prepare it. Its main features are a technical description of existing systems, a model approach for combustor dimensioning, and a serie of tutorials involving both models and analysis of experimental data.

In 2007, the Combustion Division joined a pilot programme on E-learning, organised by the TU Graz's Central Information Technologies' Service (ZID) . The lecture obtained a structured homepage (with announcements, lecture timetable, online documentation, and practice room for interactive tutorials), designed for interaction with the students outside from the lecture's time, or during the tutorials. To view the lecture, please use the following link[5]. Click "login", "Extern", Benutzername "AVGuest", Password "combustion" (entries are case sensitive). The lecture notes can be found under the tabulation "Course library".

6.2.3 Specific equipment

A detailed description of the AV power and test facilities is joint to this memorandum under the form of electronic documents. These documents are a global description[6], and a manual on operation and security[7].

6.2.3.1 Power equipments

The planning of the following elements were supervised by the AV group in close cooperation with the TU Graz Facilities and Housing Department (GuT):

- Construction of a versatile air system (2005-2009) [Leitgeb, 2007, Leitgeb et al., 2009a, Niederhammer, 2009], see figure 6.5
- Renovation of the fuel tank (2006-2007)
- Implementation of a thermal air heater (2005-2007)
- Construction of a flexible gas station for neutral and combustible gases (2006-2007)
- Implementation of a security system including a high pressure water nebuliser, toxic or explosive gas sensors and an extensive security procedure. The laboratory responds to the norms allowing students to perform workshops there. (2006-2007)
- Construction of a flexible liquid fuel station (2007-ongoing) with high-pressure pumps
- Authorisations and certification issues from TÜV and the local authorities regarding the use of this equipment (2007-ongoing)

In terms of engineering, the largest effort was put into the construction of the thermal air heater (figure 6.5), a large facility with a thermal capacity ranging from 1 to 5 MW. The construction was cost-effective, and delays took place because of financing problems. The machine was operational in March 2007, and then fully functional once connected to the air system in November 2008, and validated in May 2009. The air system was designed with the help of IPSE [Leitgeb et al., 2009a, Leitgeb et al., 2009b], which a thermodynamic model useful to plan the pressure losses and dimension the required valves, as well as think how to bring the test cell to its operation point. The HTP test rig is shown in figure 6.6. The target for combustion applications is to be in possession of a facility able to deliver from 2.5 kg/s at 750 K at 2 bar up to 8.5 kg/s at 750 K at 9 bar. The mark 9.5 bar was achieved during the tests on November the 26th, 2009.

A soundproof casing around the thermal air heater is currently under construction.

The Combustion Division plans also the construction of a stand-alone compression station in partnership with the State of Styria and the EU under the form of a EFRE[8] grant. The project time slot is 2010-2013.

[5] http://tugtc.tugraz.at/wbtmaster/courses/319004_panel5.htm

[6] ./biblio/20081126_POWER_INSTALLATIONS.pdf

[7] ./biblio/TTM_AV_Sicherheitskonzept_v1.0.pdf

[8] http://europa.eu/legislation_summaries/employment_and_social_policy/job_creation_measures/l60015_en.htm

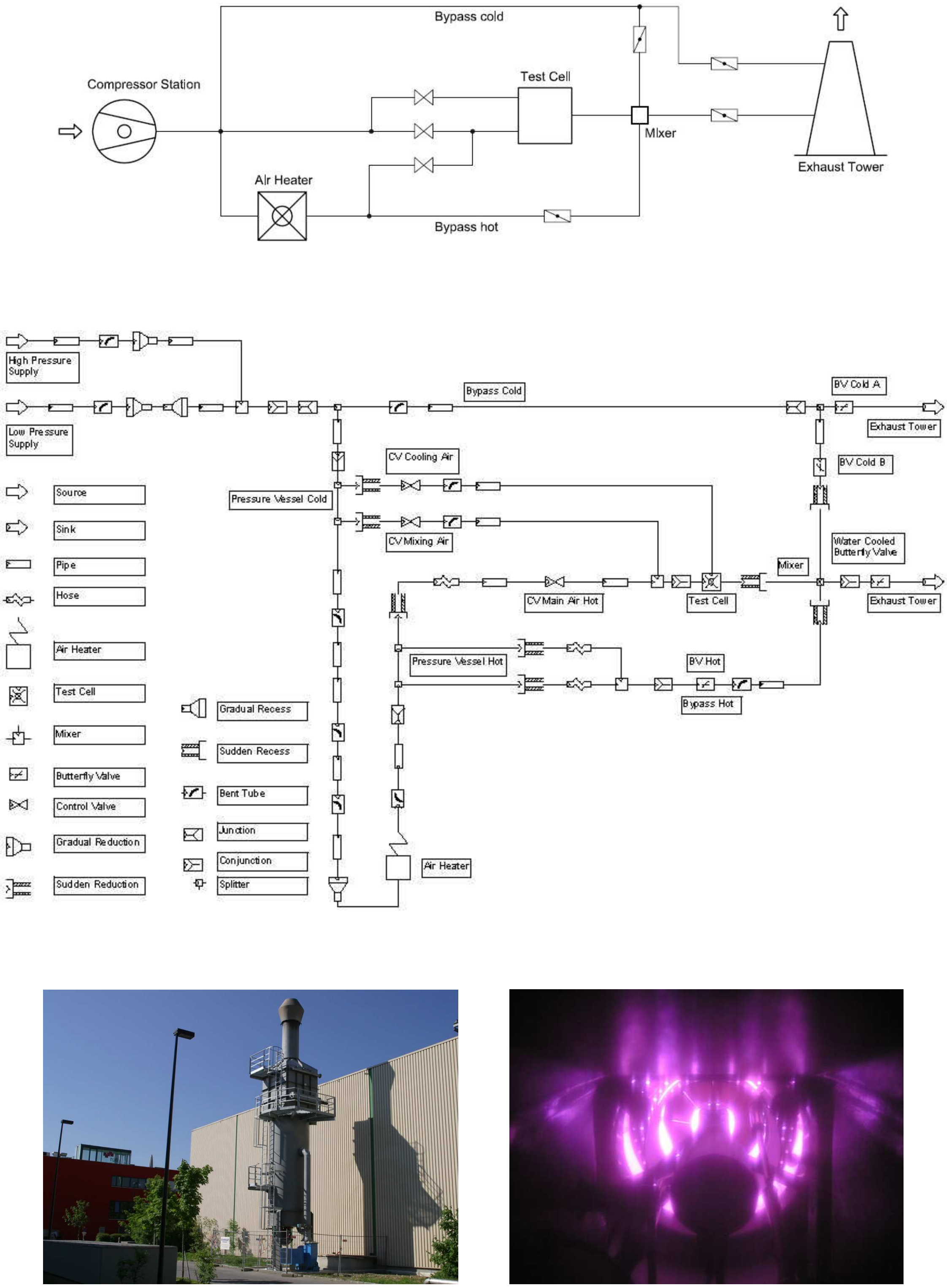


Figure 6.5: *Thermal air heater. Top: simplified air system. Middle: detailed air system. Bottom: picture of the air heater and view of the flame through the inspection hole of the ABB Burner type RL50/2-A.*

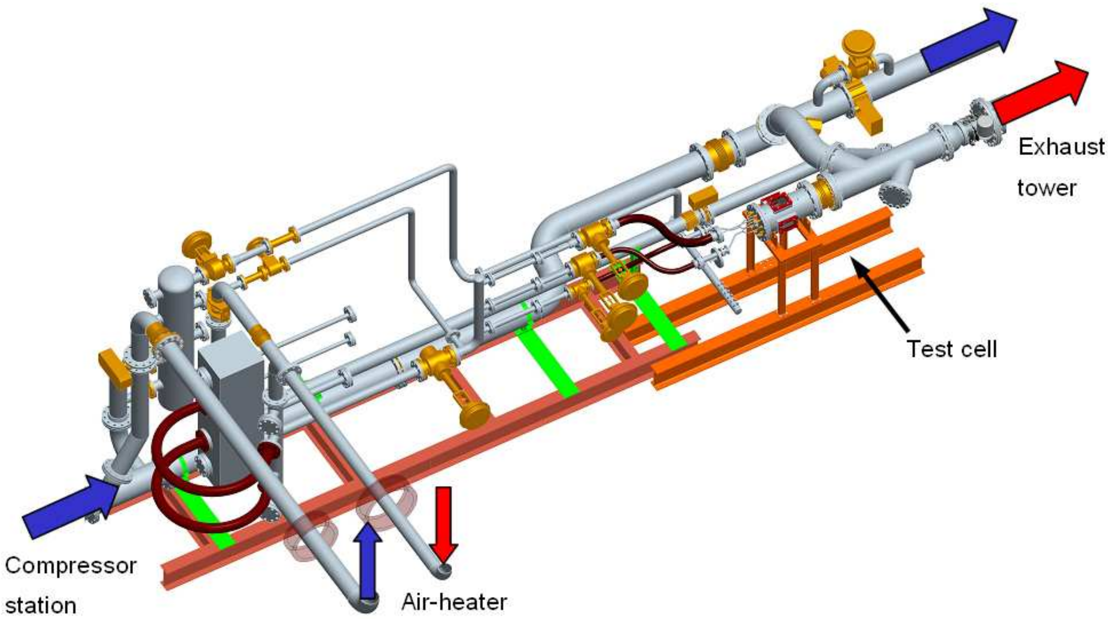


Figure 6.6: *HTP test rig*

6.2.3.2 Specific AV burner designs

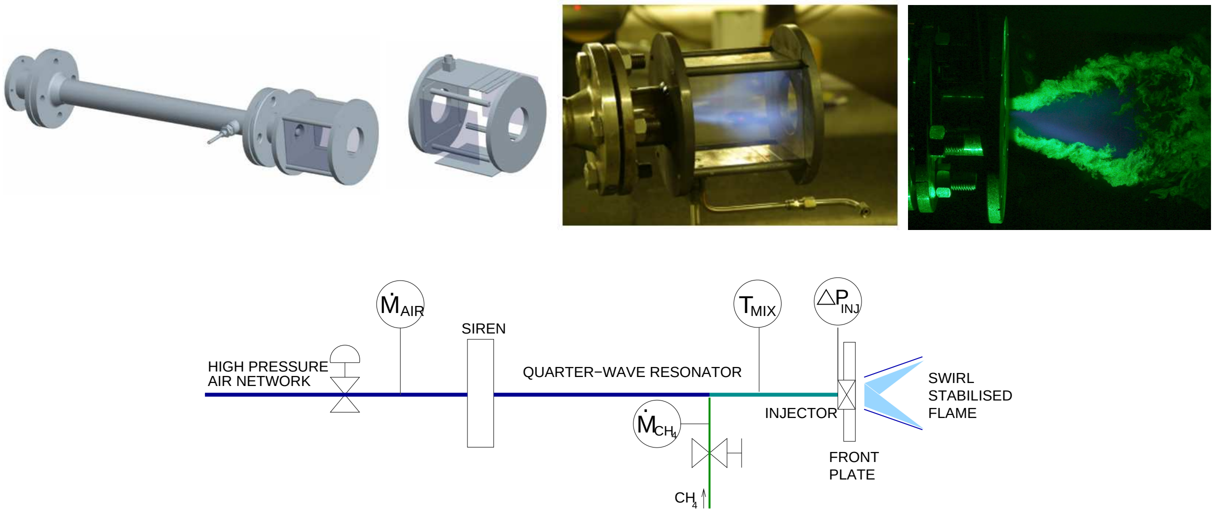
The burners presented in this section have been used for our research over the last four years, and are described in the joint publications. The burners are named after the people who constructed them, or after a specific research programme.

The "Wagner burner" (atmospheric) is a 25 kW premixed air-methane flame, swirl stabilised, that can be analysed in free or confined jet [Wagner, 2005]. The air supply is cold, connected to the pressure air network. The flame can be pulsed with help of the ONERA siren [Giuliani, 2002] that was provided by our colleagues of Toulouse in the frame of the AMADEE project. This test rig was used for laser vibrometry, PIV and high-temperature microphone measurements (figure 6.7).

The "Lang burner" (intermediate pressure) is a scale down of the Wagner burner for operation at pressurised conditions, with premixed air-methane flame, swirl-stabilised and uncooled in the primary zone. It possesses a double canal structure (figure 6.8) and is supplied by the pressurised air network [Lang, 2007].

The functions of the burner (6.8) are as follows:

- Demonstration flame for educational purpose
- Fully instrumented chamber, with online computer acquisition (via STEP7-OPC-LABVIEW). Analysis of steady state operation, as well as transients
- Swirl number analysis: set of injectors available with 30, 45 and 60 degrees
- Characterisation of the burner: pressure loss, swirl number, as a function of the operation



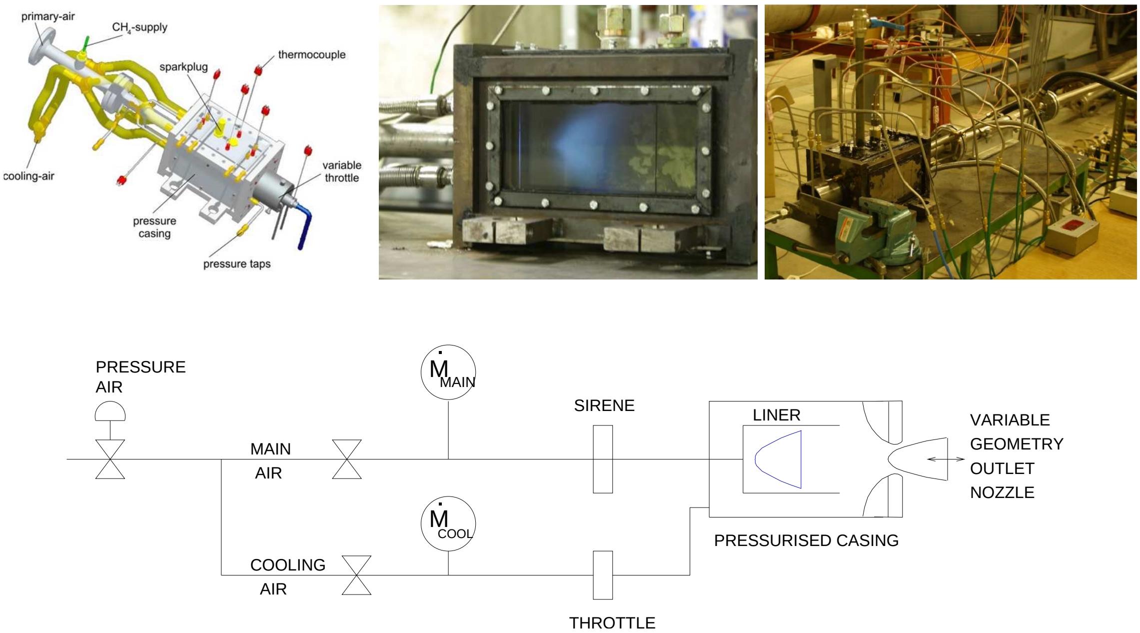
CONFIGURATION		OPERATING CONDITIONS	
Resonator length	3m	P and T_{inlet}	room conditions, 1 bar, 300K
Amplified modes	25 + N*50 Hz, N={1, 2, 3...}	Air feed	10 g/s
Axial swirl angle	45°	Methane feed	0.47 g/s
Number of blades	3	Equivalence ratio	Φ=0.8
Venturi ratio	2/5	Axial inlet velocity	U_{mean}=12.6m/s
Optional chamber	100*100*120mm	Injector pressure loss	ΔP_{inj} = 240 Pa
dimensions		Swirl number S	0.8
		Siren excitation range	110-120 dB SPL

Figure 6.7: *Wagner burner. Top left: split view of the burner, with optional chamber. Top middle and right: enclosed flame and free-jet flame configuration (flame aspect during the PIV measurements). Middle: ensemble siren, resonator and burner. Bottom: Configuration and operating conditions*

- Learning by doing: gaining know-how on optical measurements at intermediate pressure using this test chamber (visualisations, laser-vibrometry, PIV), security aspect and preparation of a combustion test
- Can be pulsed. Is mounted at the end of a resonator pipe, equipped with the ONERA siren.
- Combustion range analysis. Design point 75 kW. Operation steady from 10 to 125 kW. Tested up to 3 bar.
- Chamber optical accesses with SQ1 quartz glass, and ROBAX high-temperature resistant glass.

T. Leitgeb organised the automated measurement and control system, based on SIMATIC STEP7 technology [Leitgeb, 2007]. This choice was made because of the capacity and robustness of this technology, able to multiplex up to 800 input or outputs, ensure onboard regulation, and convert the information via an OPC server protocol so that the realtime data can be observed/acquired from any PC in-house connected to the internet.

The geometry of the Lang burner was also selected for a simulation on variable core geometry in NEWAC, as well as for the study on flame-flame interaction within the FWF project of Stefan Köberl (FWF P19955). The flow pattern, simulated with FLUENT is represented in figure 6.9. On the upper plot, the three



CONFIGURATION		OPERATING CONDITIONS AT 2 BAR	
Resonator length	3.3 m	P and $T_{frontplate}$	1.939 bar, 554 K
Amplified modes (measured)	540 Hz	P and $T_{casingin}$	1.942 bar, 331 K
Axial swirl angle	60°	P and $T_{lineout}$	1.936 bar, 596 K
Number of blades	3	P and $T_{casingout}$	1.934 bar, 486 K
Venturi ratio	1/2	Air feed (primary)	6 g/s
Chamber dimensions	96.4*96.4*200 mm	Air feed (cooling)	25 g/s
	(H*W*L)	Methane feed	0.5 g/s
Casing dimensions	120*120*230 mm	Equivalence ratio	Φ=0.7
	(H*W*L)	(25 % cooling air recirculated)	
Outlet diameter	21.6 mm	Axial inlet velocity	U_{mean}=12.8 m/s
	(fully opened)	Injector pressure loss	1.6 %
		Swirl number S	1.1
		Siren excitation	540 Hz
		T_{inlet}	285 K
		T_{outlet}	1050 K

Figure 6.8: *Lang Burner. Top: CAD view, flame aspect, and instrumented test cell. Middle: Concept and line feeds. Bottom: configuration and operating conditions*

components of the velocity are displayed in the primary zone, and the injection of cooling air along the end plate is visible especially on the bottom plot representing the streamlines. This classical bluff body aerodynamic simulates fairly the real combustion chamber aerodynamics (fig 5.6 p.68). In that case, the chamber pressure is 2 bar, the Swirl number is about 0.6, and the rear nozzle is critical (see the vector sizes at the outlet). The ratios between the velocities are in good agreement with PIV measurements realised at atmospheric conditions [Lang et al., 2008]. These simulations are reported in [Grönstedt et al., 2009].

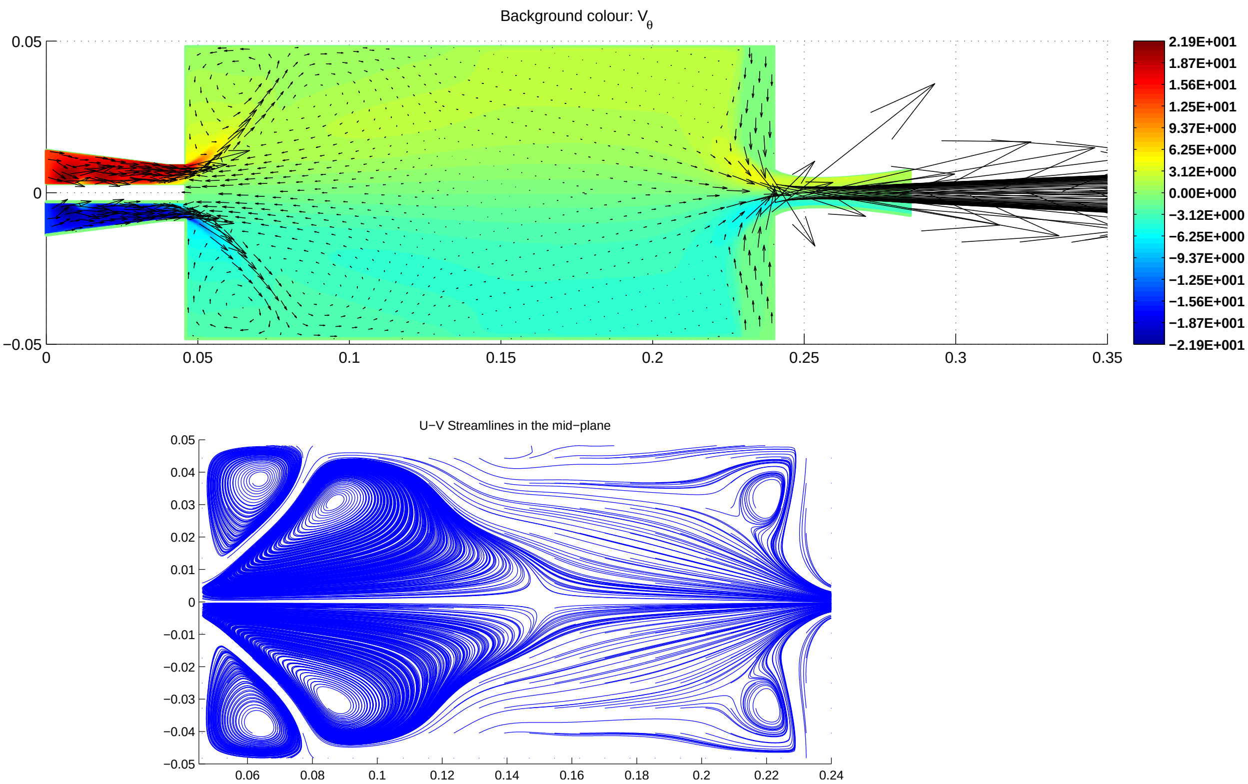


Figure 6.9: *Lang burner aerodynamics. Top: three velocity components plot. Bottom: streamlines computed on the axial and radial components.*

6.2.3.3 Other burners

The Kawanabe burner [Kawanabe et al., 2000]

One article on laser vibrometry submitted to a journal was unsuccessful while the method had not been applied to a known flame geometry. As a response to this, the first set-up used by Stefan Köberl produced a diffusion flame well described in the literature (figure 6.10) , that was used to validate this technique [Köberl et al., 2009, Köberl et al., 2010].

The air turbulence is set by a bad of rollers and fine turbulence grids placed in the air plenum. Methane is injected in the middle of the air outlet. The flame is turbulent, tube-like and stabilises about 80 mm above the inlet. The aerodynamics and turbulence levels were reported by Kawanasabe, mostly based on PIV measurements. These literature data was systematically compared with the one produced by the laser-vibrometry measuring technique for measurement technique validation [Köberl et al., 2010].

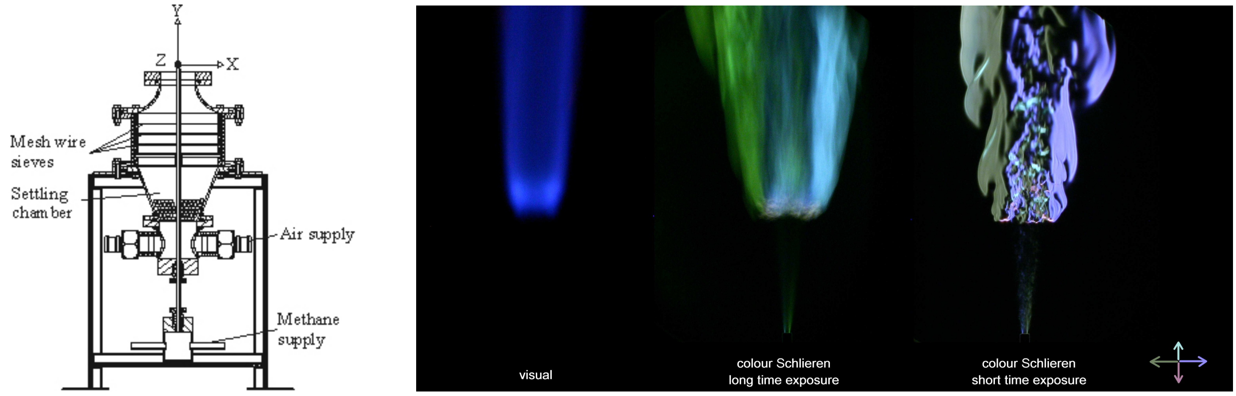


Figure 6.10: *The Kawanabe diffusion burner*

The NEWAC burner

A test sector containing two LPP modules and a pilot designed by Turbomeca (TM) was constructed in the frame of the NEWAC project. Figure 6.11 shows the test sector compatible with the HPT test rig. Each line of air and or kerosine can be fed separately. FLUENT was used to determine the pressure loss of the airbox (air feed of a given injector) at worse conditions (when the dynamic pressure is maximum, hence the volume flow at part load) and iterate on the dimensions. Particular attention was paid to the velocity profiles at the outlet, to check the hypothesis of axi-symmetry of the injection.

In order to switch from one burner to the next, all burners designed to function under pressure are mounted on a similar flange as shown in figure 6.11. All the instrumentation and feed connections are situated on the flange's rear side and do not necessitate a lot of work on the casing when being dismounted.

The ALFA-BIRD injector

This injector is designed for spray and vaporisation analysis of various fuels, at isothermal conditions. An afterburner situated downstream reduces the reactant so that no hazardous atmosphere is created in the exhaust tower.

This injector (figure 6.12) is actually similar to the injector designed by Turbomeca (TM) for the programmes PRECCINSTA and TIMECOP. It combines a pressure nozzle to a radially swirled air flow, and is a scale-up of the MAKILA burner pilot stage. A modification on the pressure nozzle was done by AV to ameliorate the atomisation. The characterisation will take place during 2010.

6.2.3.4 Computational power and specific softwares

TTM owns several high-speed PCs and is linked to UNIX machines of the TU Graz computer centre. MATLAB and FLUENT are available on UNIX machines. The program AVPB acquired 2006 in the frame of ECCOMET runs on ATHOS (ref. Compaq Tru64 UNIX V5.1B - 2650). The SC45-AlphaCluster is composed of 15 units ES45, representing a total of 60 CPUs.

For GT cycle analysis and process optimisation, the programs used are GASTURB [Kurzke, 2006] and IPSEpro [Perz, 2008, Leitgeb et al., 2009a, Leitgeb et al., 2009b].

For CFD, FLUENT is used. R. Pecnik was trained with AVBP 2006.

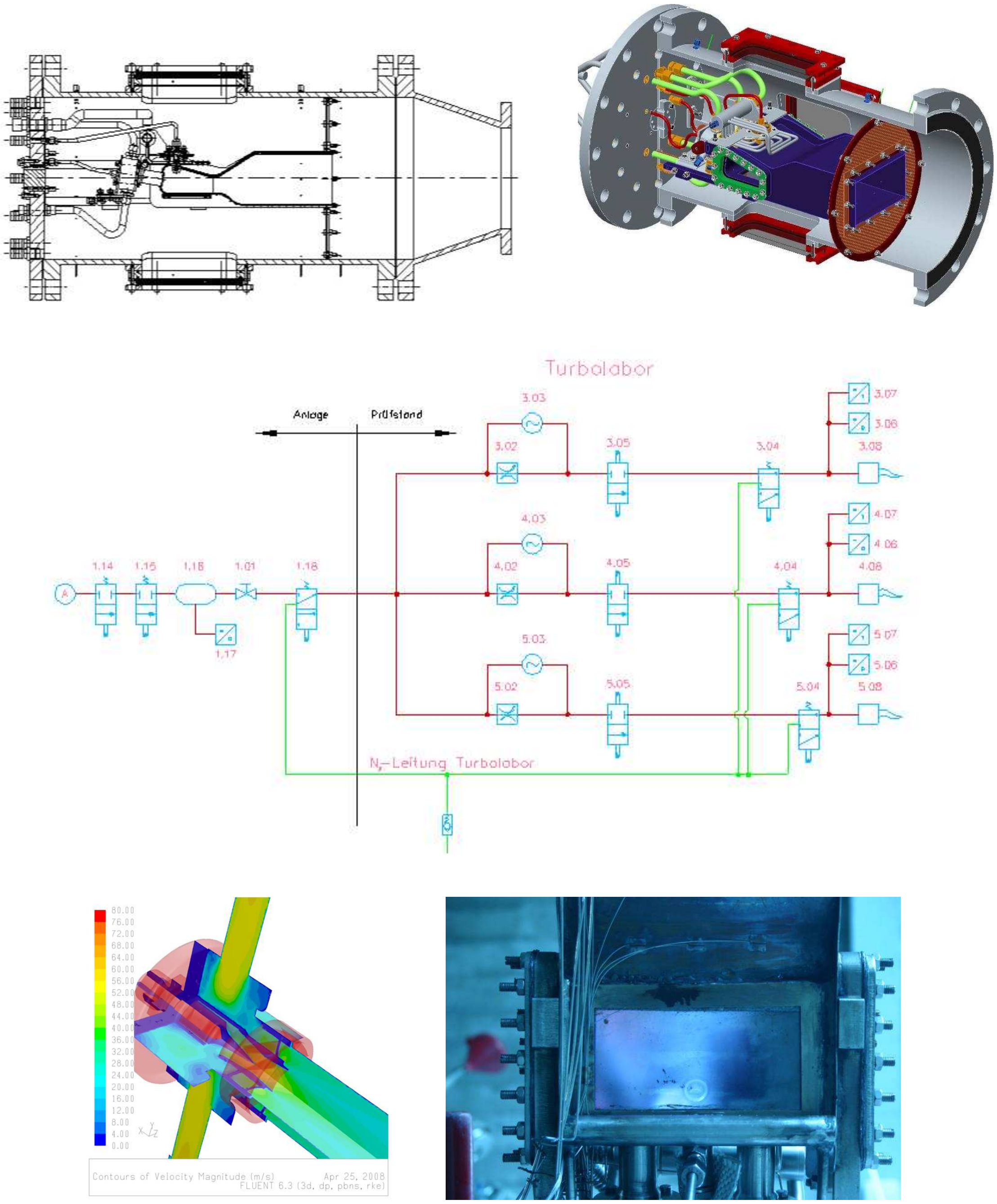
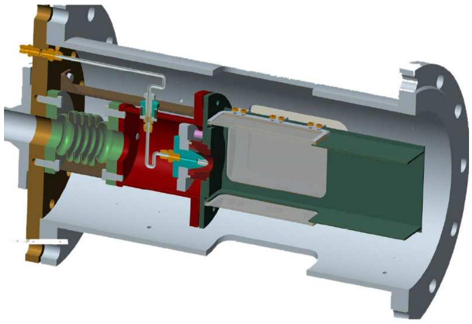


Figure 6.11: *The NEWAC test sector. Top: cut views of the pressure casing containing the flametube. Middle: kerosine feed lines. Bottom: dimensioning of the airbox with help of CFD, and ignition test on a one pilot + LPP configuration*



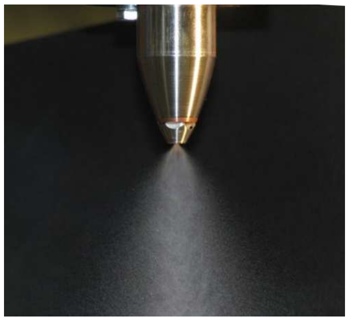


Figure 6.12: *The ALFA-BIRD injector. Left: cut of the pressurised test cell, where atomisation and vapourisation take place at elevated pressure and temperature. Right: test on the pressure atomisation on the atmospheric spray test rig.*

In the frame of an exercise on detonation simulation, AV was introduced to the Chalmers code G2D. A simulation was ran to perform an analysis on the role of a phase-shift between neighbour tubes in pulse detonation combustor [Giuliani et al., 2009b].

Other codes of interest are the MATLAB routines IN-PULSE for analysis of unsteady atomisation [Giuliani et al., 2009a], and the atomisation image analyser developed by C. Hennig [Hennig et al., 2009].

6.3 Research proposals, accepted projects and budget management

The following list states the successful grant applications done by AV. For the years 2010 and 2011, a co-operation with Ecole Centrale de Paris will be submitted for a joint FWF-ANR financing, a large EU level II project is under preparation (HEATTOP 2), and the the first round of discussions on a NEWAC II project (2013) is about to begin.

Successful project proposals of the Combustion Division

[Giuliani, 2007a] Giuliani, F. (2007a). Evaluation of active control strategies regarding airblast atomisation - A combined numerical-experimental approach. P20530 Evaluierung aktiver Luftzerstäubungs-Regelungskonzepte. FWF project with peer-review process. F Giuliani project leader.

[Giuliani, 2007b] Giuliani, F. (2007b). TU Graz activities in the frame of the EU project ALFA-BIRD, on air-blasted biofuel evaporation. Collaborative Project, Contract No. 213266. F Giuliani project leader at TU Graz.

[Giuliani and Leitgeb, 2009] Giuliani, F. and Leitgeb, T. (2009). P'-Rho', common works on thermoacoustics with Ecole Centrale de Paris. Academic exchange supported by the state of Styria.

[Giuliani et al., 2005] Giuliani, F., Pecnik, R., Gajan, P., and Strzelecki, A. (2005). Academic exchange ÖAD, about know-how exchange on advanced measurement techniques.

[Heitmeir and Giuliani, 2005] Heitmeir, F. and Giuliani, F. (2005). TU Graz activities within the EU project NEWAC, on inovative combustion systems and LPP combustion stability. F Giuliani project leader at TU Graz.

[Stelzer et al., 2009] Stelzer, F., Heitmeir, F., Giuliani, F., and Marn, A. (2009). Testanlage zur Simulation der Verbrennungsvorgänge in Gasturbinen. Infrastructure grant for the extension of the compressor station for combustion needs. F. Giuliani initiator.

[Woisetschläger and Giuliani, 2006] Woisetschläger, J. and Giuliani, F. (2006). Experimental investigation of flame-flame interaction in gas-turbine model combustors with forced flow instabilities. P19955 Flammenwechselwirkung in einer Gasturbinenbrennkammer. FWF project with peer-review process. F Giuliani co-supervisor.

6.3.1 Important project milestones

May 2005 Start of the TOSCA programme (Technology for Oscillating and Steady-State Combustion Analysis) , with the diploma thesis of B. Wagner. We borrowed then the ONERA siren. Validation tests of the atmospheric air-methane burner, and encouraging tests with laser vibrometry. The request for a FWF grant on TOSCA has no success, it will be financed by the institute.

June 2005 Start of the co-operation with PIEZOCRYST, for the analysis of a high-temperature-resistant pressure sensor, to complete the TOSCA study [Giuliani et al., 2007d]

January 2006 Start of the AMADEE cooperation with the ONERA. This will last 2 years.

May 2006 Start of the NEWAC project

October 2006 Start of the lecture on gas turbine combustion

March 2007 The thermal air heater is operational. The connection to the pressure air is a problem. The compressor station's alarm report pumping at elevated PR. The first configuration designed to function at PR 10 is to be replaced by larger pipes.

April 2007 Andreas Lang starts his PhD, Thomas Leitgeb follows in June. Both are financed with NEWAC

October 2007 Start of the E-Learning version of the gas turbine combustion lecture. Positive feedback from the students.

December 2007 Delivery of a detailed security concept for the authorisation to perform experiments in a secure area. The fire security systems (gas detector, smoke detector, fire detector and fire extinguisher) are operational. The air systems are validated by the TÜV. The final admission from the Land authorities for experiments at high conditions of pressure and temperature should be issued shortly. The laboratory is OK, if required, for certification.

January 2008 Stefan Köberl starts a PhD on a FWF financement on flame-flame interaction, under the direction of J. Woisetschläger. The applicant is co-supervisor.

July 2008 Christoph Hennig starts his PhD on a FWF financement on airblast atomisation analysis, under the applicant's supervision.

July 2008 Start of the ALFA-BIRD project.

November 2008 The air heater is fully operational. Progressive tests over the year will validate temperatures up to 750 K and pressures up to 9 bar.

August 2009 Johannes Fritzer starts his PhD on the Alfa-Bird actions.

January 2010 A EFRE grant (European Regional Development Fund) is signed between the EC, the state of Styria and the TU Graz to finance an extension of the compressor station for combustion tests at elevated pressure.

6.3.2 Budget repartition

Figure 6.13 shows the resources and budget repartition of the Combustion Division, established on a 9-years duration from 2004 to 2013 with project status quo in 2010. The current overall Combustion Division budget, including internal resources and third-party budget is approximately after 5 years existence about 2.2 MO€. This is a cost estimate (±10 %) since the repartition of the TU Graz' internal resources between the several projects or departments of the institute is not easy to assess.

The numerous sources - especially third party - are an image of the current struggle of the applicant and his direction to be able to finance their research. The difficulty lies in the multiplicity of grants, their constraints of use, and the need to adapt to the change in rules over the years (e.g. between FP6 and FP7, the Austrian Ministry of Research that suddenly stops to cover the EU projects' VAT costs in summer 2009 without offering an alternative). The funds prospective, the financial follow-up and management is therefore extremely time-consuming. Paradoxal situations happen where funds for personal are allocated, but no hardware, and vice-versa.

The repartition internal resources (TU Graz) / third party budget (EU projects + FWF) is about 1/3-2/3. To this adds-up the recently allocated EFRE grant of 580 k€ financing for infrastructures: a compressor shared with the other units that under one configuration should bring pressures up to 20 bar.

The internal + infrastructure ressources (TU Graz + EFRE) are relatively high since they contain the applicant's salary and the development of new/renovated research infrastructures, especially regarding security, necessary for the operation of the unit. This situation is exceptional and is related to the construction of advanced tests rigs, since the Combustion Division is new. In the future, this participation will probably come down to 25 % - less would be hardly sustainable - that shows the high dependency of the unit to third-party budgets.

The effort since 2004 has been put in making proposals for external budgets, and entering EU Projects. It took two years to obtain the first consequent financing (NEWAC, 2006). The grants brought us the necessary momentum to start ASAP with our Research activities. Payment delays or funding cuts can put us in great difficulties, as we experienced April 2008 in NEWAC. The global GT economic situation is rather unsteady in 2010, and the chance of success for future financing is hard to predict.

In terms of budget repartition, about the half is dedicated to the personal costs, the rest corresponds to infrastructure costs (test rig, operation costs, security, compressor station extension), indirect costs (consumables, overheads, travel costs...) and instrument costs (measurement techniques, IT, maintenance).

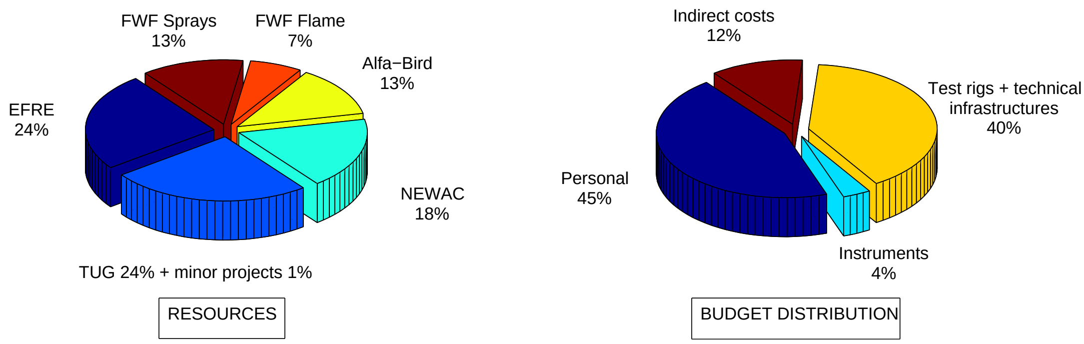


Figure 6.13: *Budget of the Combustion Division for a 6 year duration (2005-2011: 1.6 MO€): resources and repartition*

Part III

Career: Research and Development

Chapter 7

Selected papers

The focus is put on measurements and controls for turbulent combustion. The following list of selected papers covers the following themes:

- The development of measurement techniques [Giuliani et al., 1998, Giuliani et al., 2007a, Giuliani et al., 2007d]
- The analysis of kerosene atomisation/injection [Bhayaraju et al., 2005, Giuliani et al., 2009a]
- The physics of a pulsed flame [Giuliani et al., 2002c, Gajan et al., 2007, Giuliani et al., 2010]

Selected articles

[Bhayaraju et al., 2005] Bhayaraju, U., Hassa, C., and Giuliani, F. (2005). A study of planar liquid sheet breakup of prefilming airblast atomisers at high ambient air pressures. In *20th Annual Meeting of the Institute of Atomisation and Spray systems (Europe)*. ILASS 2005 (20th Annual Meeting), Orléans, France.

[Gajan et al., 2007] Gajan, P., Strzelecki, A., Platet, B., Lecourt, R., and Giuliani, F. (2007). Experimental investigation of spray behavior downstream of an aeroengine injector with acoustic excitation. *Journal of Propulsion and Power*, 23(2):390–397.

[Giuliani et al., 2007a] Giuliani, F., Bhayaraju, U., and Hassa, C. (2007a). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine conditions using laser infra-red absorption. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 2002] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2002). Influence of pulsed entries on a spray generated by an air-blast injection device - an experimental analysis on combustion instability processes in aeroengines. *Proceedings of the Combustion Institute*, 29(1):91–98.

[Giuliani et al., 2009] Giuliani, F., Hennig, C., Leitgeb, T., and Hassa, C. (2009). Effect of the initial droplet size distribution of the liquid phase combined with transport phenomena on the resulting airblast spray in the far field. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-133.

[Giuliani et al., 2010] Giuliani, F., Leitgeb, T., Lang, A., and Woisetschläger, J. (2010). Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry. *Journal of Engineering for Gas Turbines and Power*, 132. GTP-031603.

[Giuliani et al., 2007b] Giuliani, F., Schricker, A., Lang, A., Leitgeb, T., and Heitmeir, F. (2007b). High-temperature resistant pressure transducer for monitoring of gas turbine combustion stability. In *Proc. of the 18th ISABE conference*. International Symposium on Air Breathing Engines, Beijing, China. ISABE-2007-1111.

[Giuliani et al., 1998] Giuliani, F., van Beeck, J., and Riethmuller, M. (1998). Thermométrie par arc-en-ciel: technique d'acquisition de donnée à l'aide d'un laser Nd:YAG et traitement de signaux 2D. In *Recueil des actes du 6e Congrès Francophone de Vélocimétrie Laser*, pages B.3.1 – B.3.7, Saint-Louis, France. Association francophone de vélocimètrie laser.

Structure of this part

About the half of the suggested list are recent publications, and states the level of art achieved at the Combustion Division for the three aspects described above.

This Memorandum's part develops the scientific aspects of the applicant's research. It describes firstly the advances in measurement techniques developed for the specific needs of the applicant's research. Secondly, the modelling on two-phase flow transport is presented. Thirdly, the advances in the description of the physics of unsteady combustion is exposed as the logical continuity of the previous themes. Emphasis is put on the successive steps of the research. Complementary informations or results that are not available as such in the articles are also detailed.

Chapter 8

Progress in measurement techniques

In the following, the focus is put on image-based data and time-resolved processing. Optical measurement techniques have the advantage that they are non-intrusive, and can produce physical data in places where for instance a probe could not resist the heat - or would necessitate a cooling that in return needs a complicated calibration procedure.

What the different data processes have in common is a statistical approach - to establish whether a quantity can be measured with a satisfactory level of confidence based on a limited amount of data - and a spectral approach to verify whether this quantity is steady-state or not.

At first, rainbow thermometry is presented quite in details while it combines laser scattering with imaging technique, two concepts discussed in the following for other measurements (Mie scattering, Fraunhofer laser diffraction, infra-red absorption technique). Laser-based techniques have a great chance to be implemented for real-time combustion monitoring (see section 8.2.1 p.113). It is shown - and this is also the object of the HEATTOP II research proposal planned 2011 - that a single incident laser beam passing through the flame can deliver many informations about the combustion status. It is perfectly feasible nowadays to monitor the following quantities at once, making use only of a relatively compact hardware: the particle size, the particle temperature, the injection stability, the equivalence ratio, the level of pollutant emissions the gas density and the flame stability.

8.1 Advanced image-based diagnostic techniques

8.1.1 Rainbow thermometry

8.1.1.1 From refractometry to thermometry

Rainbow thermometry is a non-intrusive optical diagnostic technique (laser-based) designed to determine the temperature of spherical droplets in a spray. When observed in the so-called "rainbow" scattering solid angle interval (a region where the backward scatter is rather strong, thus allowing to observe a rainbow through a rain curtain, with the sun placed in the back), the observed interference pattern provides information on both droplet size and refraction index - respectively as a function of the distance between the two Airy peaks (figure 8.1) and the geometric rainbow angle θ_{rg}. The refraction index of the droplet being mostly a function of its temperature, the droplet temperature can eventually be determined (figure 8.2). Equation

8.1 displays the relationship between θ_{rg}, the droplet size and the interference pattern for water:

$$\theta_{rg} = \theta_1 - 46,8 \left(\frac{\lambda}{D}\right)^{2/3} \tag{8.1}$$

	θ_{rg}	[rad]	is the geometric rainbow angle, constant for all sizes of droplets of the same medium at the same temperature. In the end, θ_{rg}=f(T), see figure 8.2, right.
where	θ_1	[rad]	is the scattering angle of the peak of the main interference pattern, or first Airy fringe
	λ	[m]	is incident light wavelength
	D	[m]	is the particle diameter, measured for instance with a PDA

Please consult the specific VKI lecture serie LS1999-01, pp3-8, for detailed theory on rainbow thermometry [Van Beeck et al., 1999].

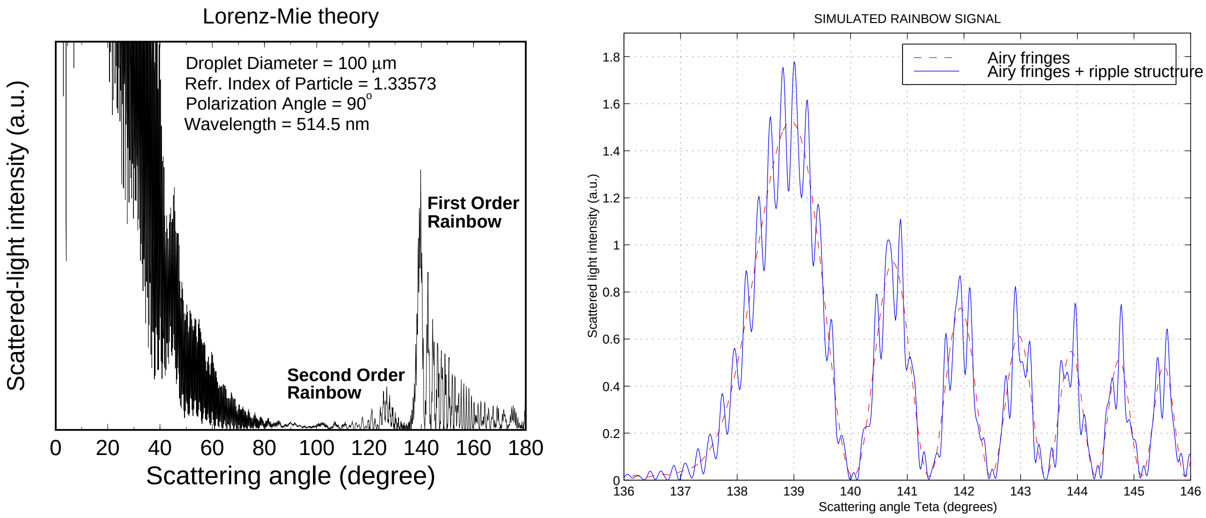


Figure 8.1: *The monochromatic rainbow pattern. Left: whole solid angle. Mie scattering of laser light, simulation. Right: focus on the primary rainbow region. Plots courtesy of van Beeck [van Beeck, 1997].*

8.1.1.2 The research on rainbow thermometry at the VKI in 1996

This optical measurement technique has been developed by Roth et al. [Roth et al., 1988, Roth et al., 1989, Roth et al., 1991] at the technical university of Stuttgart, for the diagnostic on a model fuel spray (using a monodisperse droplet generator). They observed the droplet illuminated by continuous laser light (type He-Ne) with 2 CCD array sensors. A first one was placed in forward scattering in order to determine the droplet size, and a second one was observing the first-order rainbow to get information about the angular positions of the peaks. The whole device was a coupled Rainbow-PDA method of investigation about size, temperature and speed of the droplets.

Van Beeck [van Beeck, 1997] established that the rainbow pattern should be sufficient to determine both size and temperature of a given droplet, thus simplifying greatly the acquisition chain. He also pointed out the problem of the measurement uncertainty related to non-spherical particles, and the need to check out the sphericity of the particle being measured before validating its rainbow pattern.

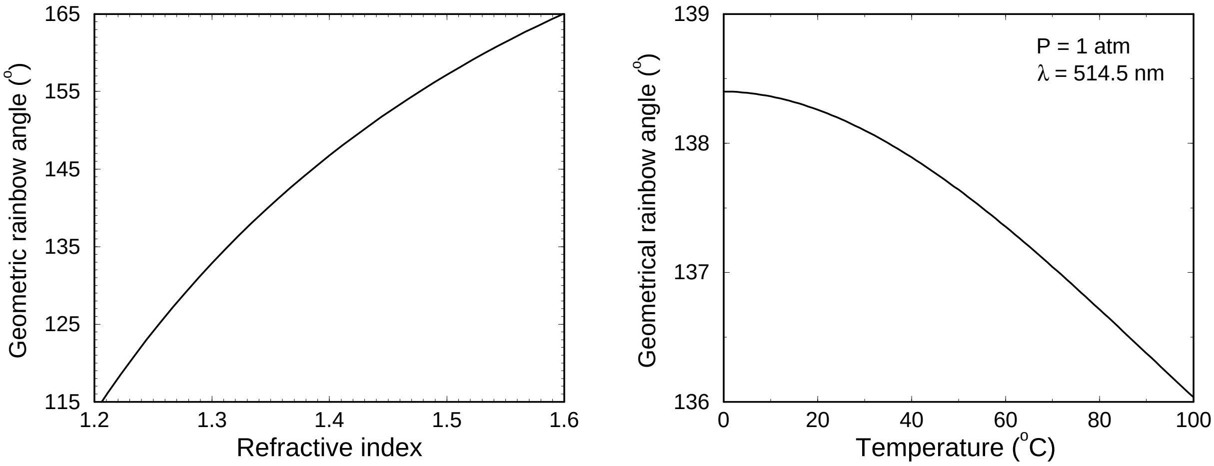


Figure 8.2: *Determination of refractive index (left) and droplet temperature (right) for a water spray as a function of the rainbow geometric angle. Plots courtesy of van Beeck [van Beeck, 1997].*

Another motivation was to extend the use of rainbow thermometry from model calibrated sprays to complex industrial sprays. The potential of this technique for mapping the spray temperature on fuel injectors, drying injectors or other process control technologies is rather high. At that time, the VKI worked among others on water sprays designed to protect fuel tanks from infrared emissions caused by a fire. Rainbow refractometry was a potential candidate to characterise the efficiency of a given spray in terms of absorbing infrared emissions, by simply observing the heat-up of the droplets.

8.1.1.3 A step towards global rainbow thermometry

The ideas we studied were the following:

- use of a pulse laser to generate high signal to noise rainbow patterns
- analysis of a full 2-D picture instead of a linear CCD camera

In the technical report VKI SR 1997-14 [Giuliani, 1997], attention is paid to the energy pulse and its possible intrusion in terms of heat-up or momentum transfer with the droplets lightened by the laser. The very first experiments were performed with a ruby laser, type J.K. Lasers Serial N°8397 (Lumonics, Millenium Laser Technologies, 694nm) on rather big droplets (about 2mm diameter). The pulse energy, 1J is great enough to print out the shadow of a droplet on black photographic paper. This exercise involved a triggering system, where the falling droplet is first detected by an optosensor, triggering then the ruby pulse. A false colour rainbow is presented in figure 8.3.

The technical report VKI PR 98-11 [Giuliani, 1998], makes use of the results of the previous study on an industrial flat water pray, nozzle type TP4005 that delivers droplets of 200 μm mean Sauter diameter (SMD) at an operating pressure of 3 bar. The water could be heated up by two electric water heaters of type Vulcanic mounted in serie, each heater being equipped with three heating bodies with a maximum power of 6kW. In order to augment the measurement rate, a single-cavity YAG laser was used (MiniYag, Continuum, from 1 to 15 Hz, 532 nm, maximum energy 0.02 J per pulse). However, it was found out quickly that the

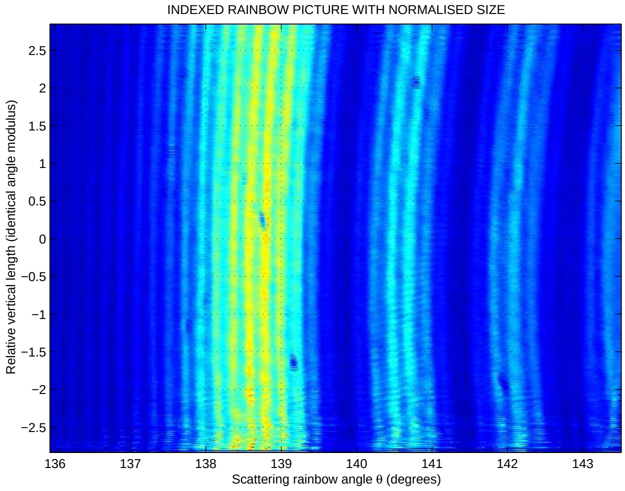


Figure 8.3: *Rainbow image measured with a pulse laser, dimensioned, false colours*

direct use of rainbow thermometry to a complex spray is not straightforward (large droplet size distribution, hence large particle temperature distribution, non-spherical particles, multi-scattering effects, existence of temperature gradients in the droplets etc.), leading to a high uncertainty on the temperature measurement.

It appeared that the systematic analysis of the rainbow pattern on the centerline of the image was misleading. Figure 8.4 shows several rainbow samples. The top three may be correct (issued from droplets of different sizes at different temperatures) while the bottom row represents "bad" rainbows, issued from non-spherical droplets or having a multi-scattering effect such as seen on the last shot. So that the rules for automated rainbow image processing had to be defined. As a start, a selection tool based on the full images of rainbow patterns had to be developed, in order to sort out the patterns issued from spherical droplets from the ones issued from still oscillating particles, or deformed rainbows due to multiple scattering. A conic calculation is performed in ref. [Giuliani, 1998] to determine the shape of the bows to be observed by the camera, as a function of the scattering angle θ.

Provided the rainbow pattern is integrated over the whole picture following the curvature of the bows, the resulting interference pattern offers a higher signal to noise ratio than the centerline signal. This method was presented in an article at the 6th Francophone Congress for Laser Vibrometry in Saint-Louis, France, September 1998 [Giuliani et al., 1998]. The methodology for automated rainbow image processing is summarised in figure 8.5:

1. The curvature of the bows is estimated as a function of the optical settings and of the camera CCD chip dimensions and resolution. Each curve is part of an ellipse. The wider the observation angle, the greater the droplet size range that can be investigated, but the lower the resolution and the greater the curvature gradient within the picture.

2. A sample is submitted. For a real spray, a representative temperature map would necessitate more than a kilosample of valid rainbows per measurement point.

3. A picture processing is applied, specialised for horizontal edges selection. The ripple bows are analysed, their curvature is approximated with a polynomial. It is then checked out that they match the simulated curvature.

4. The rainbow pattern is integrated along a line always normal to the curvature.

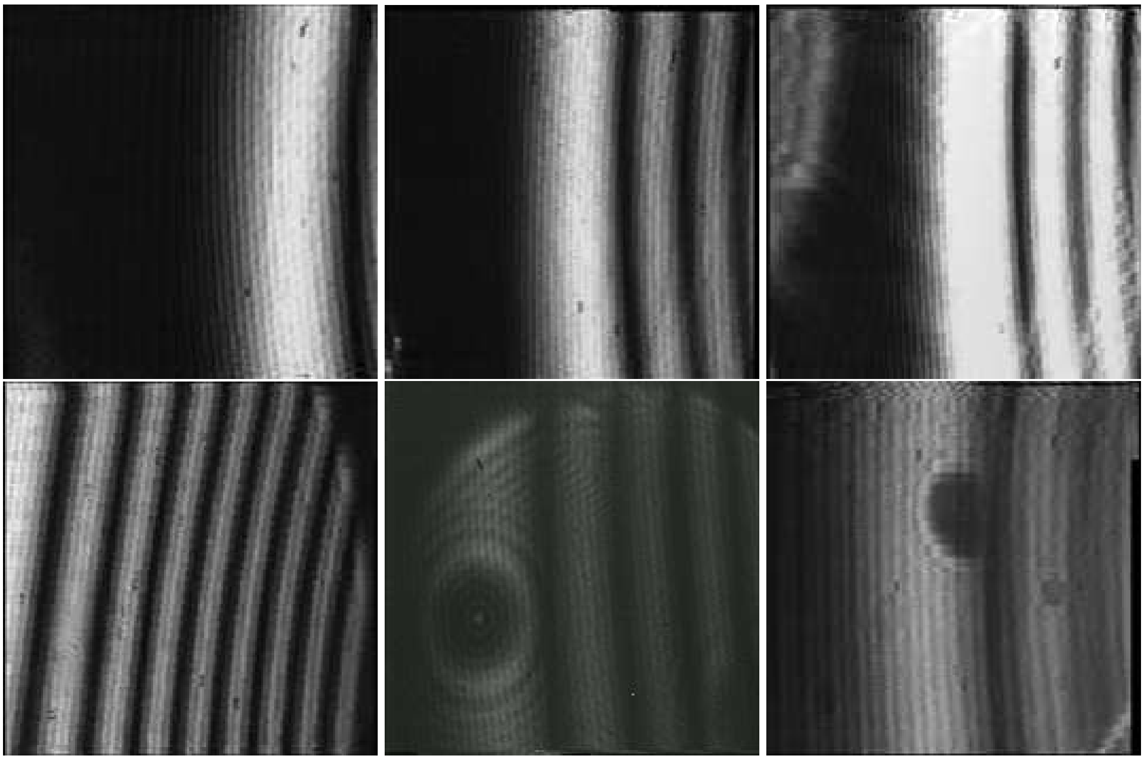


Figure 8.4: *Rainbow samples issued from a heated-up water spray [Giuliani, 1998]. The two first samples ought to be validated.*

5. This plot shows the difference between a single line profile and an integrated profile. The ripple is more regular on the integrated pattern, and the Airy peak position will be determined with a greater accuracy.

6. In case of the presence of a parasitic interference on the picture (multi-scattering, or impurity), this integration process allows to obtain a fair rainbow signal.

8.1.1.4 Project follow-up

In the follow-up on rainbow thermometry, the applicant served as a consultant.

At VKI, D. Gianoulis and L. Zimmer took care of automating the process. Facing the huge amount of data necessary to perform a satisfactory measurement, plus the related processing time, they tried several strategies including the use of pictures containing several rainbow patterns, detected with a pattern recognition process. Still, the results where not satisfactory. Van Beeck decided then to renounce to a precise temperature measurement per droplet size range, and to analyse directly the interference pattern corresponding to the sum of many superimposed rainbow patterns. The measurement volume was then larger, containing more than one illuminated droplets. This process, called Global rainbow thermometry (GRT) [van Beeck et al., 1999] allows to determine an average temperature, related to the local SMD of a complex spray. M. Vetrano et al. worked out a precise inversion method on the GRT pattern, and their results on GRT validation were recently published [Vetrano et al., 2006].

At ONERA, A. Atthasit was doing his PhD thesis on the interaction of monosized and monodisperse droplet streams, using the rainbow technique. This was the chance to observe a set-up as defined by Roth

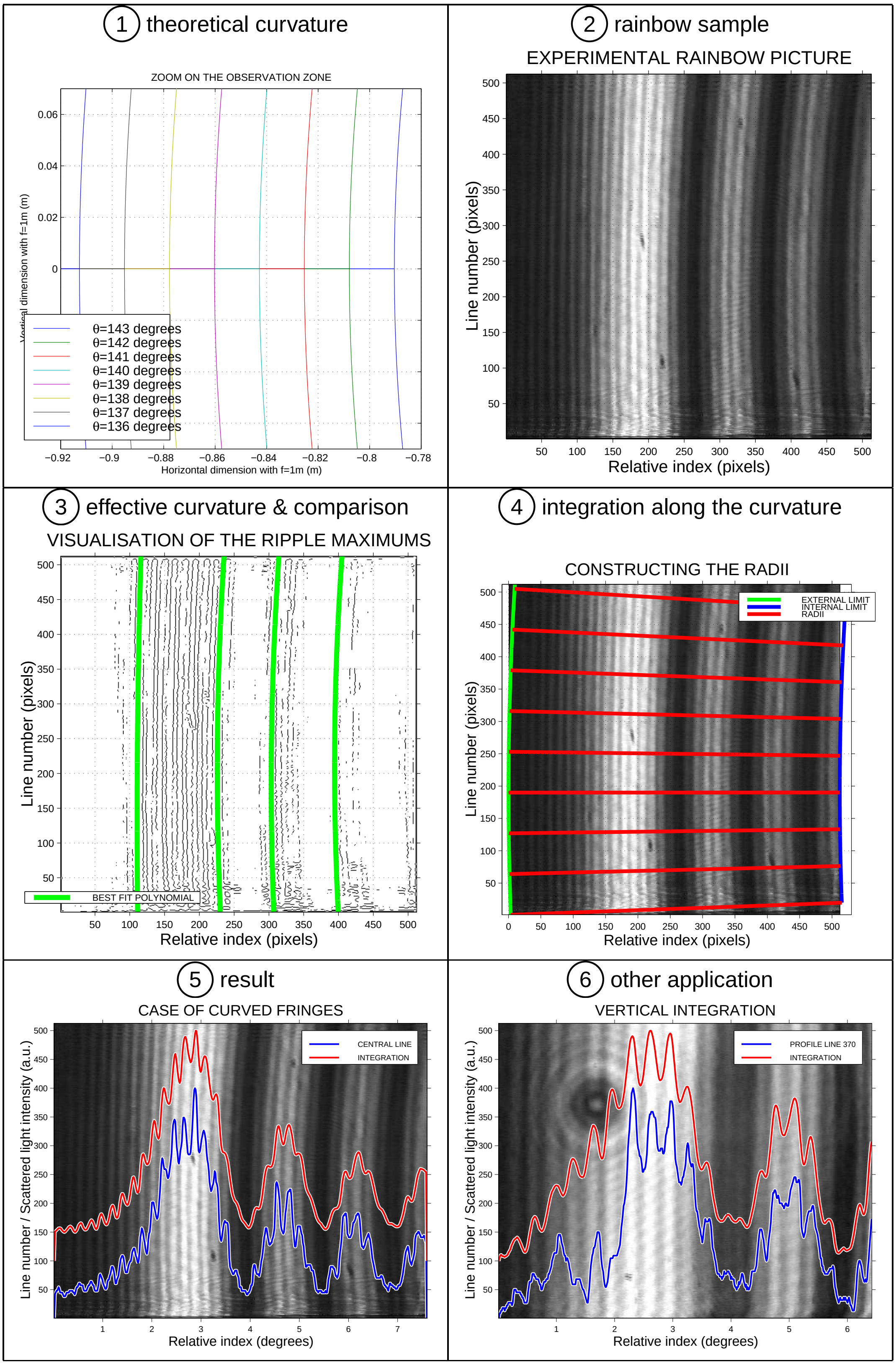


Figure 8.5: *Rainbow image processing, methodology and results*

et al. We collaborated on one article presented at the FLUVISU conference in Rouen, 2001 [Atthassit et al., 2001].

At the Stuttgart University of Technology, Jochen Wilms with whom the applicant was in touch at the end of his PhD, did also use rainbow refractometry [Wilms, 2005] for the analysis of multicomponents droplet evaporation, with encouraging results in view of direct use on real fuels.

Literature from author related to Rainbow Thermometry

[Atthassit et al., 2001] Atthassit, A., Biscos, Y., Giuliani, F., and Lavergne, G. (2001). Mesure de la température des gouttes en évaporation et en combustion par la technique arc-en-ciel. In *Recueil des actes du 9^e congrès francophone de visualisation et de traitement d'images en mécanique des fluides, FLUVISU*, pages 79–84. Rouen, France.

[Giuliani, 1997] Giuliani, F. (1997). Experimental study on rainbow interferometry using a pulse laser. Technical Report VKI SR 1997-14, von Karman Institute.

[Giuliani, 1998] Giuliani, F. (1998). Rainbow thermometry: droplet temperature measurement in a spray using a Nd:YAG laser. Technical Report VKI PR 98-11, von Karman Institute.

[Giuliani et al., 1998] Giuliani, F., van Beeck, J., and Riethmuller, M. (1998). Thermométrie par arc-en-ciel: technique d'acquisition de donnée à l'aide d'un laser Nd:YAG et traitement de signaux 2D. In *Recueil des actes du 6e Congrès Francophone de Vélocimétrie Laser*, pages B.3.1 – B.3.7, Saint-Louis, France. Association francophone de vélocimètrie laser.

[Van Beeck et al., 1999] Van Beeck, J., Giuliani, F., and Riethmuller, M. (1999). Rainbow interferometry: principles & developments. In *Optical Diagnostics of Particles and Droplets*, volume VKI LS 1999-01, Rhode-St-Genèse, Belgium. von Karman Institute. VKI RP 1999-27.

8.1.2 Advanced spray visualisation techniques

The following discusses essentially visualisation techniques developed at first for qualitative analysis of pulsed spray, so that the spray behaviour at unsteady air flow inlet conditions can be detailed. From there, we also experimented particle image sizing, a topic ongoing at TU Graz for the refined analysis of the atomisation process.

8.1.2.1 Phase-locked Mie scattering visualisations for the analysis of spray density fluctuations

Mie-scattering and background lighting techniques provide qualitative pictures of the spray and can be phase-conditioned to describe a repeatable motion (set-up for Mie scattering displayed in figure 8.6). During the applicant's PhD thesis [Giuliani, 2002] [1] [2], the effort was put on the description of the dynamics of an air-blast spray submitted to medium range frequency pulsations in the air flow ($f \in$ [50-500 Hz]). The pulsation was ensured by a siren engineered at ONERA (see ref. [Giuliani et al., 2007c], page 2). This siren

[1] French version: `http://www.isae.fr/fr/bibliotheque/nos_catalogues/catalogue_bibliotheque_campus_supaero.html`
[2] English version: `./biblio/20020625_these_fabrice_english.pdf`

consists in a rotating cogged wheel, which teeth periodically shear a sonic air jet generated by a choked Laval nozzle. By setting the rotation frequency of the wheel, one sets the pulsation frequency on the air. An opto-electronic sensor reports on the real-time position of the wheel and delivers a reference TTL signal related to the pulsation status.

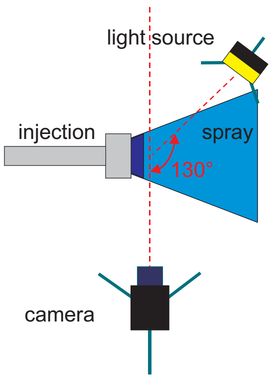


Figure 8.6: *Mie scattering visualisation technique for the analysis of spray density fluctuations*

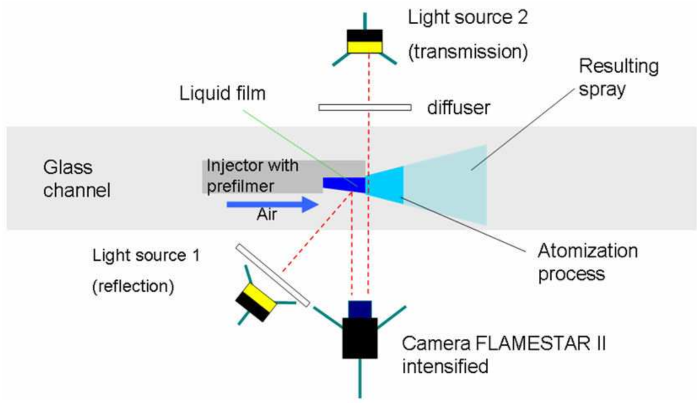


Figure 8.7: *Setup at DLR for background lighting technique*

The measurement technique and post-processing are described in figure 8.8. The goal is to highlight the effect of air pulsation on the air-blasted spray as shown in the res. 256 phase-locked pictures are taken. The IMAGE 5 software developed by Berthoumieu [Berthoumieu, 2002] performs the MAXIMUM process in real-time (only the highest intensity per pixel is kept over the 256 records as a resulting image). Attention has to be paid to the low camera aperture, to avoid saturation. Complementary results are shown in figure 9.7 p.133.

Post-processing techniques can help for instance to determine the velocity of the droplet front (about $U_{ref}/2$, where U_{ref} is the air mean velocity at the injector outlet [Panda and McLaughlin, 1990]), or cross the data with other measurements, such as the coherent vortices (figure 9.7 p.133 based on LDA measurements).

8.1.2.2 Particle and pattern image sizing

During the applicant's stay at DLR, we studied the effect of intermediate pressure on the airblast atomisation of kerosene, using a flat airblast with or without prefilmer [Giuliani et al., 2004b, Bhayaraju, 2007]. The effort was put on the observation of the prefilming surface, and the few millimetres following the injector where the atomisation turns complete. The ambition was to define design guidelines for the injectors (prefilmer surface for an ideal kerosene thickness and prefilmer lentgh - or simply the configuration with / without prefilmer).

Background lighting visualisations

The background lighting is very similar to the Mie scattering set-up, with the difference that the camera and light source are facing each other with the spray in between. Two main aspects have to be considered

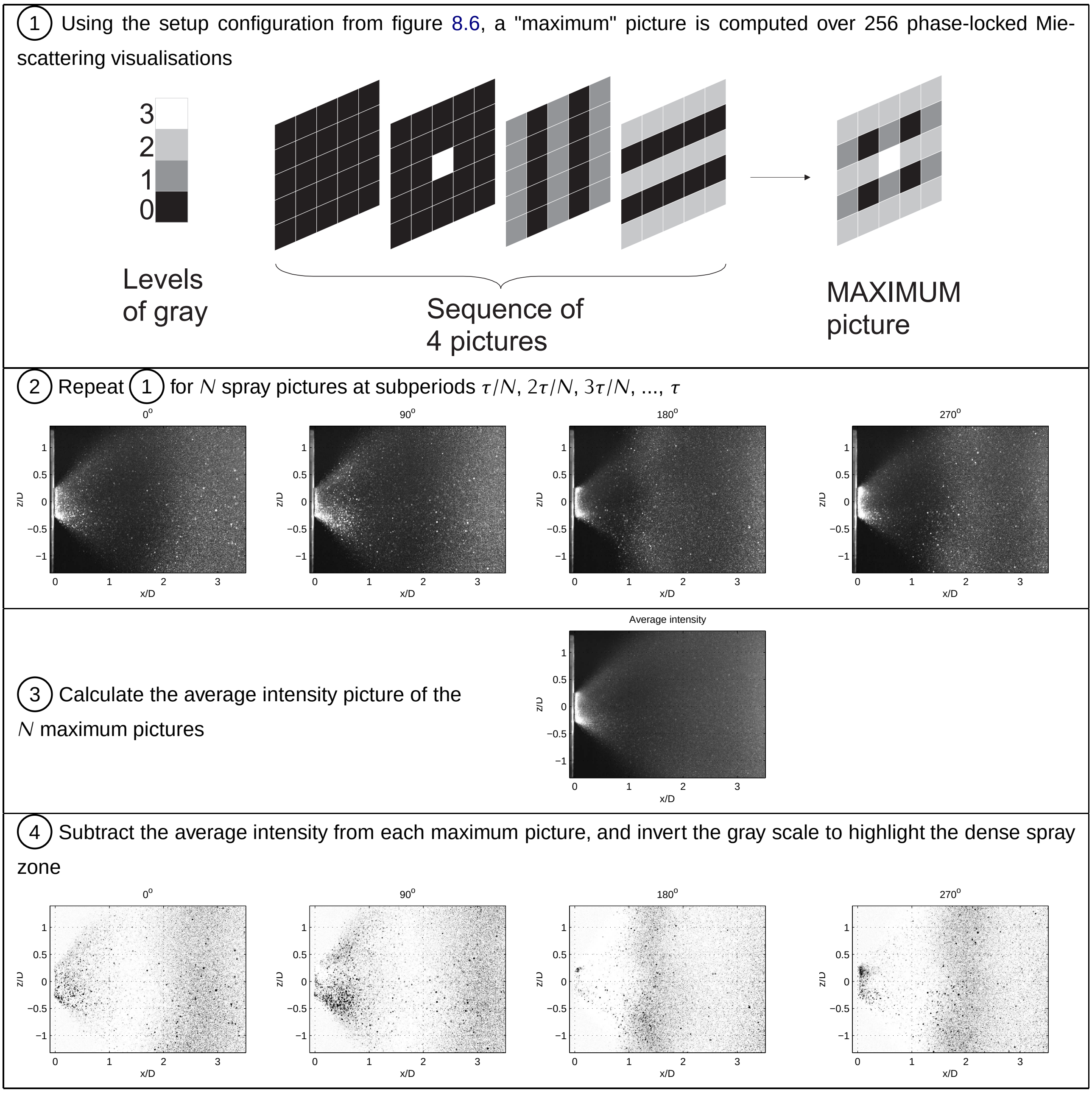


Figure 8.8: *Spray image processing to derive the high density zones within the airblasted atomisation*

carefully: the homogeneity of the light halo, and the camera settings (aperture, zoom, exposure time, depth of field) that require a fair compromise between contrast, particle sharpness and narrow depth of field permitting sizing.

As a result, it is possible to observe with great accuracy the subsequent atomisation processes in a liquid ligament issued from a 5mm outlet diameter pipe and excited with a solenoid valve at 100 Hz (figure 8.9).

The set-up at DLR was built on the isothermal kerosene spray test-rig (figure 8.7, see the MOPAA report for technical details on the test rig [Giuliani and Hassa, 2003]). Several flat prefilmers where used, with variable lengths (0 to 4 mm) and slot widths (300 and 500 μm). In order to observe simultaneously the

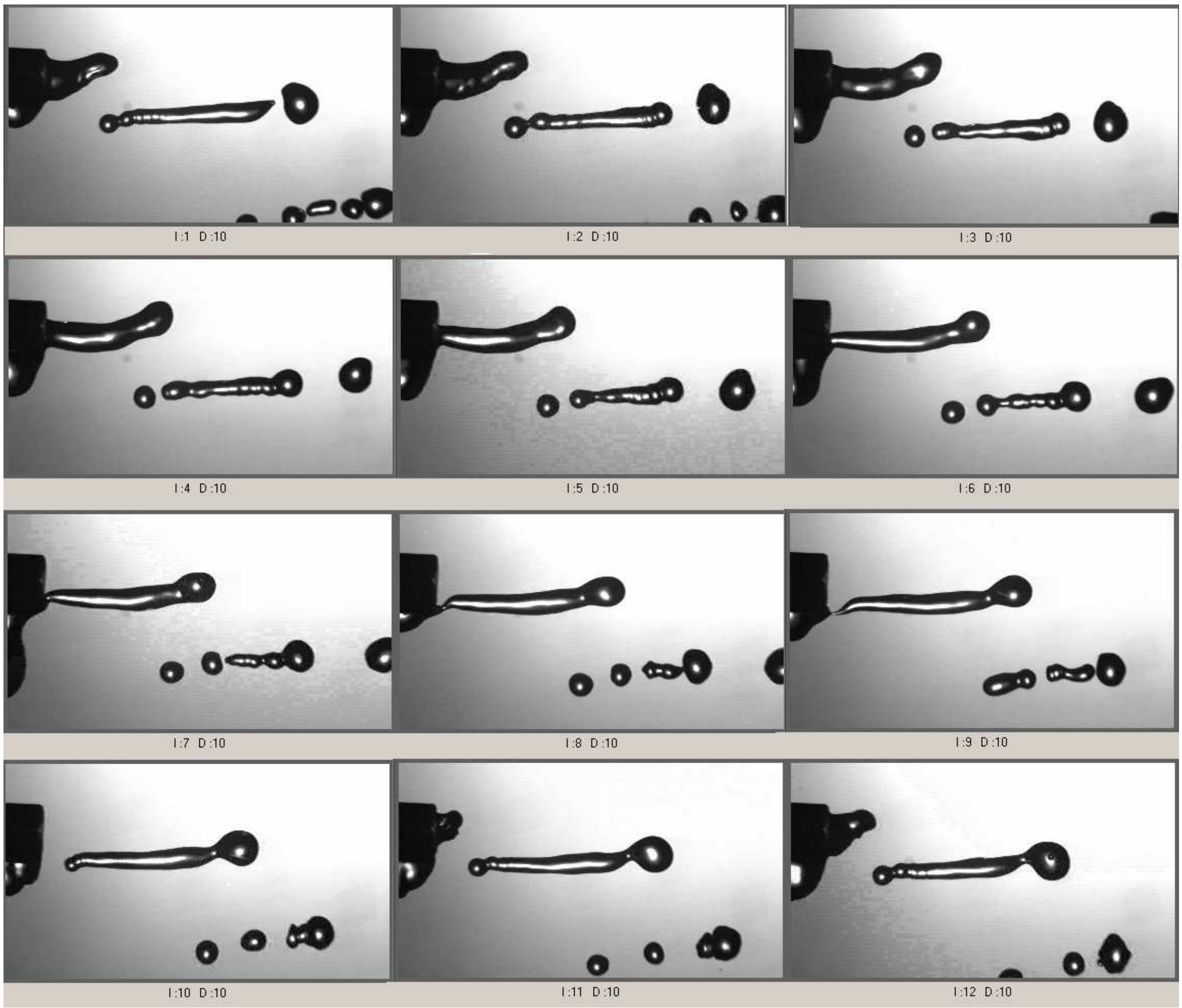


Figure 8.9: *Liquid ligament segmentation: experiment realised by Giuliani [Giuliani, 2002] with background lighting to check the reproducibility of the pulse liquid "General Valve Series 9" from Parker Hannifin. Pipe outlet diameter: 5 mm. Liquid: water. Flow rate: 2 g/s. Pulsation: 100 Hz.*

structures taking place on the prefilming surface and after the injector, a second light source was needed, reflecting the light on the prefilmer surface. Attention had then to be paid to the balance of light issued from the two sources.

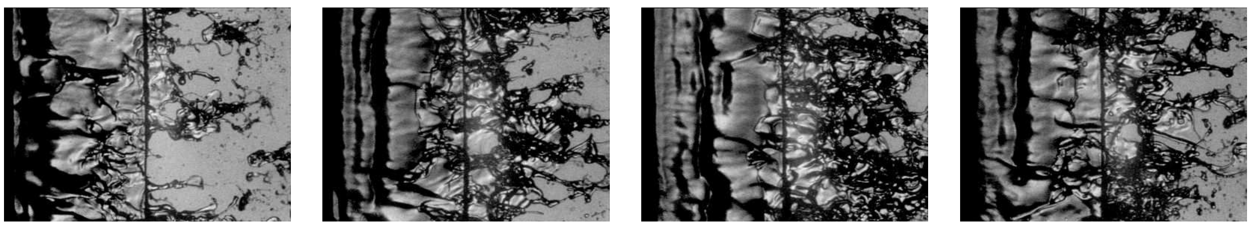


Figure 8.10: *Samples of atomisation images using the background lighting technique. Transparent prefilmer. Length = 4 mm, width = 300 μm, air 30 m/s, liquid 1 m/s, P = 2 bar, T=290 K*

Image processing

The idea was to measure directly the main features of the waves propagating on the prefilmer, the ligaments resulting from the primary atomisation, and the particle size after the secondary atomisation. Background lighting pictures are adequate for this, since with a reasonable image resolution and a perfect optical setting, the particle borders are clearly materialised [Berthoumieu and Carentz, 2000].

Based on measurements performed by Bhayaraju and Giuliani, Christoph Hennig developed an image processing software (see the notice for further details, as well as article [Hennig et al., 2009]) on a MATLAB basis. In comparison with the IMAGE sofware from Berthoumieu, ours suited the 16 bits-format delivered by the Lavision camera with intensity amplifier we used. The operations were otherwise in many aspects similar, up to the binarisation and particle sizing method. It also turned out that FFT-based analysis of this very kind of image is not the best method. Hennig analysed integrated profiles (longitudinal) in order to edit some statistics such as the prefilm length along the prefilmer before film breakup (figure 8.11, see also Bhayaraju et al. [Bhayaraju et al., 2005, Bhayaraju and Hassa, 2006, Bhayaraju, 2007]). Based on the available material, we observed a power-law like behaviour of this length as function of the air velocity, with interestingly a slope comparable to the one of the SMD (see the established correlation Eq. 9.4 p.139), suggesting a function in $\sqrt[-4]{P}$.

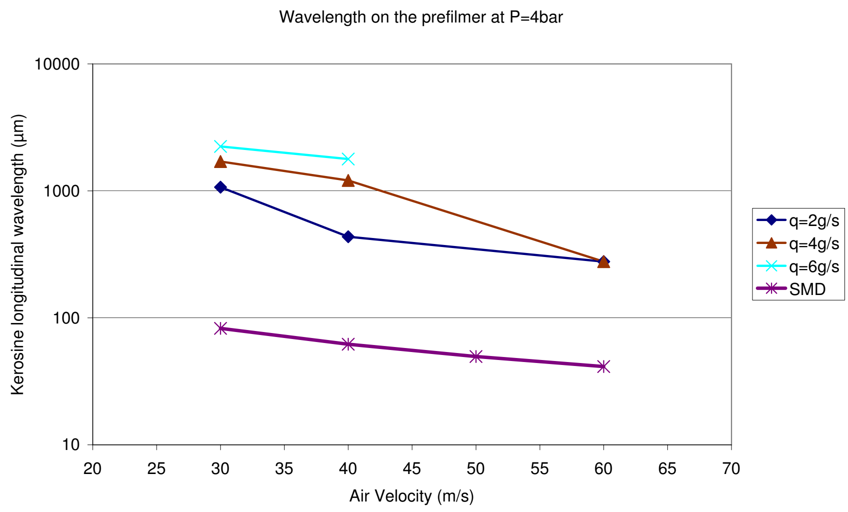
Ann Hines continued the work of Hennig on image analysis, by extending the analysis to the near- and far-field atomisation. Quite an effort was done on the choice of the image processing algorithms, in order to be able to process a large number of pictures (several hundreds) in a relatively small time. Some pattern recognition techniques such as the Hough Transform were also tested, with promising results, but still these are quite demanding in terms of numerical power. In the end, the processing accomplished the following routine: binarise the images, select and measure the retained particles, and perform the statistical analysis. This is represented in figure 8.12.

The binarisation method was inspired by the works of Marmottant et al. [Marmottant and Villermaux, 2004]. It consists in comparing one spray picture with a reference picture. Pixel by pixel, the intensity is compared. If the ratio between these intensities is inferior to one, this means that the spray pixel is darker than the reference pixel. It will be considered as liquid (coded 1). In the opposite case, it is air (coded 0). The reference picture can be the background picture (for the analysis of the resulting spray) or the average intensity per pixel over a serie of a 100 spray pictures (for the analysis of liquid structures along the prefilm).

Follow-up of the study

The process shown in figure 8.12 is a promising work-in-progress. Measurement uncertainties are to be analysed further into details, as well as 2D-3D geometries assumptions leading towards a quantified intermediate-atomisation description. The ambition is to develop a particle measurement technique developed for non-spherical particles, not having yet achieved complete atomisation. This tool would be important to understand at which regime the successive break-up takes place, how far from the injector and at which conditions. It would also refine the modelling on transfer issues (momentum, heat) between the transporting phase and the liquid phase during atomisation. In the end, it would provide design guidelines for ameliorating the atomisation in the least favourable conditions (part-load).

Umesh Bhayaraju did during his PhD thesis a parallel between the atomisation regime at the injector's lip and the resulting atomisation and particle diffusion in the far field. He put a main effort on describing



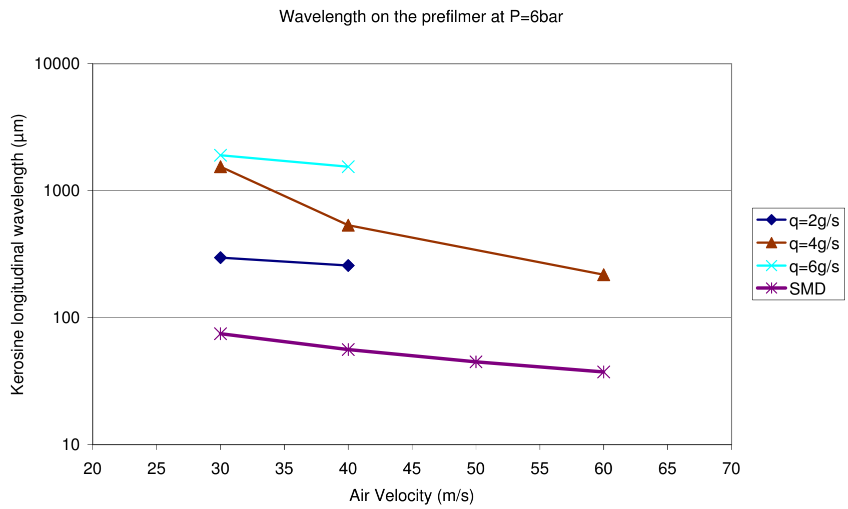


Figure 8.11: *Prefilm length appearing on the surface of the prefilmer before film breakup as a function of the air velocity and kerosene mass flow rate. Measurement under pressure at ambiant temperature.*

the liquid prefilm dynamics. He also provided the DLR with a large database of atomisation images, with a detailed description of the resulting spray.

A cooperation with DLR is currently ongoing (PhD of Christoph Hennig since July 2008 at TU Graz), so that the images of Bhayaraju have been processed again using our technique validated with calibration images. The results were published in 2009 [Hennig et al., 2009].

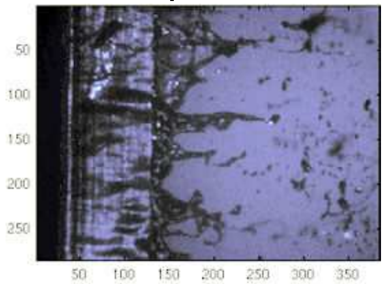
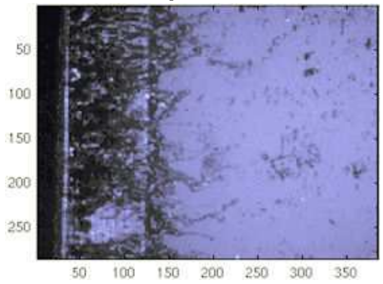
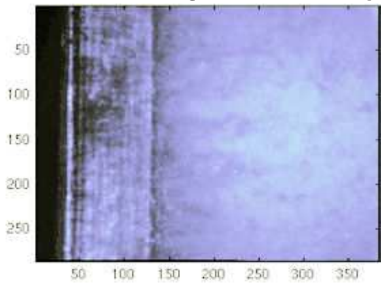
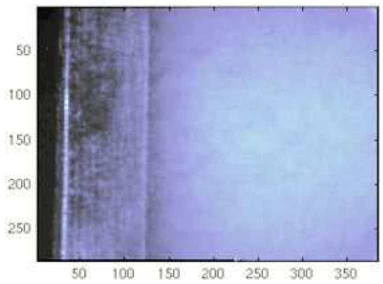
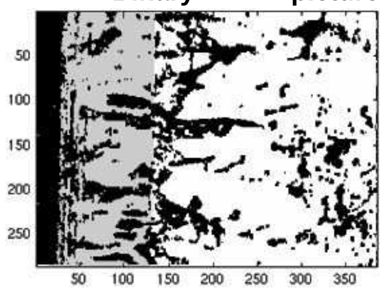
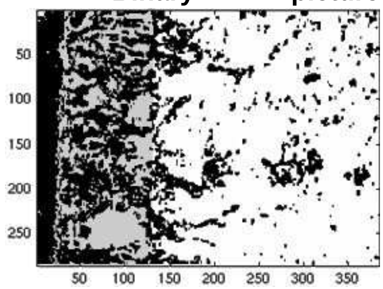
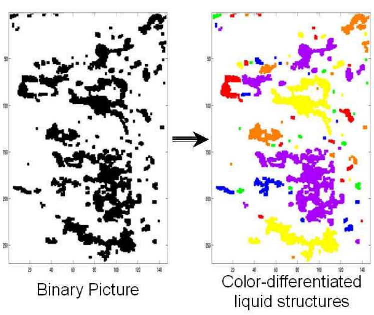
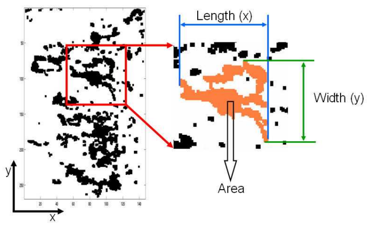
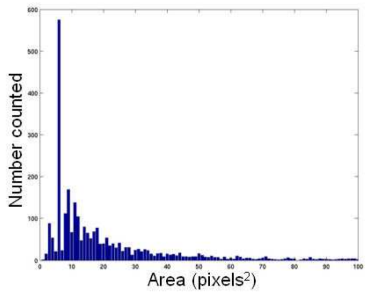
<table>
<tr>
<td>(1) Image sample I_s. All shown measurements are performed at U_{air}=30 m/s, U_{kero}=0,2 m/s, T=293 K</td>
<td>Sample, P=2 bar
</td>
<td>Sample, P=6 bar
</td>
</tr>
<tr>
<td>(2) Average intensity over 100 image samples I_{mean}</td>
<td>Average intensity
</td>
<td>Average intensity
</td>
</tr>
<tr>
<td>(3) Binary image $I_{bin} \equiv \frac{I_{mean}}{I_s} \geq 1$ where the particles are marked "1" (black) and the rest levelled to 0 (white, air or background)</td>
<td>Binary picture
</td>
<td>Binary picture
</td>
</tr>
<tr>
<td>(4) Differentiation of each single particle, and fill-in of closed areas ("flood-in" algorithm). Reject the particles in contact with border.

</td>
<td>(5) Measurements per particle: number, lengths, area

</td>
<td>(6) Metrics conversion and statistical analysis, and classification according to the location: "prefilmer", near field or far-field atomisation

</td>
</tr>
</table>

Figure 8.12: *Particle image sizing process*

Literature from the author related to image-based spray analysis

[Bhayaraju et al., 2005] Bhayaraju, U., Hassa, C., and Giuliani, F. (2005). A study of planar liquid sheet breakup of prefilming airblast atomisers at high ambient air pressures. In *20th Annual Meeting of the Institute of Atomisation and Spray systems (Europe)*. ILASS 2005 (20th Annual Meeting), Orléans, France.

[Gajan and Giuliani, 2001] Gajan, P. and Giuliani, F. (2001). Caractérisation d'un système d'injection de turbomachine en régime pulsatoire forcé. *Rapport ONERA RF 3/06107 DMAE*.

[Giuliani, 2002] Giuliani, F. (2002). *Analysis on the Behaviour of an Aeroengine Air-Blast Injection Device with Forced Entries*. PhD thesis, ENSAE No 346, Toulouse, France.

[Giuliani et al., 2004] Giuliani, F., Berthoumieu, P., Becker, J., and Hassa, C. (2004). The effect of ambient air pressure on planar liquid sheet disintegration at gas-turbine conditions. In *19th Annual Meeting of the Institute for Liquid Atomization and Spray Systems (ILASS Europe), Nottingham, UK*, pages 68–75.

[Giuliani et al., 2000] Giuliani, F., Diers, O., Gajan, P., and Biscos, Y. (2000). Caractérisation d'un système d'injection de turbomachine en régime pulsatoire forcé. *Rapport ONERA RF 4/05103-01F DMAE*.

[Giuliani et al., 2002a] Giuliani, F., Diers, O., Gajan, P., and Ledoux, M. (2002a). Characterization of an air-blast injection device with forced periodic entries. In *Proceedings of the IUTAM Symposium on Turbulent Mixing and Combustion, Queen's University at Kingston, Canada, June 3-6, 2001 Pollard and Candel (eds) Kluwer Academic Publ.*, pages 327–336.

[Giuliani et al., 2001] Giuliani, F., Gajan, P., Biscos, Y., Diers, O., and Ledoux, M. (2001). Analyse de l'écoulement diphasique généré par un injecteur de type aérodynamique en régime pulsatoire forcé. *Recueil des actes du 9^e congrès francophone de visualisation et de traitement d'images en mécanique des fluides, FLUVISU, Rouen, France*.

[Giuliani et al., 2005] Giuliani, F., Gajan, P., and Diers, O. (2005). A physical model on air-blast atomisation with modulated air inlet flow. In *Trends in Numerical and Physical Modeling for Industrial Multiphase Flows*. Cargèse, France.

[Giuliani et al., 2002b] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2002b). Influence of pulsed entries on a spray generated by an air-blast injection device - an experimental analysis on combustion instability processes in aeroengines. *Proceedings of the Combustion Institute*, 29(1):91–98.

[Giuliani et al., 2009] Giuliani, F., Hennig, C., Leitgeb, T., and Hassa, C. (2009). Effect of the initial droplet size distribution of the liquid phase combined with transport phenomena on the resulting airblast spray in the far field. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-133.

[Hennig et al., 2009] Hennig, C., Giuliani, F., Freitag, S., and Hassa, C. (2009). Image particle sizing of an air blasted liquid sheet of kerosene at intermediate pressure. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-093.

8.2 Line-of-sight laser-based measurement techniques

8.2.1 Incentive of the TOSCA project

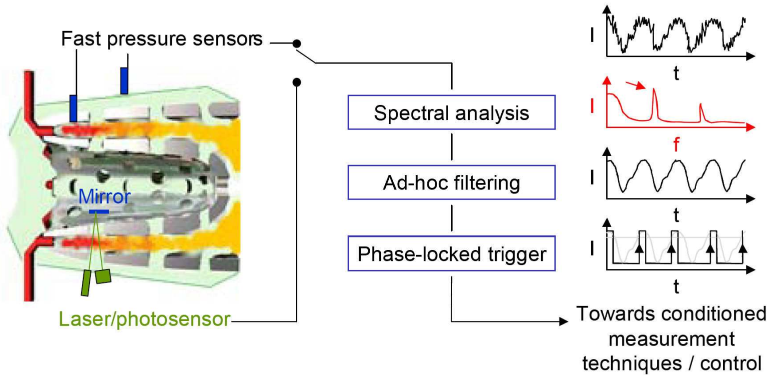


Figure 8.13: *Sensing strategies for combustion stability monitoring (TOSCA project, 2005-2007). Left: combustor with wall-mounted pressure sensor OR optical set-up. Right: schematic data processing for real-time feedback loop.*

A spin-off thematic strongly related to ONERA and DLR's previous projects but having no continuation there, and fitting the combustion management problematic, is the development of embedded sensing techniques in gas turbine combustors, with focus on the stability of the combustion process. We called this project TOSCA (Technology for Oscillating and Steady-State Combustion Analysis). The aim is to select a measurement technique placed onboard that shall survey in real-time one significant parameter on combustion stability (e.g. the unsteady pressure, in terms of dominant frequency and amplitude, for sound and pseudo-sound, see Hirschberg and Rienstra [Hirschberg and Rienstra, 1994]) under aggressive conditions (high pressure ratio, high temperature, presence of a flame, vibration, corrosion, start and stop). This system requires a broad-operation range, a long lifetime and low drift. It shall also be small, robust, and easy to implement or to replace.

Two strategies are analysed in details at TU Graz (figure 8.13) based on wall-mounted fast-response pressure transducer and in-situ optical sensors. In the first case, a high temperature-resistant pressure sensor is mounted directly on the flametube. It reports in real time and without cooling artifacts on the combustor acoustics. A partnership was developed with PIEZOCRYST (an AVL subsidiary, and a partner of VIBRO-METER in GT applications). The high-temperature resistant piezoelement is a $GaPO_4$ cristal (gallium phosphate, see the specifications[3]). The main property of $GaPO_4$ is its ability to deliver a piezoelectric signal independently from temperature on a broad operational range (some specifications of the $GaPO_4$ sensor follow: 0...200 bar, -70...560°C, 2 Hz...50 kHz). A specific sensor was tested by us (old denomination PIEZOCRYST: P-2, new denomination VIBRO-METER: CP-502) on the intermediate pressure single-sector combustor. The results have been presented at the ISABE conference in Peking, 2007 [Giuliani et al., 2007d].

This section develops into details the incentives of the second strategy, where optical elements are placed in the diffuser and observe the flame through the cooling holes. Therefore the flow conditions near the optical accesses are not as aggressive as in the liner itself. Laser-based measurement techniques where emitter and receiver are placed in-line can quickly provide several informations on the injection or combustion status when analysing the obscuration (IRA, spray density), the laser light forward scattering on a limited solid angle (Fraunhofer diffraction for particle sizing) or the appearance of a given specie (e.g. OH

[3]http://www.piezocryst.com/downloads/gapo4_material_constants.pdf

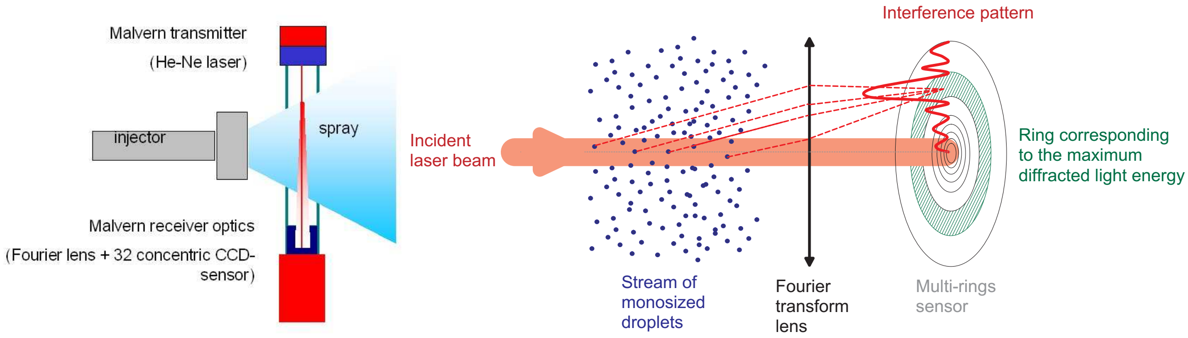


Figure 8.14: *Principle and free jet particle size measurements with a MALVERN instrument. Left: setup. Right: measurement principle.*

radical) with help of fluorescence. Laboratory applications such as LDA/PDA will not be discussed there.

The drawback of line-of-sight methods is that the measurement is limited to one point and that it is integral over the whole penetration of the laser in the medium of interest. However, the advantage in comparison to more demanding laboratory diagnostics is the time-defined signal, with possibility to investigate a given parameter (e.g. flame density) over a very large spectral band. This is the decisive factor that made us put the research effort on this theme.

8.2.2 Fraunhofer diffraction (MALVERN)

MALVERN measurements based on the Fraunhofer diffraction for particle size measurements (with Mie-scattering correction) were originally developed by Swithenbank et al. [Swithenbank et al., 1976]. It can be discussed whether this is a line-of-sight measurement or not, since the interferometric pattern resulting from forward particle scattering is analysed on a given solid angle (figure 8.14) on a multi-rings CCD sensor.

We used a MALVERN instrument in two studies (PhD and the MOPAA program [Giuliani, 2002, Giuliani and Hassa, 2003]), since this instrument is relatively straightforward to use for parametric analysis. However, we highly recommend NOT to use windows with it. A PDA although being more demanding does not suffer as much as a MALVERN from multi-reflections problems. The MALVERN tests conducted on the DLR spray test rig, basically a double glass canal hence 8 optical interfaces and a great number of prime-and second-order reflections, were purely an horror. The instrument had to be tilted and the results were corrected in post-process. Nevertheless, time-signal reconstruction methods are possible for a PDA, but they are not accurate and necessitate a large quantity of data [Becker, 2003, Becker and Hassa, 2004]. Taking advantage of the high acquisition rate of the MALVERN (2,5 kHz for the Incitec ECPS particle sizer), we could reconstruct the periodic fluctuation of the particle size in a pulsed spray (see figure 9.8 p.134). This was the very first spectral analysis we performed directly on the signal of an in-line measurement technique. The details for the measurement and processing technique are reported in [Giuliani, 2002] as well as in an ONERA technical note.

8.2.3 Hydrocarbon vapour concentration based on infra-red extinction (IRA)

Infra-red extinction, or absorption (IRA) is a measurement technique of the hydrocarbon vapour concentration flux. It was originally developed by Chraplyvy et al. [Tishkoff et al., 1980, Chraplyvy, 1981] for isothermal fuel spray characterisation and for internal combustion engine purposes. An advanced measurement technique development with detailed measurement error analysis was performed by Drallmeier et al. [Drallmeier and Peters, 1991, Jennings and Drallmeyer, 1996].

The method was adapted by Brandt [Brandt, 1999] for airblast isothermal injection at intermediate pressure at the DLR. We used the same setup in the frame of the LOPOCOTEP EU Project on a swirl-cup injector with parametric geometry. The motivation was to cross the concentration measurements with PDA measurements previously performed by Becker [Becker, 2003, Becker and Hassa, 2004], and take profit of the time-resolved signal to perform a stability analysis of the injection. The results have been published in a project deliverable and in two international conference papers (clickable ECM 2007) [Giuliani et al., 2004a, Giuliani et al., 2007a, Giuliani et al., 2008a, Giuliani and Hassa, 2009].

8.2.3.1 Measurement principles

The line-of-sight extinction is analysed over two wavelengths (visible and infrared). Equation 8.2 shows how four simultaneous measurements are required in order to estimate the concentration C: the collected intensities of visible and infrared lights, in presence and in absence of the spray. The main hypothesis of this method is that, if the line-of-sight extinction due to Mie scattering is similar for both infrared and visible wavelengths due to the presence of the spray, only infrared light will be absorbed by the vapour fuel, the latter being transparent to visible light. The spray shall be diluted, and the particle line-of-sight scattering intensity offers a linear behaviour as a function of the particle size over the two wavelengths (usually true for particles bigger than 10 μm, hence the major part of the liquid volume distribution for SMD's greater than 10 μm for an airblast injector). A comparison between line-of-sight intensities of both wavelengths allows to estimate the vapour concentration flux C (or hydrocarbon vapour mole fraction). These intensities will always be normalised with a reference signal in absence of spray, the direct transmission intensities that are marked with a "0" underscript. In other words, the line-of-sight intensities I_{VIS}, $I_{0\ VIS}$, I_{IR} and $I_{0\ IR}$ have to be measured:

$$C = \frac{1}{\alpha_{IR}\ L}\ \ln\left(\frac{(I/I_0)_{VIS}}{(I/I_0)_{IR}}\right) \tag{8.2}$$

where

$\alpha(\lambda)$	[-]	is the vapour absorption coefficient in the IR range,
L	[m]	is the length of laser penetration through the medium.

The product $\alpha_{IR}\ L$ being constant at isothermal conditions, the relative concentration can be computed. For absolute measurements, a precise calibration with known vapour quantity has to be done. In the present case, we just consider the relative concentration.

The required setup is presented in figure 8.15. The original signal sampling system using a mechanical chopper was replaced by an AD card for online measurement and spectral analysis.

8.2.3.2 Time-resolved approach

Stability of the combustion is strongly related to the stability of the injection. Becker observed a preferred frequency at 2600 Hz in the PDA inter-particle times for a configuration using a strong swirl number. After characterising the natural spectrum of the photosensors (or noise at rest), the effect of the other factors were analysed. The spectra in presence of the spray were always compared to the reference spectrum

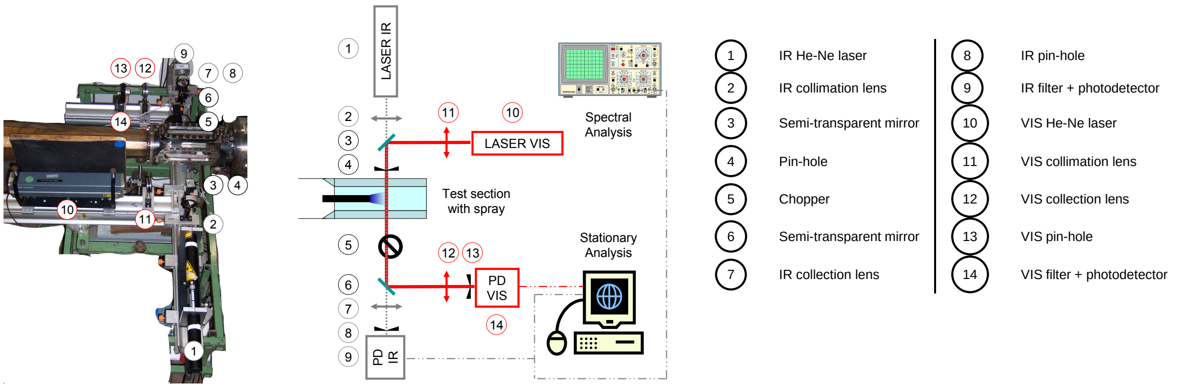


Figure 8.15: *Instrumentation for IR extinction measurements.*

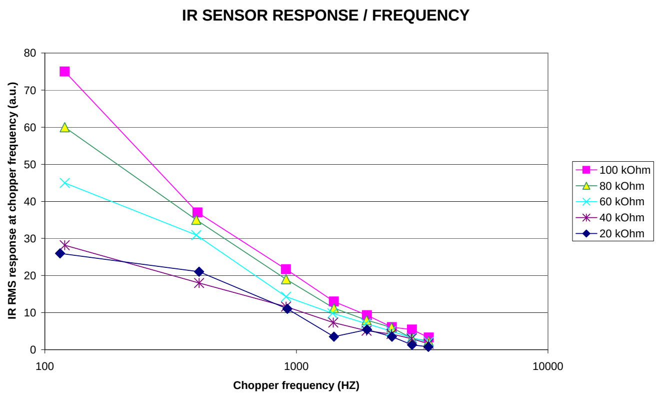


Figure 8.16: *IR sensor frequency response, as a function of the Peltier heatsink-resistor setting*

without spray. In accordance with [Becker and Hassa, 2004] a peak was also found at 2600 Hz, which is the most remarkable.

In order to precisely estimate the gain of the signal at a given frequency, one has to determine precisely the noise level of the photosensors, and their spectral signature. Figure 8.16 shows the characteristic photosensor response in $1/f$ (the exciter was then the mechanical chopper obscurating the sensor, at several rotating frequencies f). This decrease in sensitivity becomes quickly critical in terms of measurement uncertainty when exploring the high frequency domain. We shall see later on how the technology used in a laser vibrometer eludes this problem.

A semi-automated acquisition chain was developed at DLR to perform a concentration mapping for a given configuration, with the possibility to reconstruct the absolute radial concentration distribution, with help of an Abel transform. A systematic comparison is then performed between the spectrum of each sensor's signal and their signature at rest. In case an instability peak appears, the resulting concentration fluctuation can be measured, and mapped as well. This technique can detect natural spray oscillations, preferably of the longitudinal mode. The DLR technical activity report details this process, which is summarised in the conferences articles.

8.2.3.3 Further developments within ECCOMET and ALFA-BIRD

IRA showed a satisfying level of accuracy and a good match with previous 2-phase flow measurements concerning fuel placement. This technique could ease the benchmarking of airblast injectors performed at realistic GT operating conditions in comparison with more demanding techniques such as LIF, for its reliability, its flexibility and its ability to monitor the stability of kerosene atomisation.

The PhD of Bernhard Wagner at ONERA in the frame of ECCOMET (a co-supervision with CERFACS and TU Graz/TTM/AV) focuses on the analysis of multicomponent fuel evaporation using the IRA technique. This PhD is the continuity of a previous one (Bruno Frackowiak, 2007 [Frackowiak, 2007], who was supposed to start a post-doc at our place on the FWF3 project in 2007 - unfortunately the proposal took too much time before being accepted). A comparison with other measurement techniques such as LIF will be done. In the end, the IRA method shall be validated for fast parametric studies, and the evaporation models shall be refined.

The same technique will be used in the frame of the ALFA-BIRD project to analyse the vaporisation of next-generation agro- and synthetic fuels. The reference fuel is then kerosene jet A1. The focus is put on the compatibility of existing injection technologies, including Low-NOx, with replacement fuels.

8.2.4 Laser vibrometry

8.2.4.1 A lightweight method for flame stability monitoring

The motivation is to use a line-of-sight measurement technique to observe gas density fluctuations within the flame, without seeding. For a qualitative analysis, an alignment of a laser and photosensor such as in the previous section would suffice. However, we have previously established (figure 8.16) that the sensibility of such an assembly is rather poor when entering the high frequency domain.

Woisetschläger et al. [Mayrhofer and Woisetschläger, 2001, Hampel and Woisetschläger, 2006] used a laser vibrometer to detect coherent turbulence in a turbine flow. Laser vibrometry (LV) is originally a laser-based measurement technique dedicated to the analysis of surface vibrations. This technique was adapted at TU Graz as a line-of-sight measurement technique for the observation of coherent vortices in the wake of a turbine blade. The advantage of LV in comparison with the previous method is a high sensitivity over a large spectral bandwidth, with the possibility of mapping the coherent structures. The application to reactive flows was the next step, realised under the applicant's supervision. This very incentive has been the major research effort of the applicant at TU Graz, and was reported in number of articles and conferences [Giuliani et al., 2006, Giuliani et al., 2007c, Giuliani et al., 2007b, Lang et al., 2008, Giuliani et al., 2008b], with one journal article en route [Giuliani and Köberl, 2009].

A fully automated LV measurement technique was developed at TU Graz and tested in other places such as on the ASC burner at DLR Cologne, allowing rapid flow dynamic description, with related postprocessing routines for phase defined data. LV can be performed on the whole flame domain as long as optical access allow it. The measurement is integral over the laser penetration in the medium of interested, but tomographic methods such as an Abel inversion can be applied if the flame geometry allows it. For practical purpose, LV can map the density fluctuations with help of a reference signal. The volume of LV data is relatively small in comparison with more demanding methods such as PIV or LIF to describe a given coherent structure dynamic. The advantage of LV is its high spectral sensitivity, and ability to detect fluctuations in the high-frequency domain, where other detection techniques offer a lower signal-to noise ratio.

8.2.4.2 Measurement technique

The principle of LV is shown in figure 8.17. A laser interference pattern between a reference beam and an object beam (reflecting on the studied surface) is analysed. If the surface moves, the path difference between the two beams changes and so does the interference. In order to detect motion amplitudes greater than the laser wavelength, and to distinguish a forward from a rearward movement, a Bragg cell is used to slightly shift the reference beam wavelength. Steady-state is then represented by a fixed frequency corresponding to the modulated interference. Any surface motion will provoke a Doppler effect on this carrierwave. A frequency demodulation allows to derive the vibration frequency and the motion amplitude of the object surface.

Mayrhofer and Woisetschläger [Mayrhofer and Woisetschläger, 2001] used a variant of this technique for density fluctuation analysis of ambiant air, keeping the geometrical path constant (the object surface is a mirror at rest) so that mainly density fluctuations alter the optical path, advancing (negative density gradient) or retreating (positive gradient) the phase front of light. As a result, LV can detect the presence of passing-by coherent structures. The relationship between LV signal voltage u' and density fluctuation ρ' is derived from [Mayrhofer and Woisetschläger, 2001, Hampel and Woisetschläger, 2006] as follows:

$$u'_f = \frac{G}{k}\int_Z \frac{\partial \rho'_f}{\partial t} dz \tag{8.3}$$

where

G	[m^3/kg]	is the Gladstone-Dale factor, related to the refraction index of the medium ($G = 2.510^{-4} m^3/kg \ \pm 3\%$ for air-CH_4 mixture over an equivalence ratio interval varying from 0.4 to 1, as well as for the resulting burnt gases, computed after the method of Gardiner and Hidaka [Gardiner Jr., 1981]).
k	[mm/s/V]	is an instrument gain factor
Z	[m]	is the penetration length of the laser through the medium.

Subscript f means phase-averaged at a fixed frequency, so that u_f and ρ'_f correspond to the narrowly band-passed signals - or phase averaged signals - of the time-signals $u'(t)$ and $\rho'(t)$ at frequency f.

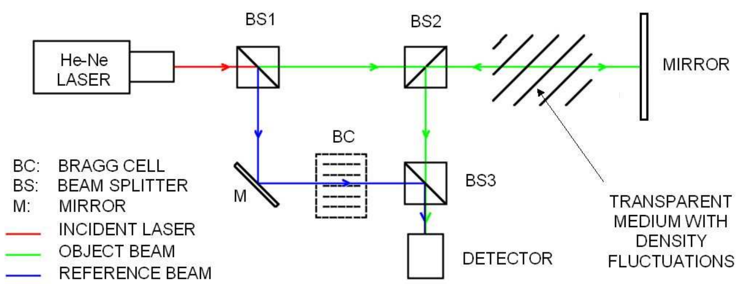


Figure 8.17: *Principle of laser vibrometry*

Since the LV's physical measurement is related to the density time derivative, the spectral bandwidth of the instrument is much superior to the one of an assembly consisting of a laser placed in-line with a sensor (see the characteristic decay in $1/f$ in figure 8.16). In the Fourier domain, the transform of a time derivative is equivalent to the frequency times the transform of the time signal:

$$F\left(\frac{du}{dt}\right) = i\omega F(u) \tag{8.4}$$

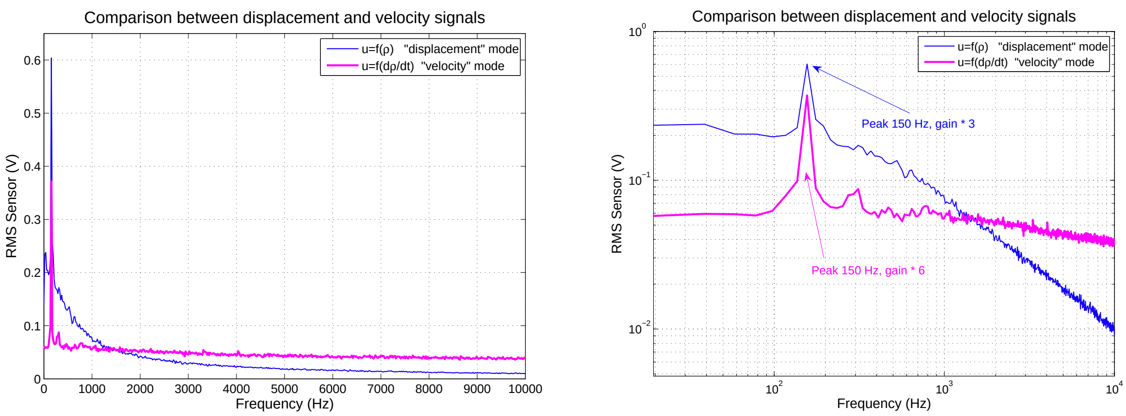


Figure 8.18: *Sensitivity of laser vibrometry, and comparison between its two modes. The same measurement is represented at linear and logarithmic scales.*

therefore in the very situation of the laser vibrometer, the $1/f$ factor is compensated. Figure 8.18 compares the two kinds of output delivered by the LV: the physical one (called "velocity mode", since it normally measures the realtime velocity of a vibrating surface - in our case the density time derivative) and an integrated one ("displacement mode", or "velocity" signal integrated over time - in our case an image of ρ). As expected, the "displacement mode" has a $1/f$ decay signature while the "velocity mode" keeps a quasi-constant sensitivity over a large bandwidth, offering a better sensitivity than the "displacement mode" after 1 kHz. The gain factor is also better in the "velocity mode" since it does not suffer from alteration due to the integration process (factor 2). Therefore, laser-vibrometry can perform with a high accuracy measurements detailed turbulence analysis in the high frequency domain where most time-resolved density measurement techniques cannot operate (e.g. laser deflectometry, Rayleigh scattering, schlieren...).

8.2.4.3 Processing technique

The first works on laser vibrometry for flame density fluctuation measurements that combine both phase-averaging and spectral analysis approach were done in the frame of a common work TU Graz - ONERA Toulouse during the AMADÉE academic exchange programme. The focus was also put on flow visualisation methodology and the results were presented at the FLUVISU conference [Lang et al., 2008].

The different burner types and setups that were tested are presented in the articles. We detail here essentially the missing steps of the processing technique that are only summarised in the articles for a matter of length.

Forced oscillation

We used the ONERA siren, which pulsation generates a fluctuation of swirl number at the jet outlet, accompanied from a ring vortex detachment. The resulting vortices are peripheral to the injection jet and are usually transported by the flow at half the injection velocity (see Panda et al. [Panda and McLaughlin, 1990] for the vortical detachment and [Giuliani et al., 2002c, Giuliani et al., 2007c] for the detailed jet dynamic description). So that the very instability we analyse here, a vortex-driven oscillating flame, is known.

To perform the phase averaging process presented in figure 8.19, one requires the LV measurement at a given point (a LV called "LV scan" is mounted on a 3-axes traversing machine, so that a whole grid of

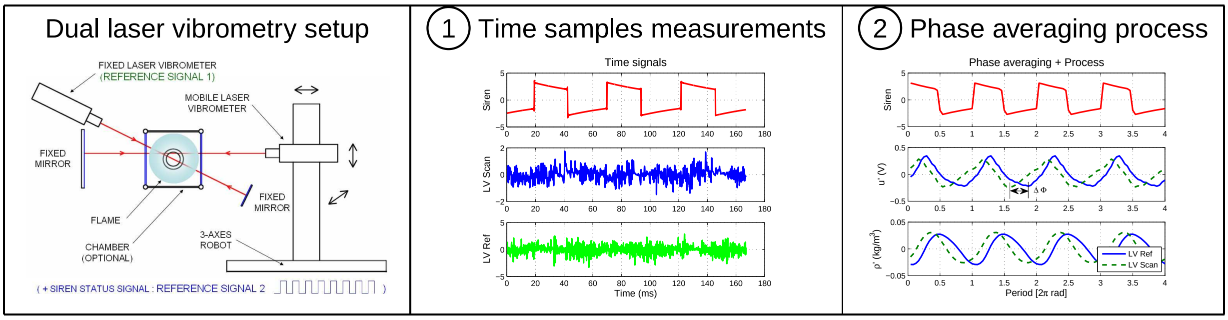


Figure 8.19: *DLV arrangement, measurement and phase-averaging process*

points is measured). The synchronisation signal is given by a fixed sensor mounted near the flame (high temperature pressure sensor, or second LV - hence the denomination "dual laser vibrometry" DLV), or by the siren itself. With forced oscillation, the siren TTL is the best reference. However, the reference signal fluctuate so greatly that with the proper low-pas filtering, a threshold-trigger is also possible to mark the start of each pulsation cycle (recommended when the transit time from the siren to the burner can be a problem).

Natural flame resonance

In case of the natural resonance, there is no more TTL from the siren available, and a filtering on the reference signal may lead to a too high uncertainty on the pulsation begin (in case of the DLR-ASC burner mentioned above, the previous method still works). We rely then on a cross-correlation process described in figure 8.20:

1. The time signals are sampled.

2. A FFT of the signals is performed, the amplitude spectrum edited, followed by a resonant frequency peak detection process (here at 175 Hz). This operation is performed N times per time signal.

3. At this particular frequency, the amplitude and phase shifts between the measured signals (LV fixed, LV scan, and siren status signal) are measured in the Fourier complex domain. No averaging is done so far on the power spectrum, while tiny changes in frequency peak position during the signal sampling would make the phase-shift measurement inaccurate.

4. The N phase-shifts are displayed in an histogram, on a $]-\pi \ \pi]$ interval. In case of resonance, a preferential phase-shift appears.

5. The average peak amplitude is computed. As a result, a phase-average process can be performed on u'_f:

$$\forall \ t \ \in \ [0 \ \tau[\ [\tau] \qquad u'_f(t) = \frac{\sum n_i \ A_i \ \sin(2\pi f t - \Delta\phi_i)}{\sum n_i} \tag{8.5}$$

where n_i is the number of occurrence of phase-shift $\Delta\phi_i$ issued from the phase-shift distribution histogram (figure 8.20-4) and A_i is the corresponding average peak intensity.

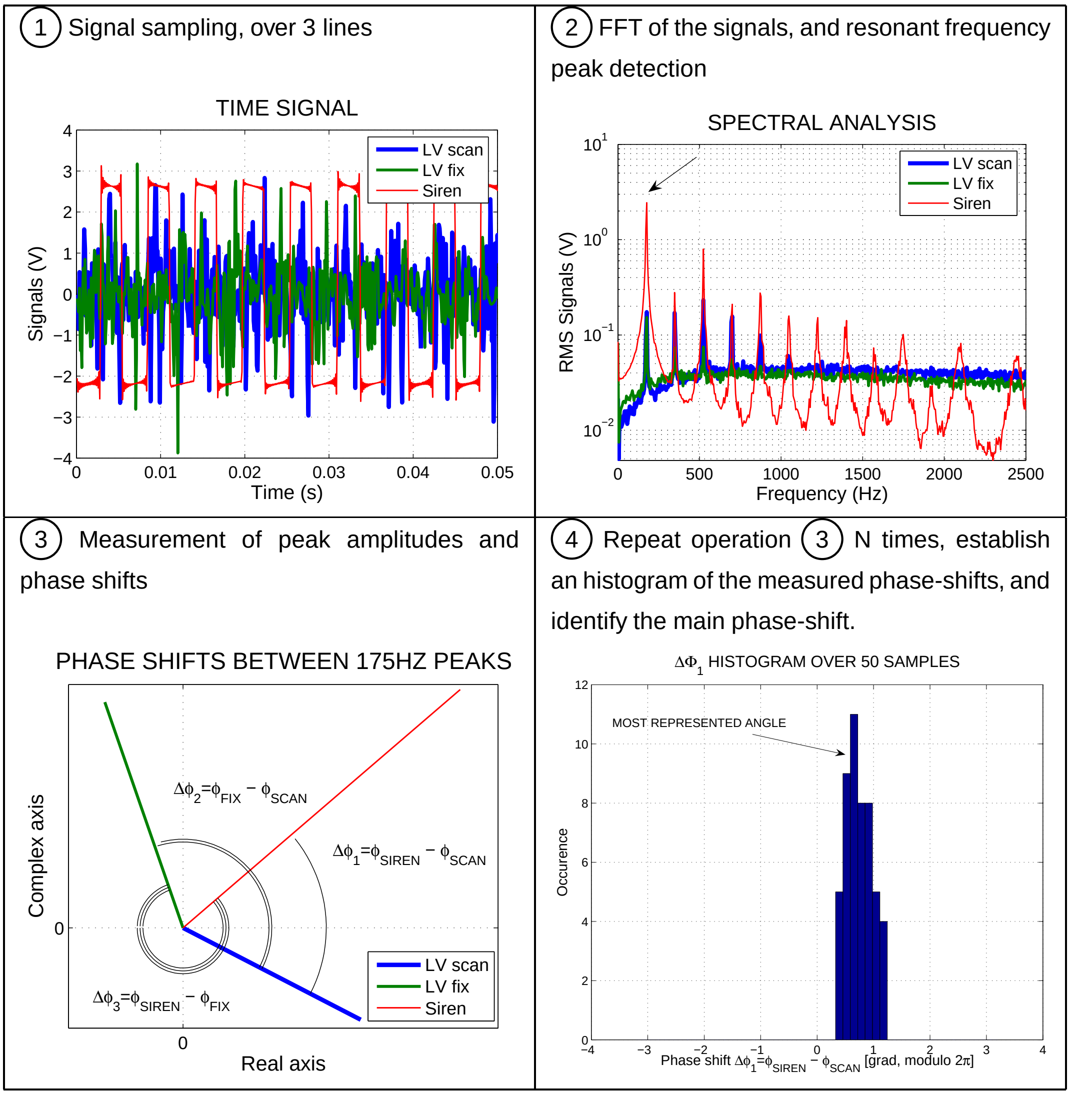


Figure 8.20: *DLV signal processing*

Density fluctuation mapping technique

Once u'_f is determined, the relative density fluctuation ρ'_f is derived from equation 8.3 as:

$$\rho'_{f\ LS}(t+d\tau) \simeq \rho'_{LS}(t) + \frac{k}{GZ}u_f(t+d\tau)d\tau \tag{8.6}$$

with end condition $\bar{\rho}'_{f\ LS} = 0$, where LS means integrated over the line-of-sight depth Z. The factor term k/GZ is assumed to be constant (the variation of G can be neglected).

The mapping method consists in reorganising all phase-defined quantities as a function of their coordinates (figure 8.21, 1), sorted with an increasing phase angle over one pulsation period. A smoothing interpolation ('Matlab v4') is used on the u'_f grid to provide a voltage map (figure 8.21, 2). The ρ'_f map computed with Eq. 8.6 is represented in figure 8.21, 3. Finally, due to the nearly axial symmetrical geometry of the jet, an Abel transform is possible in order to retrieve the local density fluctuation ρ', and obtain a quantitative measurement of ρ' provided the integration path Z was measured precisely. Although the Abel inversion generates its major uncertainty on the centerline (this underlines the lack of axial symmetry of the jet), it also positions the observed structures more precisely at the jet periphery than the integral measurement does (Fig. 8.21, 4).

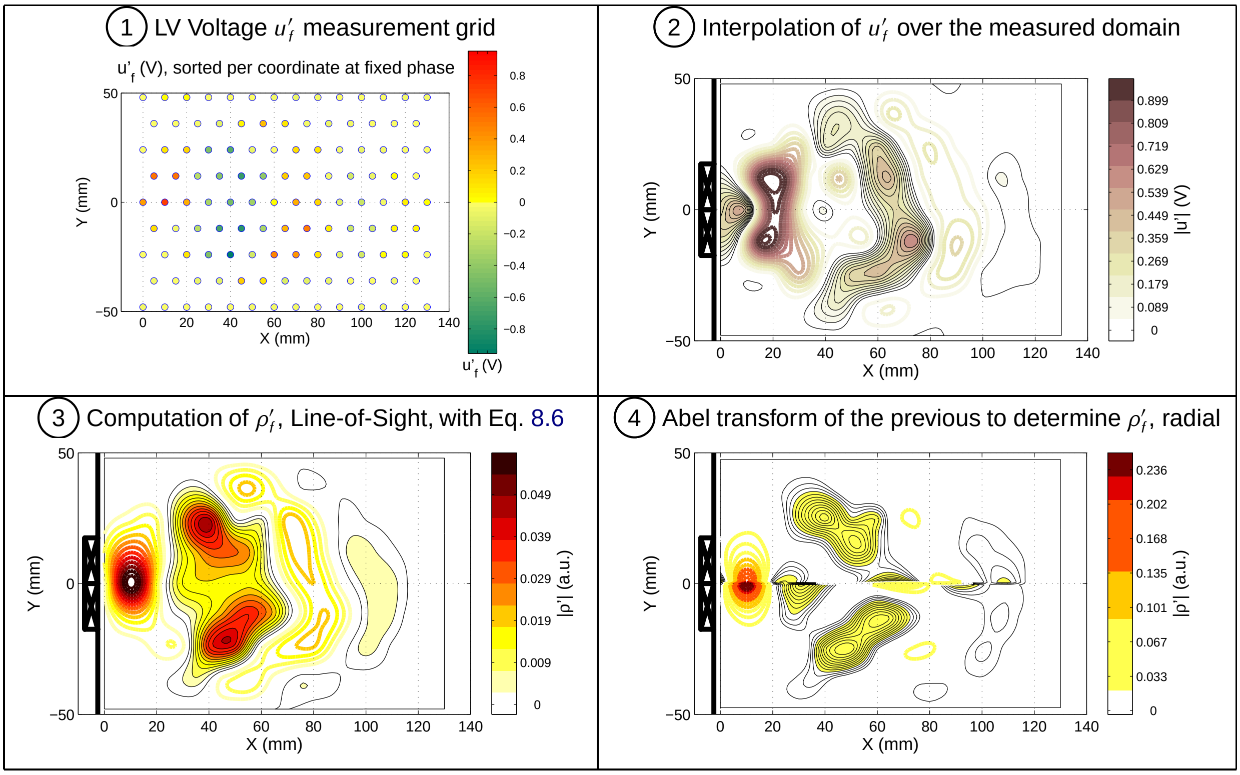


Figure 8.21: *Fluctuating density mapping process. 1-2 Map of the scanning LV filtered voltage $u'_f(t)$ at frequency f=175 Hz and phase subperiod t=dτ. 3 map of the relative density fluctuation $\rho'_{f\ LS}(t)$ (line-of-sight, computed with equation 8.6). 4 Abel transform of the latter to obtain a radial distribution of density fluctuation within the plane. All contour levels: qualitative results only, arbitrary units.*

8.2.4.4 Further developments

The following themes are currently under investigation:

- estimating the measurement error on density fluctuation induced by the vibration of the windows (common work with the DLR on the ASC burner)
- with the help of tomography to turn back to the local temperature and heat release fluctuations on a free jet flame configuration. Comparison with other measurements (FWF project on flame-flame interaction)
- test on a LPP module in the frame of NEWAC. First application on a strongly vaporised but still 2-phase flow.
- fully automated measurement technique with a user-friendly interface, including the data processing

Related literature from author on line-of-sight measurement techniques

[Giuliani et al., 2004] Giuliani, F., Becker, J., and Hassa, C. (2004). Investigation of vapour phase, LOPOCOTEP deliverable 4.15. In *EU FP6 - GROWTH Project*. DLR-IB-325-04-04.

[Giuliani et al., 2007a] Giuliani, F., Bhayaraju, U., and Hassa, C. (2007a). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine conditions using laser infra-red absorption. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 2008a] Giuliani, F., Bhayaraju, U., and Hassa, C. (2008a). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine combustor inlet conditions using laser infra-red absorption. In *32nd International Symposium on Combustion*. Montreal, Canada, The Combustion Institute.

[Giuliani et al., 2007b] Giuliani, F., Lang, A., Leitgeb, T., , Woisetschläger, J., and Heitmeir, F. (2007b). Time-resolved analysis of density fluctuations in a resonant air-methane flame using dual laser vibrometry for gas turbine combustor qualification tests. In *Proc. of the 18th ISABE conference*. International Symposium on Air Breathing Engines, Beijing, China. ISABE-2007-1187.

[Giuliani et al., 2008b] Giuliani, F., Lang, A., Leitgeb, T., and Woisetschläger, J. (2008b). Phase-defined density fluctuation maps of a resonant air-methane premixed flame using laser vibrometry. In *32nd International Symposium on Combustion*. Montreal, Canada, The Combustion Institute.

[Giuliani et al., 2007c] Giuliani, F., Lang, A., Leitgeb, T., Woisetschläger, J., and Heitmeir, F. (2007c). Using dual laser vibrometry to monitor the stability of gas turbine combustion. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 2010] Giuliani, F., Leitgeb, T., Lang, A., and Woisetschläger, J. (2010). Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry. *Journal of Engineering for Gas Turbines and Power*, 132. GTP-031603.

[Giuliani et al., 2009] Giuliani, F., Leitgeb, T., and Woisetschläger, J. (2009). Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry. In *ASME Turbo Expo, Gas Turbine Technical Congress & Exposition*, Orlando, FL USA. GT2009-59682.

[Giuliani et al., 2007d] Giuliani, F., Schricker, A., Lang, A., Leitgeb, T., and Heitmeir, F. (2007d). High-temperature resistant pressure transducer for monitoring of gas turbine combustion stability. In *Proc. of the 18th ISABE conference*. International Symposium on Air Breathing Engines, Beijing, China. ISABE-2007-1111.

[Giuliani et al., 2006] Giuliani, F., Wagner, B., Woisetschläger, J., and Heitmeir, F. (2006). Laser vibrometry for real-time combustion stability diagnostic. In *ASME Turbo Expo 2006: Power for Land, Sea and Air*. Barcelona, Spain. GT2006-90413.

[Köberl et al., 2009] Köberl, S., Giuliani, F., and Woisetschläger, J. (2009). Energy spectra measurements for the density fluctuation in a jet flame using dual laser vibrometry. In *Proc. of the 4th ECM*. European Combustion Meeting, Vienna, Austria, The Combustion Institute.

[Lang et al., 2008] Lang, A., Leitgeb, T., Woisetschläger, J., Strzelecki, A., Gajan, P., and Giuliani, F. (2008). Analysis of a pulsed flame at intermediate pressure. In *ISFV13 - 13th International Symposium on Flow Visualization / FLUVISU12 - 12th French Congress on Visualization in Fluid Mechanics*, Nice, France.

Chapter 9

Progresses on atomisation process and particle transport in a modulated air flow

This chapter reports on the application of the measurement techniques described before. The incentive is the understanding of the physics of a spray modulated by a fluctuating air stream. The background is the understanding of the mechanism of combustion instability in liquid-fuelled combustors, as well as the investigation on control methods able to maintain combustion at steady-state. The results of different measurement methods are compared and crossed with each other provided they are phase-averaged. This part provides complementary or detailed results not shown in the articles (e.g. more phases describing a pulsation cycle). Firstly, a refined description of the aerodynamics of a modulated air stream flowing through an airblast injector (single phase flow) is done. Secondly, the atomisation model is presented (droplet size distribution as a function of the operating conditions: air mass flow, liquid mass flow and ambient pressure). Thirdly, the transport model of particles as a function of both atomisation and air flow conditions (two-phase flow) is established.

9.1 Injection jet aerodynamics in presence of a forced flow modulation

The presence of a combustion instability is reproduced using the ONERA siren. This device modulates the flow upstream at a given frequency. As a result, the flame itself is being pulsed, this instability is of the type vortex-driven flame oscillation [Yu et al., 1991].

The conditioned LDA measurement technique used to characterise the aerodynamics of the modulated air flow, as well as the specific processing techniques, have been described for different applications in the following references [Giuliani et al., 2002a, Giuliani et al., 2001a, Giuliani et al., 2001b, Diers et al., 2001, Giuliani, 2002, Giuliani et al., 2002c].

Taking profit of the automated TSI LDA set-up, a large amount of data was taken over a structured 3D grid at the airblast outlet. We discuss now different graphic representations, helping to interpret the same data.

Figure 9.1 shows the phase averaged measurements in the jet longitudinal plane ($Y = 0$) as well as in a plane normal to the jet ($X/D = 1/2$). Over one pulsation period, the inner recirculation zone performs a come-and-go motion while the jet envelope deforms from a wide to a narrow cone.

Figure 9.2 represents the same situation, expressed this time in polar coordinates, after a radial integration of velocity profiles over cartesian maps. This process suffers from the lack of axisymmetry in some parts of the jet. Still, the orders of magnitude found are representative, and can thus be used for comparison with CFD calculations.

As the jet motion induces many movements, one needs a "generic tool" in order to classify this swirler. This is the reason why the swirl number S is introduced, characteristic of a swirl jet global morphology. It is defined as the ratio between tangential and axial momentum flux (taken in the direction of the axis, [Beér and Chigier, 1972]). As the experiment takes place under atmospheric conditions, the terms related to the static pressure are neglected, so that S is expressed as follows:

$$S = \frac{2 \int_0^{2\pi} \int_0^{r_{max}} \rho\ u\ V_\theta\ r^2\ dr\ d\theta}{D \int_0^{2\pi} \int_0^{r_{max}} \rho\ u^2\ r\ dr\ d\theta} \tag{9.1}$$

A weak swirl number is representative of an axial jet (usually $S < 0.6$, where the flow rate goes in the jet axis direction), whereas a strong swirl number is representative of a radial swirled jet ($S > 0.6$ where the flow rate is centrifuged on the walls of the chamber). Figure 9.3 shows this fluctuation, alternating from a jet-like behaviour to a strongly swirled one and back.

To represent the strain exerted on the injected kerosene, streamlines are drown in 3D starting from the kerosene distribution crown. To obtain these streamlines, the basic material is a "brick" of data performed along a structured 3D mesh. The latest is based on a linear interpolation of all LDA measurements. A $X = 0$ plane is also defined, forcing the velocities at the front plate to be zero, and copying the results from the plane $X/D = 1/20$ on the reference diameter. Figure 9.4 allows to catch the "clumsy swimming octopus" dynamics of the pulse jet, opening and closing its tentacles in the meantime at it kicks for a swirl motion.

Another observation performed on this data reveals the presence of big ring vortices ("donuts") being generated around the jet at the front plate, detaching the front plate, and then be transported by the flow. In the articles, these are revealed by the second invariant criterion (called also λ_2 criterion) from Jeong and Hussain [Jeong and Hussain, 1995]. Figure 9.5 uses the same "data brick" than used for computing the streamlines, and focuses on the extreme jet velocities to materialise the jet envelope and the different recirculating zones, the vorticity (based on a curl of the velocity field) or the axial gradient. This is a way to materialise in 3D the ring vortex. It was argued during the Symposium Combustion conference whether the emitted instability from the siren is a donut-shaped vortex, or an helicoidal one. This 3D observation (unpublished so far) supports the first idea.

9.2 Liquid fuel particle transport in a modulated air flow

9.2.1 Measurements on atomisation process with pulsed air entry

Figure 9.6 summarises the aerodynamics observed in a pulse spray: dense droplet fronts accumulate between two consecutive ring vortices, and are then transported by the flow. The phase-series superimposing

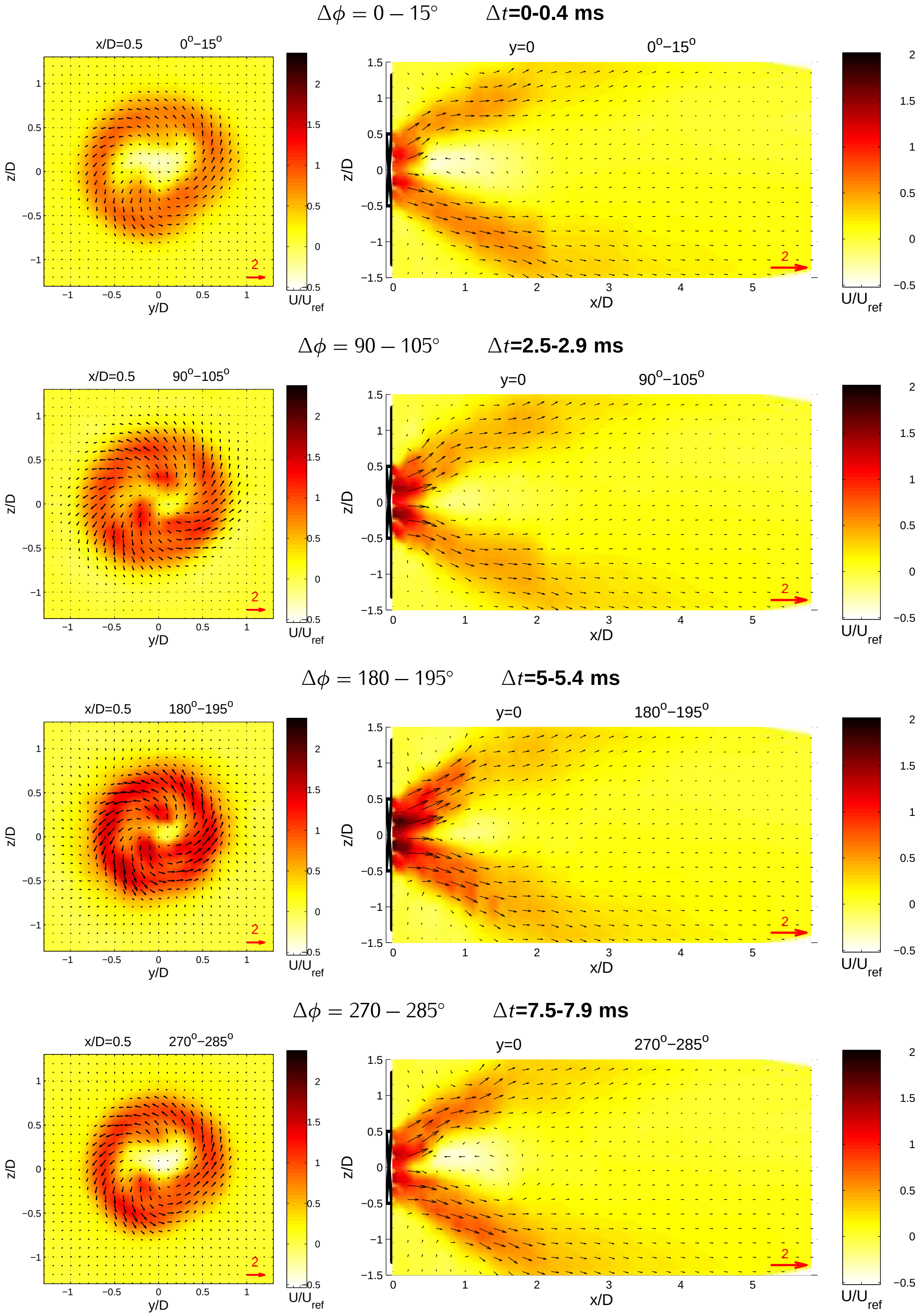


Figure 9.1: *Pulsed velocity flowfield in free-jet configuration at 100 Hz. Left: measurement plane at X/D =1/2, and right: Y=0. Phase-averaged LDA measurements. Background colour and vectors: relative axial velocity*

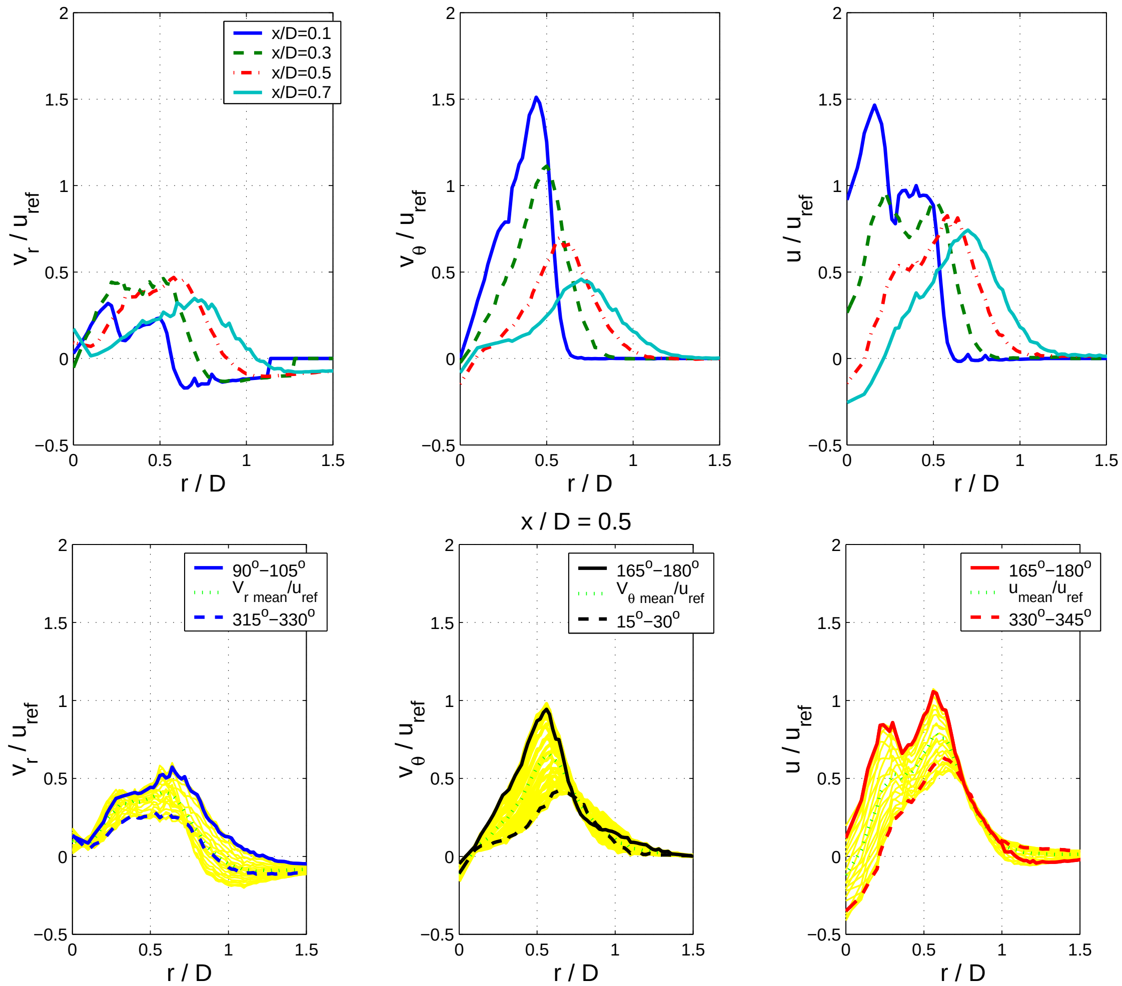


Figure 9.2: *Velocity profiles in cylindrical coordinates*

phase-locked spray pictures and vorticity (figure 9.7) establish this fact.

The fluctuation of the droplet size population was investigated when the spray is being pulsed with the help of a conditioned MALVERN technique. The results are reported in figure 9.8. A decay of the SMD fluctuation was observed with augmenting the pulsation frequency. We connected then the transport time scales with the size of the droplets. In a word, the fronts are mostly made up of "small" particles. The Stokes number, characteristic of the velocity response of a spherical particle put into a flow, was redefined to match this category of "small" droplets, that appear to have a value $St < 0.2$ [Giuliani et al., 2002c].

9.2.2 Air-blast atomisation model

Realistic droplet size and velocity probability density functions of atomised kerosene are required so that assessments with correct orders of magnitude are done to determine a representative particle dimension (the SMD) but also to determine the real-time liquid flux. A 1D correlation is wished. The correlations presented hereby are issued from a post-process of data obtained by author at DLR Cologne [Giuliani and Hassa, 2003, Giuliani et al., 2004b] in the frame of the MoPAA project (Measurement of Prefilming Airblast Atomisation, a joint DLR-ONERA study).

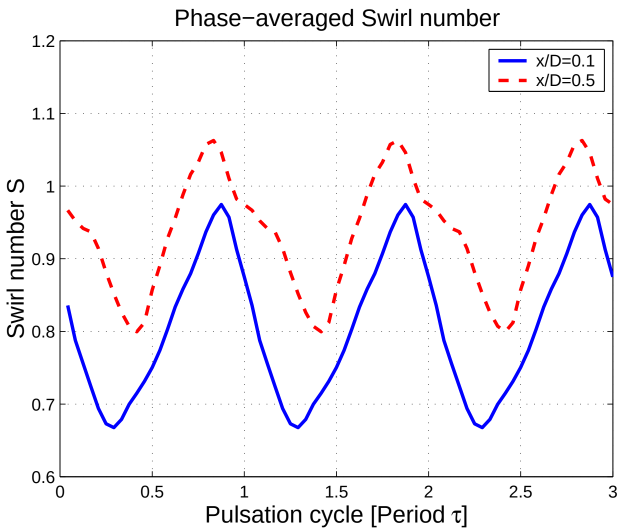


Figure 9.3: *Phase-averaged swirl number, displayed over 3 pulsation periods, computed at $x/D = 0.1$ and 0.5*

The DLR spray test rig is designed for non-reactive fuel spray analysis under realistic levels of pressure and temperature for gas turbine operation. Technical details can be found in [Brandt et al., 1998]. The maximum parameters are: air pressure up to 20 bar, air mass flow rate up to 1.3 kg/s, air temperature up to 920 K and kerosene flow rate up to 10 g/s. The test cell has a square section of 40*40 mm.

The flat liquid atomiser used has a prefilmer length of 4 mm, over an height of 18 mm (see Fig. 9.9, left). Kerosene is injected through a slot of 300 μm. The spray in the centerline is assumed to be two-dimensional, where the effect of the injector's tip vortices are minimal, as can be seen on the 3D plots for velocity (middle plot), and $D32$ (right plot). Its body is profiled to minimise blockage. 2-component particle size and velocity measurements were realised with a Dantec 57X10 PDA.

In the following, measurements performed on the centerline at 15 mm downstream the injector are considered. This is an optimal distance from the injector between particle size measurements with an acceptable validation rate of spherical particles and the high spray density responsible for a high data rate. This measurement point also catches very small droplets that evaporate further downstream. Traverses were performed along the X-axis to integrate the overall droplet size distribution and check that the centerline measurement is representative of the spray: the traverse $D32$ matches the single point $D32$ with a 3 % confidence interval. So that the droplet size distribution measured at the single point is representative of the droplet size distribution integrated over the whole traverse.

Lefebvre [Lefebvre, 1989a] notes that no universal droplet size distribution model can be offered for airblast atomisation since the latter is injector-design dependent. A statistical approach is therefore necessary. Usually, a Rosin-Rammler PDF (RR) is used to fit the volume distribution. In this study, we considered two other distributions: Gamma PDF (Γ) for the droplet volume distribution, and Log-Normal PDF (LN) for the size distribution. Least root square fitting methods were used. Compared to the RR distribution, better qualitative results were found to match the volume distribution using a Γ PDF (compare the columns $D32_{measured}$ and $D32_{\Gamma}$ in table 9.1). A LN PDF was observed to perform the most representative particle size distribution fitting. However, when computing the $D32$, due to its algebra the LN PDF tends to overrate the big droplets' number, ending with errors up to 20 %. On the other hand, both Γ and RR PDFs overrate the small droplet number, but this has little effect on the $D32$. One example of distribution fit is displayed in figure 9.10.

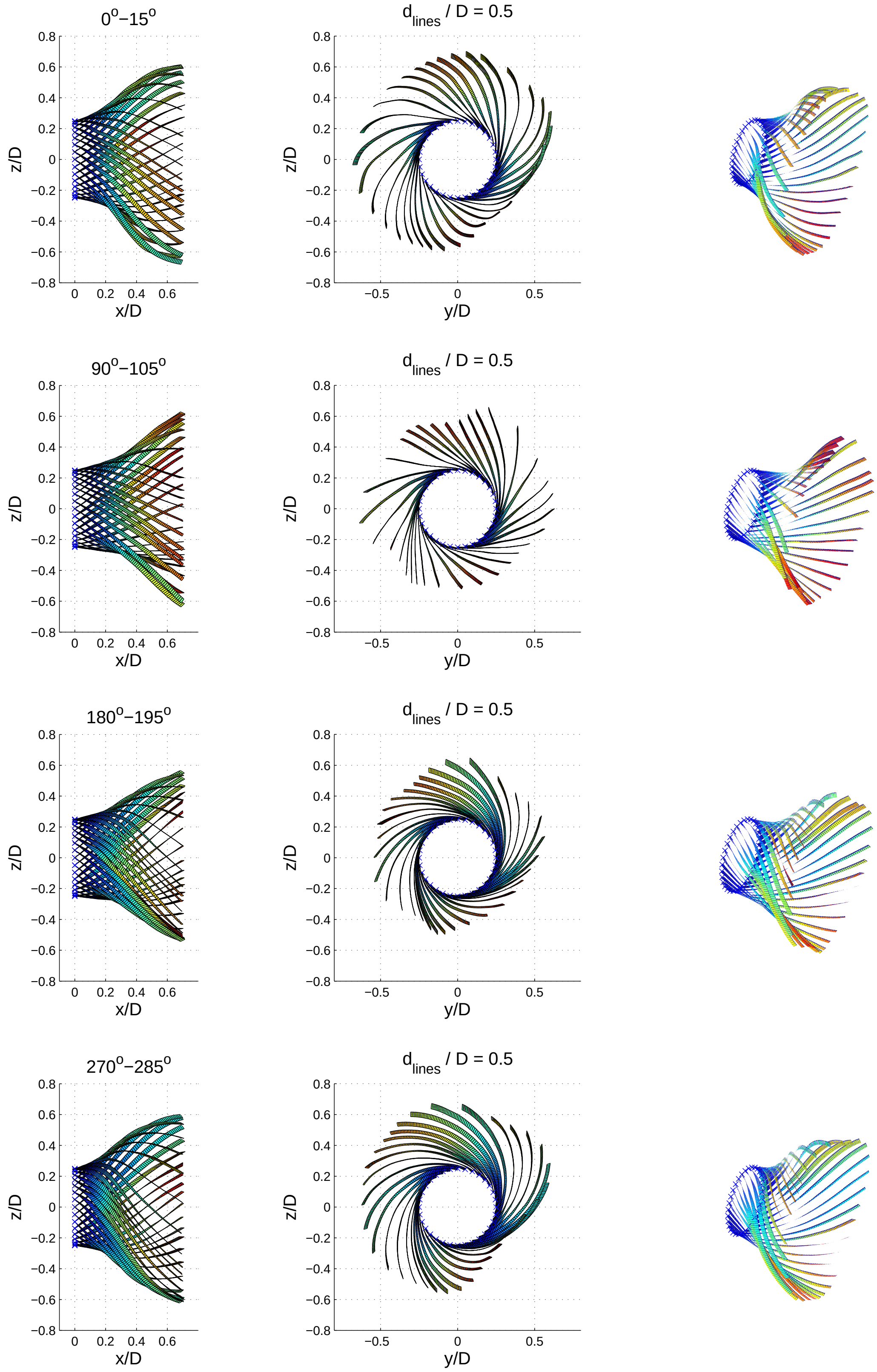


Figure 9.4: *3-D streamlines for free-jet configuration, emitted along a $d/D = 1/2$ diameter circle placed in the injection section (mixing layer, where the liquid phase is injected). Left: profile view of the 3-D streamlines. Middle: front view of the 3-D streamlines. Right: Three-quarter. Air pulsation at 100 Hz*

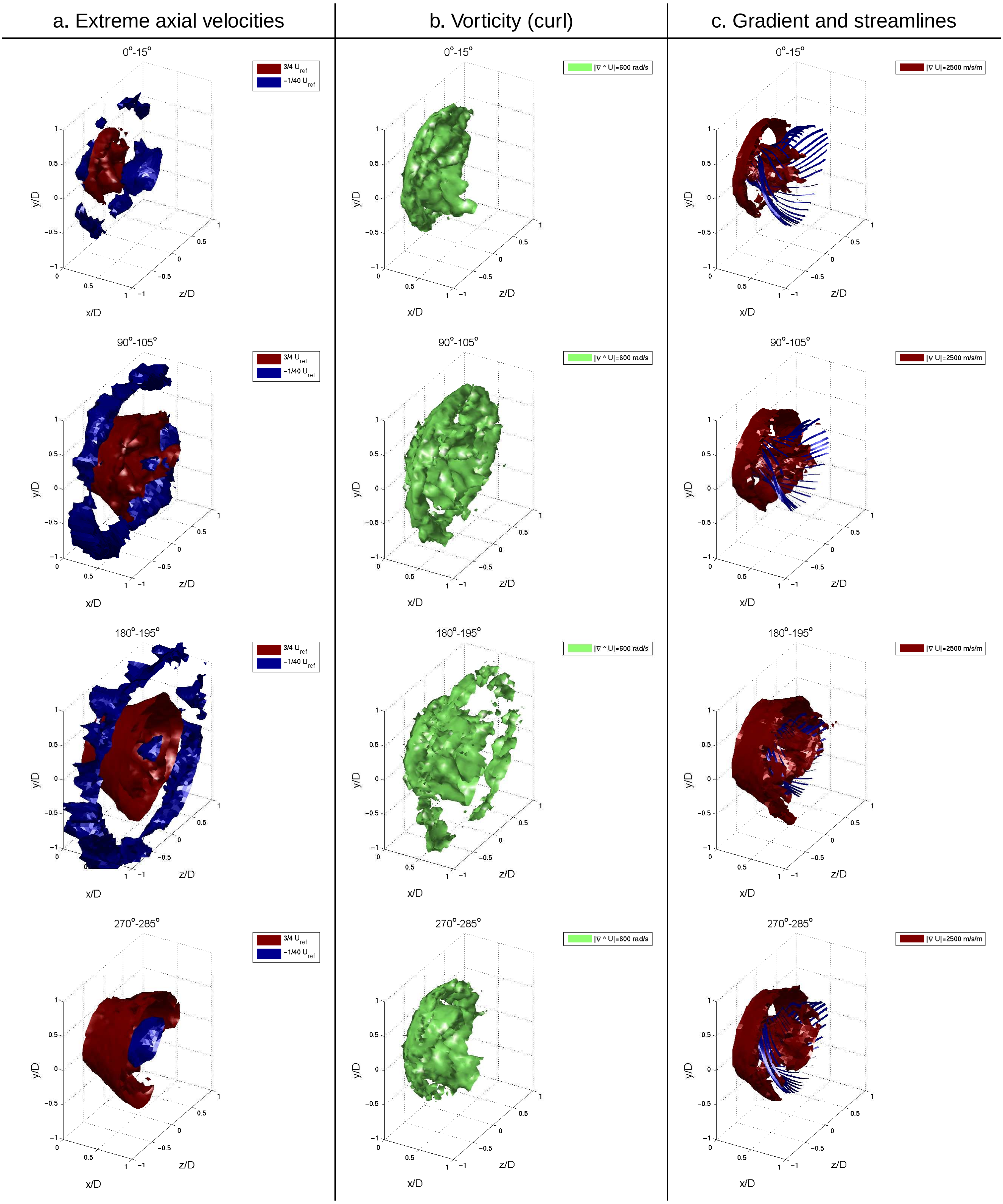


Figure 9.5: *3D analysis of the airblast aerodynamics, measured with conditioned LDA and phase-averaged. Left: extreme axial velocities* u *to sort out the air jet shape and the recirculating zones. Middle: analysis of the field vorticity, applying the curl operator* $\nabla \wedge \mathbf{U(u,v,w)}$*. Left: analysis of the mixing layer positions (gradient operator and normalisation:* $|\nabla \mathbf{U(u,v,w)}|$*) comparison with the 3D streamlines emitted from the liquid injection*

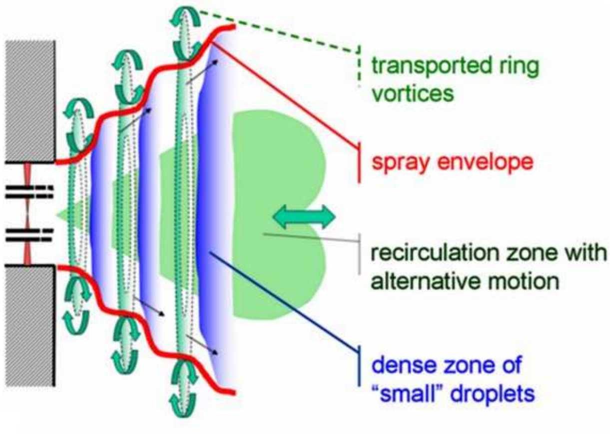


Figure 9.6: *Pulse airblast spray dynamics*

Table 9.1: *Particle size measurement: parameters, $D32$, Γ fit and correlation check*

We	Air pressure P (bar)	Air velocity V_g (m/s)	Gamma fit a	(Γ parameters) b	$D32$ measured (μm)	$D32_\Gamma$ (μm)	D32 correlation (μm)
87	1.6	60	5.68	10.03	46.64	46.89	48.49
98	1.8	60	5.85	9.54	46.09	46.23	47.27
180	3.3	60	5.87	8.1	39.7	39.4	38.08
410	3.3	90	4.46	6.07	27.62	27.08	26.45
733	3.3	120	4.4	5.44	19.44	18.48	16.93

In the following, we consider the Γ PDFs results as a basis for a correlation. Table 9.1 covers several measurement points realised at 15 mm of the injector lip, at ambient temperature. The film load was varied from 0.225 to 0.45 g/mm, not affecting the SMD but having an impact on the spray width (see [Giuliani et al., 2004b]). The Weber number varied from 80 to 750. The parameters a and b of the Γ distribution are reported so that:

$$PDF_D = \frac{1}{b^a\,\Gamma(a)} D^{(a-1)} e^{\frac{D}{b}} \qquad \text{with} \qquad \Gamma(a) = \int_0^\infty e^{-t} t^{a-1}\, dt \tag{9.2}$$

where D is expressed in μm.

Based on this study, a linear correlation for a and b was established, matching the measured $D32$ with a 5 % confidence interval for Weber numbers from 80 to 410, and 15 % for We up to 730:

$$a = -0.026 V_g + 7.5 \qquad\qquad b = -1.24P - 0.045(V_g - 60) + 11.8 \tag{9.3}$$

where V_g is expressed in m/s and P in bar.

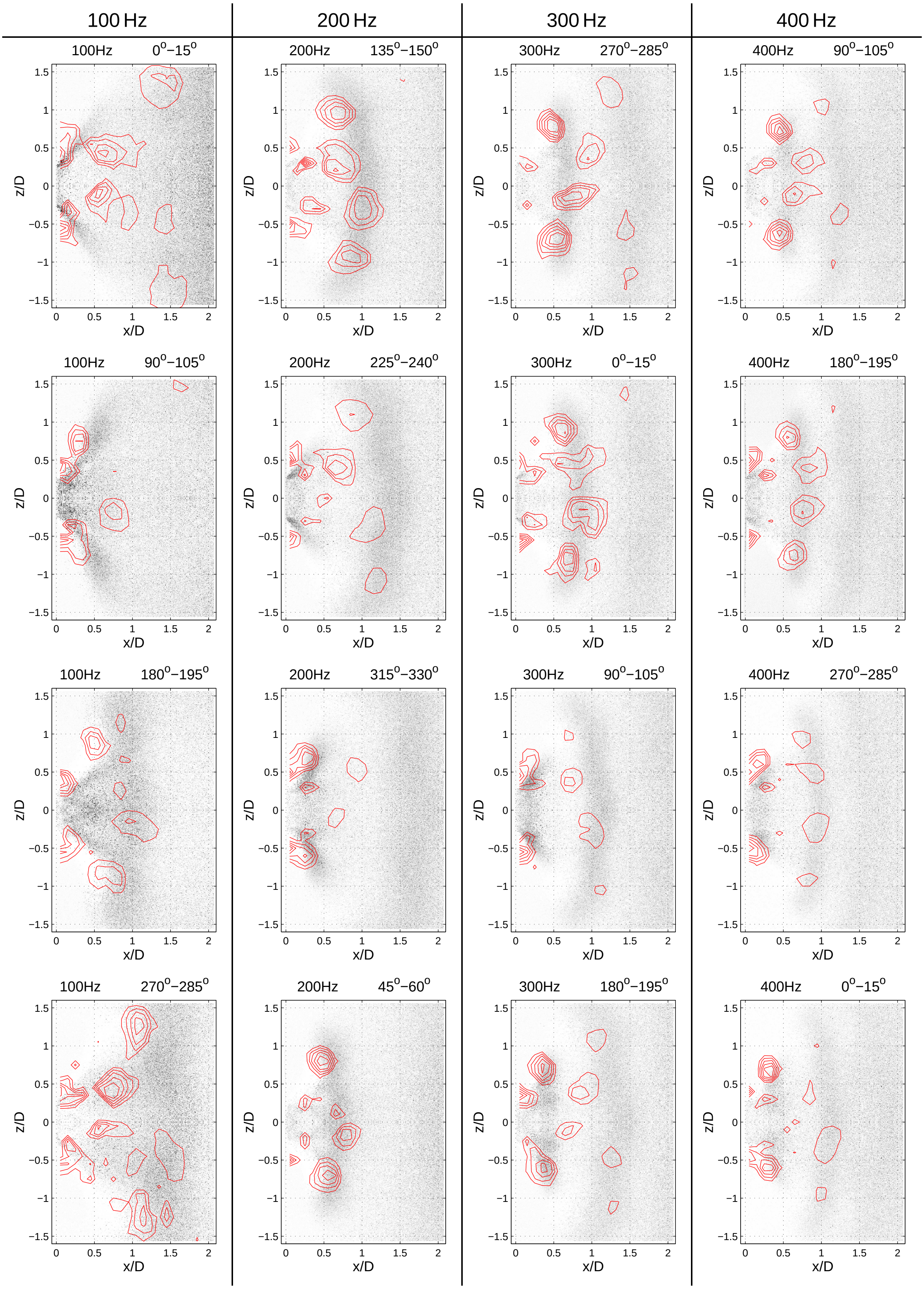


Figure 9.7: *Dense spray zones processed with the technique from figure 8.8 p.107 for free-jet configuration in the near injector zone, with corresponding vortical structures computed with the λ_2 criterion based on LDA measurements. Continuous liquid flow, pulsed air at 100 (left column), 200 (middle left), 300 (middle right) and 400 Hz (right). The phase angles are disposed so that the third picture starting from the top represents the highest flow rate at injection section*

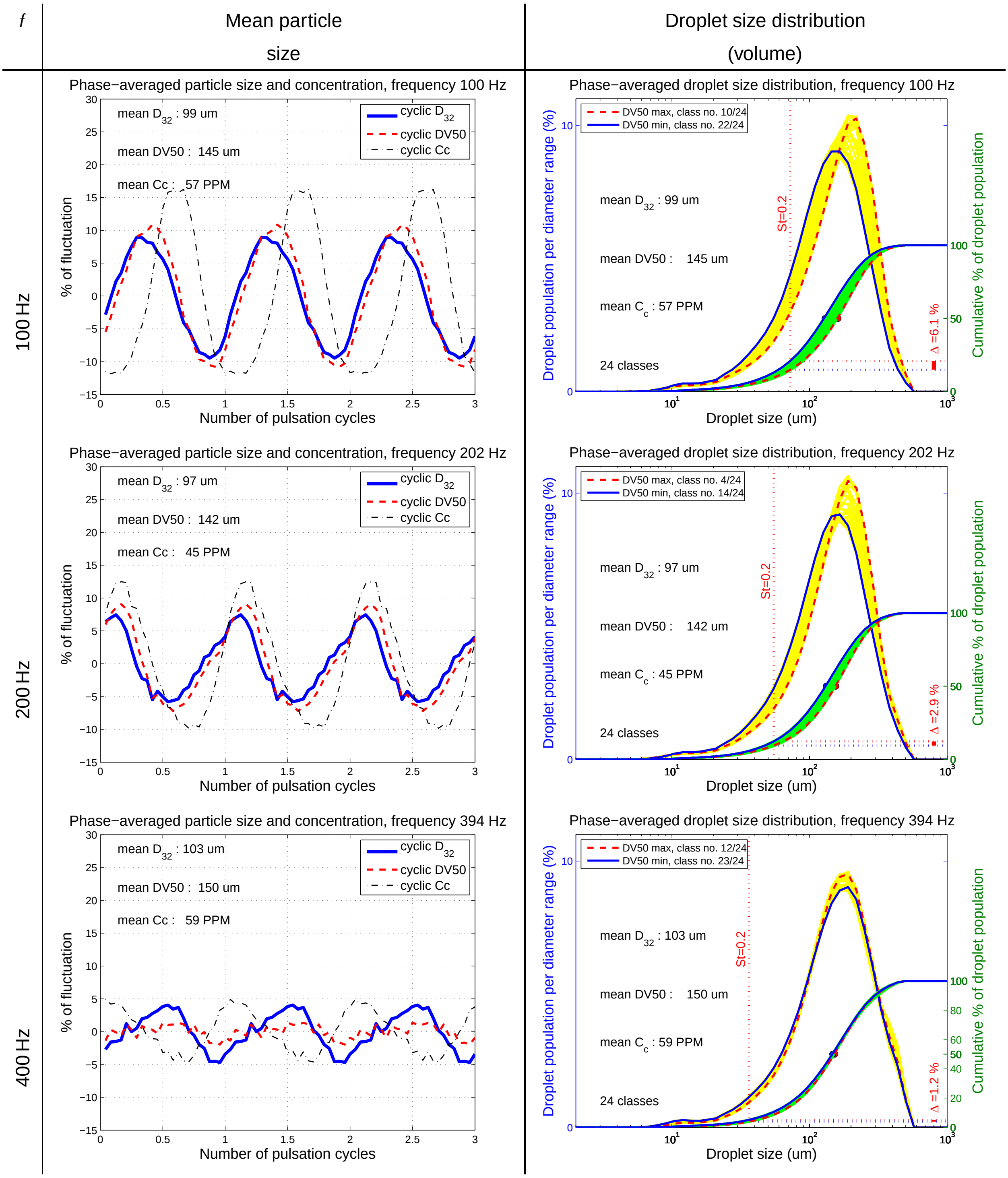
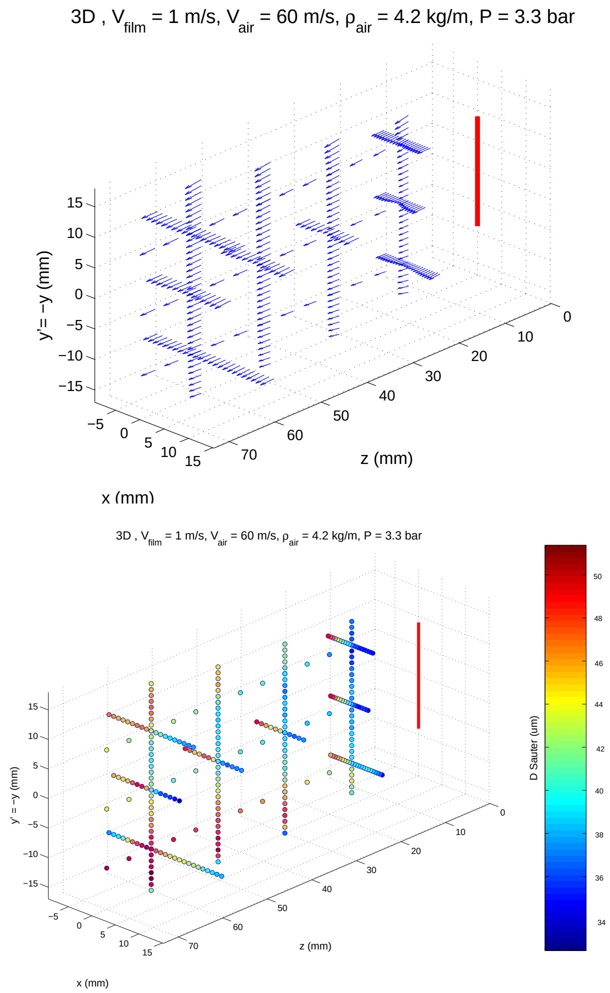


Figure 9.8: *Phase-averaged evolution of the droplet size distribution, with the conditioned MALVERN measurements, of the mean particle diameter (left) the droplet size distribution (right, distribution in volume of liquid). The limit for droplets having a Stokes number* $St < 0.2$ *is displayed. The distribution pro size and cumulative distributions are shown on the same plot*



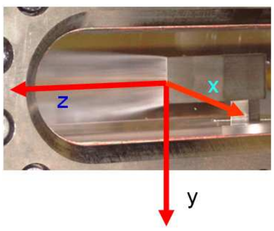


Figure 9.9: *PDA Measurements on the flat prefilmer. Top left: particle velocities. Top right: D32 measurements. Left: injector and resulting spray, with coordinate system.*

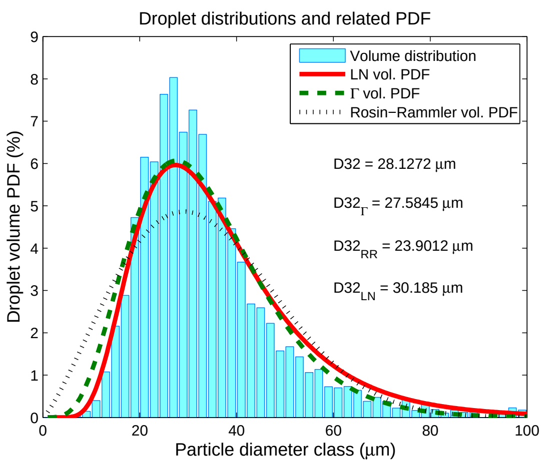


Figure 9.10: *PDF fits compared with PDA measurement, and* $D32$ *comparison*

9.3 BBO-Model and IN-PULSE code structure

A pulse particle transportation code was developed to simulate this effect of dense spray generation. This code, baptised IN-PULSE has a MATLAB structure for its non-evaporating version [Giuliani et al., 2005, Giuliani et al., 2009a], and a Fortran one for its evaporating + non-isothermal extension (Gajan et al. [Gajan et al., 2007]). It is a one-dimension Lagrange-based model, where basically the droplet acceleration in a flowfield is determined with the Basset-Boussinesq-Oseen equation [Bissières, 1997], and the evaporation is a function of the d^2 law [Spalding, 1951]. This approach with basic models fits the analysis of a complex spray, and the effort was put on the fluctuating inlet conditions.

IN-PULSE can assess:

1. the effect of pulsed air on the steady atomisation
2. the effect of modulated atomisation at the atomiser's lip (resulting in a fluctuating D32 at constant liquid flow rate)
3. the effect of intermittent kerosene injection (fluctuation of Q_{kero} at constant D32)
4. any combination of the latter with phase-defined shifts. The inlet conditions of the time-resolved volume PDF for steady-state atomisation, modulated atomisation by air and pulsed kerosene flow are shown in figure 9.12.

9.3.1 IN-PULSE for the validation of the atomisation model

As a first assumption, the liquid is introduced as already fully atomised in the computational domain, with a PDF on its size repartition as determined previously. At elevated We numbers (above approx. 200 in this study), the atomisation scales are reduced and primary and secondary break-up mechanism take place simultaneously, leading to sheet stripping. Thus it may be assumed that the atomisation process at elevated pressure and velocity is compact and local.

Each emitted scalar in the computational domain represents a droplet size class, weighted with the probability density corresponding to the same diameter. It appears iteratively with zero velocity at the injector's lip, is logged in position and velocity at each time step and is then counted in the far field by a probe.

The simulation is set at air velocity V_g=60 m/s, pressure P=3.3 bar, ambient temperature T=283 K. The mass flow rate remains symbolic (a normalised total value "100" is injected in the computational domain at each time step). Precise metric assessments requiring the results on PDA data rate and spray diffusion published in [Giuliani and Hassa, 2003, Giuliani et al., 2004b] will not be treated here. Provided the flow is steady state, the simulation is supposed to reproduce the PDA measurement, as shown in Fig. 9.13 for model validation. Both measured size and volume distribution are represented on the left. The velocities per droplet size scatter at the extremes because of the lack of data for extremely small and big droplets. The terminal velocity of 60 m/s is not achieved yet 15 mm downstream the injector. On the right hand side, the simulation is produced. The trends and features are well reproduced, especially the particle velocity per size where the highest volume distribution is situated, where the particles are still in the acceleration phase. The $D32$ differs by 4 %, the mean velocity differs by 2.8 %.

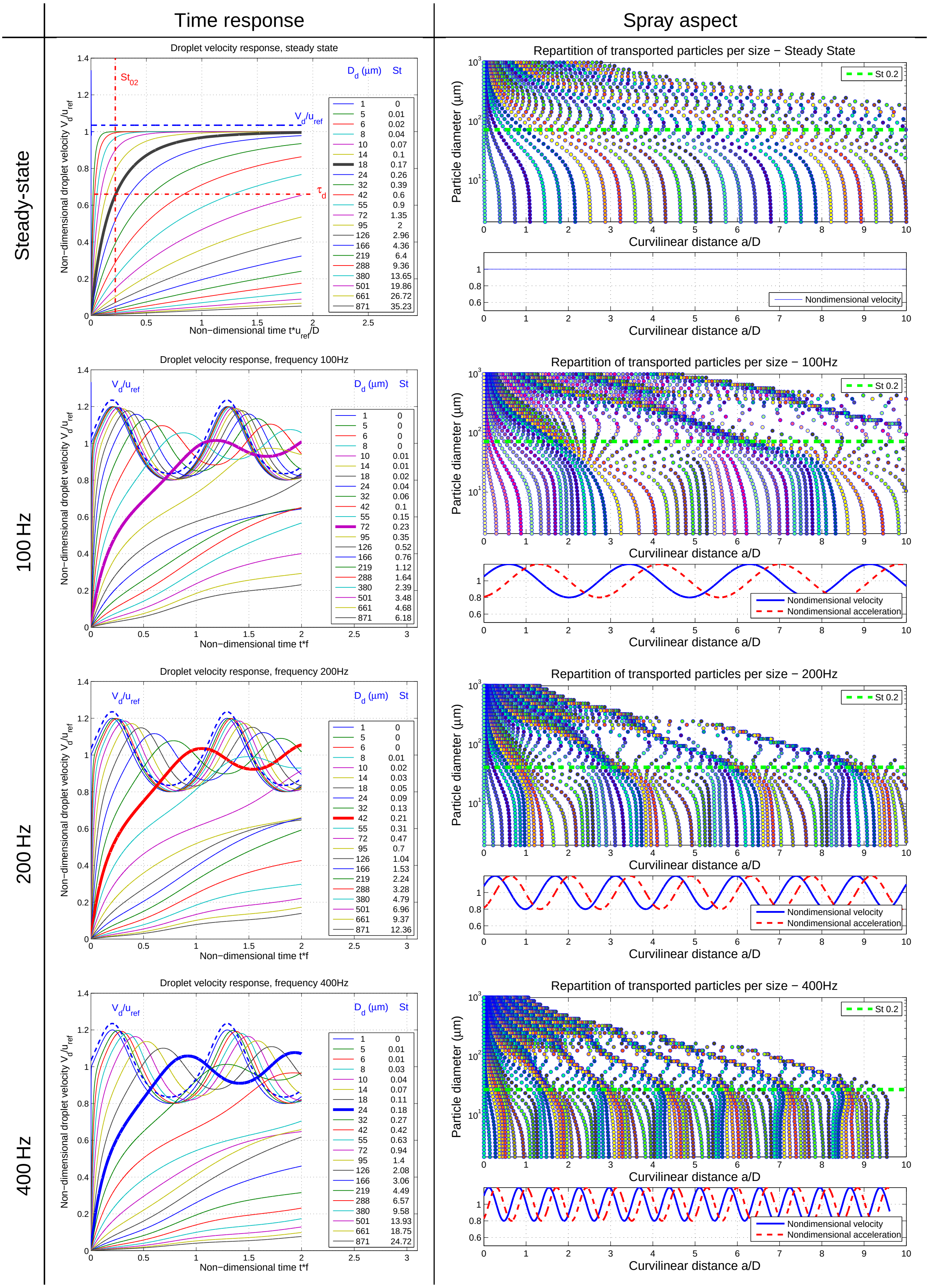


Figure 9.11: *Time (left column) and space (right) response of droplets introduced in a pulsed air flow field, as a function of their diameter and stokes number. The limit St=0.2 is marked in bold on all plots*

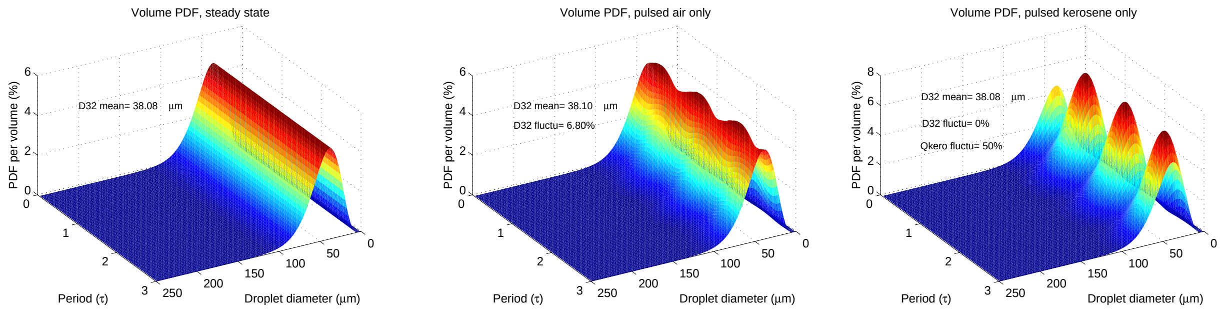


Figure 9.12: *Possible inlet conditions for the introduction of the atomised phase: steady state (left), constant kerosene flow with modulated PDF (middle), and pulsed kerosene flow (right)*

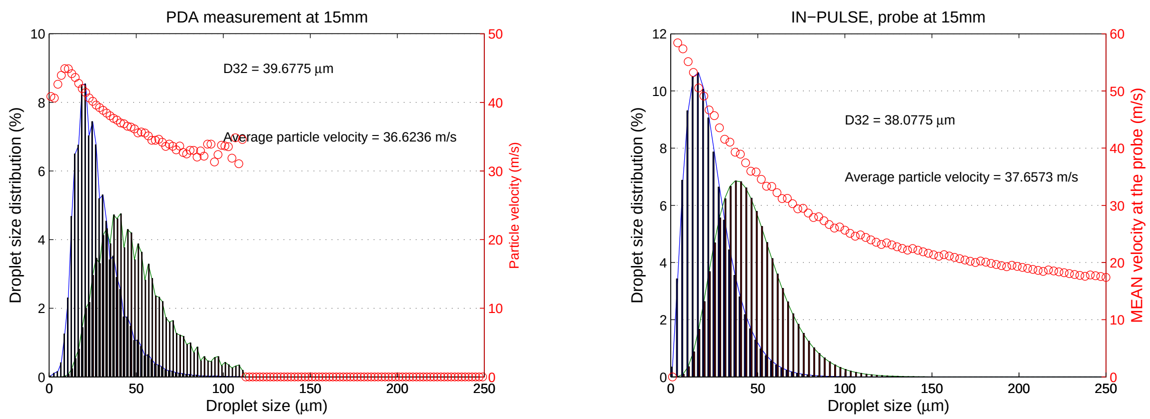
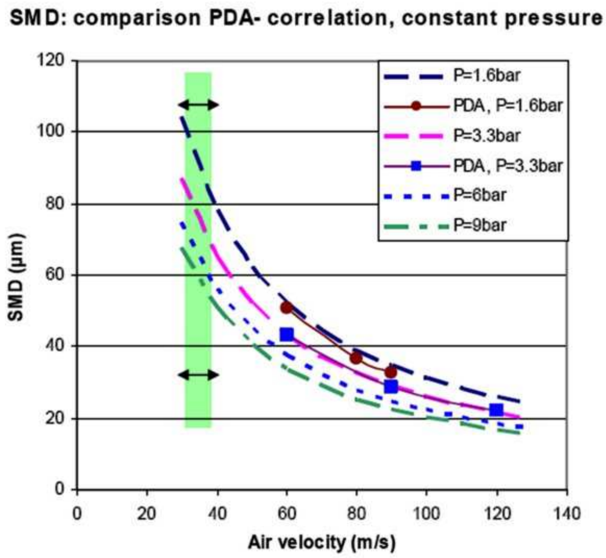


Figure 9.13: *Comparison between PDA measurement and simulation. Particle size distribution, volume distribution and velocity per droplet size measured 15 mm down the injector are shown*



$$\|SMD\| = \left\| \frac{6.237\ 10^{-2}}{U_g\ \sqrt[4]{P}} \right\| \quad (9.4)$$

where the SMD is computed in m, P is expressed in Pa and the air velocity U_g in m/s

Figure 9.14: *SMD correlations taken at constant pressure, for several air velocities (DLR [Giuliani and Hassa, 2003, Giuliani et al., 2004b])*

9.3.2 Effect of combined unsteady atomisation and transport on the spray in the far field

IN-PULSE is used for a better understanding of the physics of a practical case: the formation of droplet fronts when modulating the air inlet velocity. Two different explanations to the generation of droplet front in the far field (the "far field" is situated at about $2D$ from the front plate, where D is the reference injection scale. This position is an average position of a swirl stabilised flame-front) have been offered for quite a similar experiment:

- For Giuliani et al. from ONERA [Giuliani et al., 2002c, Gajan et al., 2007], the pulsed spray results from a sorting of particles as a function of their size in an unsteady flowfield. They considered the atomisation process at the injector tip as constant (constant droplet size distribution resulting from a steady atomisation process), and that the changes in velocity in the air flow are responsible for a droplet sorting by size, as a function of their Stokes number (St= droplet response time when put in a flow / characteristic time of the flow). This droplet sorting generates a succession of dense zones mostly composed of small droplets (where $St < 2$).

- For Eckstein et al. [Eckstein et al., 2003] from Munich University of Technology, the SMD fluctuation responds linearly to the atomisation regime with fluctuating velocity. In other words, due to the velocity fluctuation at the atomisation place (shaded velocity interval on figure 9.14), the droplet size fluctuation mainly takes place at the tip of the injector. This generates a discontinuous spray which is then transported at mean flow velocity.

Both theories have been evaluated using IN-PULSE, and reported in Cargèse in 2005 [Giuliani et al., 2005]. For the Eckstein et al. hypothesis, we considered the order of magnitude on the SMD fluctuation range found in the MOPAA experiments performed at DLR from 2002 to 2004, and reported in figure 9.14. The methodology for the simulation is presented in figure 9.15, and the result on the SMD fluctuation as a function of the pulsation frequency in figure 9.16.

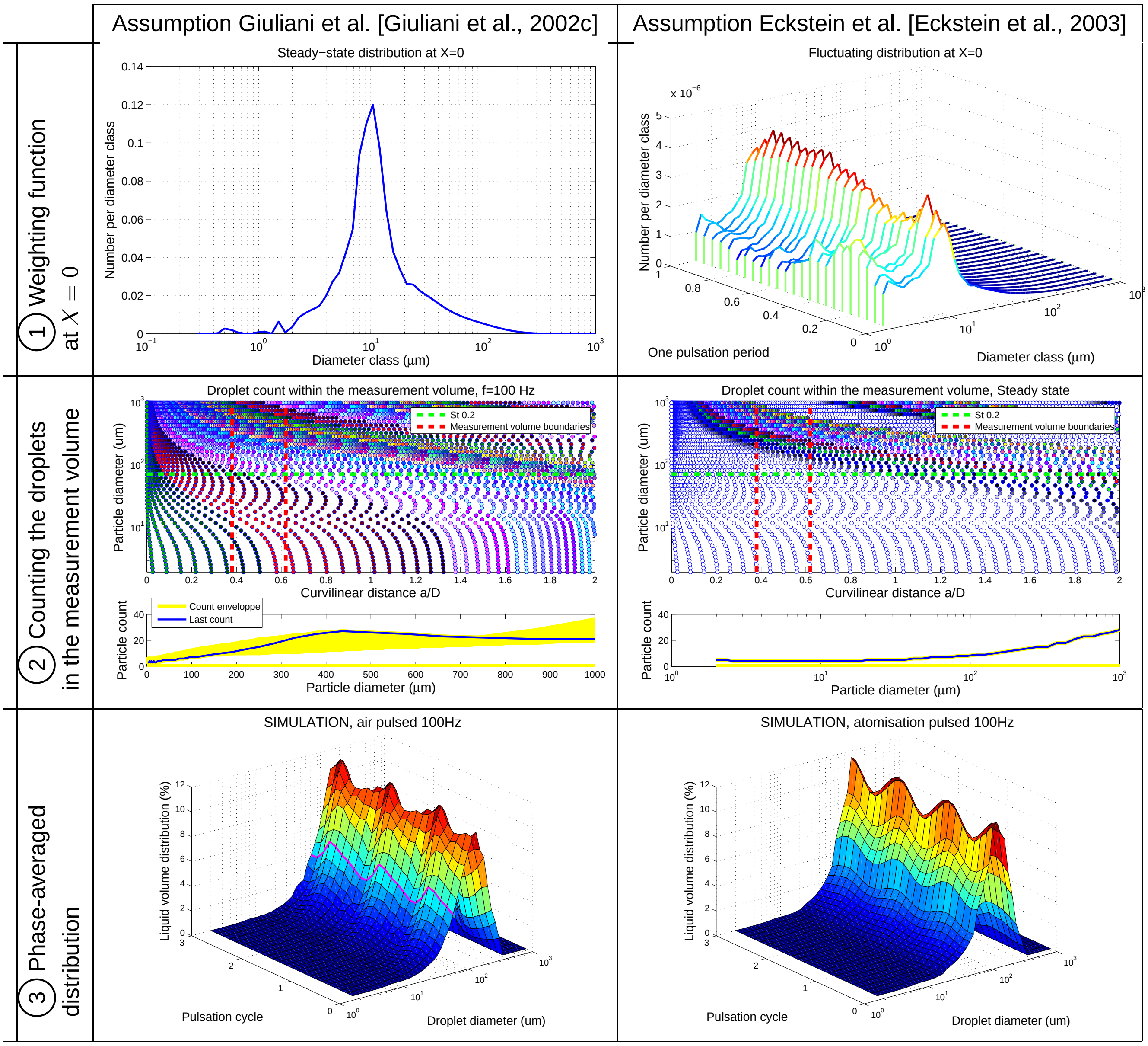


Figure 9.15: *Method for reconstructing the phase-averaged droplet size distribution. Left: the droplet size distribution is steady-state at the injection, and the distribution fluctuation in the far field is due to the air flow modulation. Right: the atomisation is pulsed at the injector lip, and the air flow is steady-state*

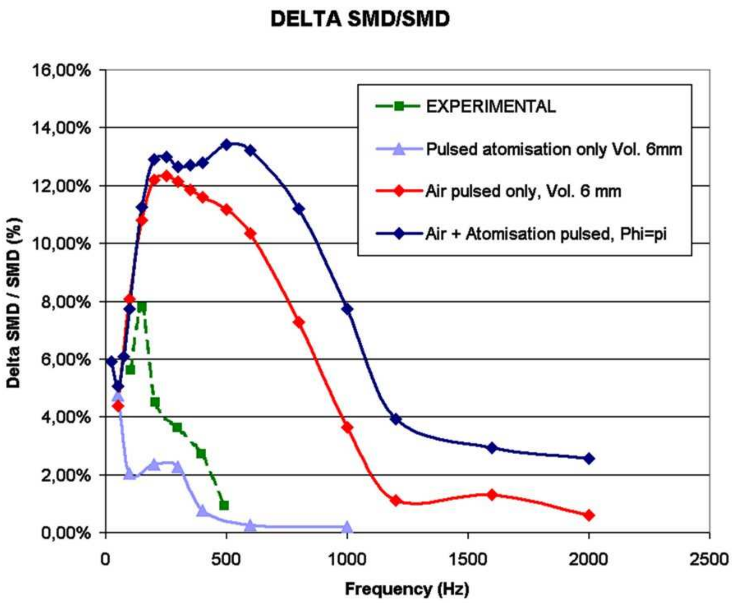


Figure 9.16: *Role on the atomisation and transportation processes in pulse spray, as a function of the frequency. Reference: SMD measuremenst performed on the ONERA pulse spray with a MALVERN.*

9.3.3 Results

9.3.3.1 About the physics of two-phase flow with pulse air

The comparison in figure 9.16 shows that taking into account the ONERA configuration, both mechanisms (pulse atomisation and sorting due to the droplet size in a pulse air flow) act effectively on the spray discontinuities and match the measurement trend on specific frequency domains. In terms of amplitudes, the fluctuation observed on the SMD seems indeed to be mostly driven by the transportation effect. It also shows that the two effects act complementarily, when simultaneously taken into account as it probably physically happens.

Müller et al. [Müller et al., 2006] restrict the observation of Eckstein et al. to the low-frequency domain (the film disintegration in presence of an oscillating air flow can be only be described as a quasi-stationary process on a narrow low-frequency bandwidth). The range of interest is therefore [50 - 500Hz], which is also about the current technological limit for precise phase-resolved injection actuation.

9.3.3.2 About the best strategy towards injection control

Several control strategies are reviewed in article [Giuliani and Hennig, 2010]. The model spray used is the one displayed in section 9.2.2 p.128. The results show the extreme dependance on the particle size distribution, acting not only on the SMD but also on the amount of pulsed liquid mass flow rate. As a result, when the problem is situated in the low frequency region as it most often happens, a pulsation with controlled phase shift should damp partially a combustion instability. At higher frequencies, a control making use of a shaker, or a direct control of the atomisation process would be more effective.

Fig.9.17 shows a tentative to damp a spray modulated by a 10 % air pulsation by means of a kerosene pulsation, which is the most suitable technique to face the fluctuation levels involved. As can be seen on this figure (top), this strategy is efficient to some extent in the interval [0.4 4 kHz] where the fuel fluctuation curve with phase-shift $\phi = \frac{3\pi}{2}$ is situated below the reference curve. Damping could even be better than shown when adjusting the fuel pulsation amplitude and the phase-shift for a specific frequency. The bottom plot shows the fluctuation in terms of SMD, that does not systematically reproduces the trends of the kerosine mass flow rate fluctuation for a given phase-shift.

This example reminds that actuation is to be used only when necessary. For instance, the actuation via the fuel disturbs the spray in the interval [0-0.4 kHz] more than the air pulsation. Furthermore, when activated the phase-shift shall be set precisely, since the fuel fluctuation adding-up to the problem can make the things much worse at the wrong phase-shifts (see the curves at $\phi = \frac{\pi}{2}$ and π). If a phase-shift can currently be well-managed at low frequencies, precise control above the kHz region may be a problem.

Again, the situation displayed in Fig.9.17 is typical of the probe position, and of the spray particle size distribution.

9.3.4 Model discussion, and project follow-up

The model IN-PULSE was adapted to reproduce the spray characteristics in the far field as a function of the inlet conditions. A correlation on the atomisation of an airblast with prefilmer was used to assess realistic inlet conditions. Based on these, order of magnitudes on the required actuation can be computed, so that IN-PULSE can be used as a simple predictive and/or dimensioning tool for combustion instability risk analysis.

The previous examples were done for non-vaporising particles, in absence of prefilmer. The trends were reproduced, but the amplitudes do not match those measured with for instance a MALVERN instrument. The 1D-transportation code did not take into account damping effect, diffusivity or turbulence, interaction between particles, successive break-up mechanisms etc., and as a result the computed amplitude levels were overestimating the measured SMD fluctuations. A more consistant CFD code (3D, 2-phase flow, RANS or LES for the air flow, Eulerian module for the particles, 2-way coupling, particle-particle interaction, evaporation) shall provide realistic levels of amplitude.

The immediate potential for improvement lies in a more detailed modelling on the introduction of the liquid phase in the computational domain. Concerning the droplet size PDF, further attempts to represent with more precision the low St particles will be done based on the use of truncated LN distribution. In the near future, IN-PULSE will become a user-defined function of a numerical code, to facilitate similar studies for liquid actuation assessment in 2D and 3D, with evaporation, and under reactive conditions.

Gajan et al. [Gajan et al., 2007] (clickable version) implemented vaporisation in the IN-PULSE algorithm to simulate the fluctuation of equivalence ratio, mostly due to the evaporation of the small droplet size category. This version of IN-PULSE will be used and further developped for the ALFA-BIRD project on the analysis of the evaporation of biofuels. The Atomisation model will be then based on the two-phase flow diagnostics established at high temperature and intermediate pressure by the ONERA.

Related literature from author on atomisation and transport processes

[Bhayaraju et al., 2005] Bhayaraju, U., Hassa, C., and Giuliani, F. (2005). A study of planar liquid sheet breakup of prefilming airblast atomisers at high ambient air pressures. In *20th Annual Meeting of the Institute of Atomisation and Spray systems (Europe)*. ILASS 2005 (20th Annual Meeting), Orléans, France.

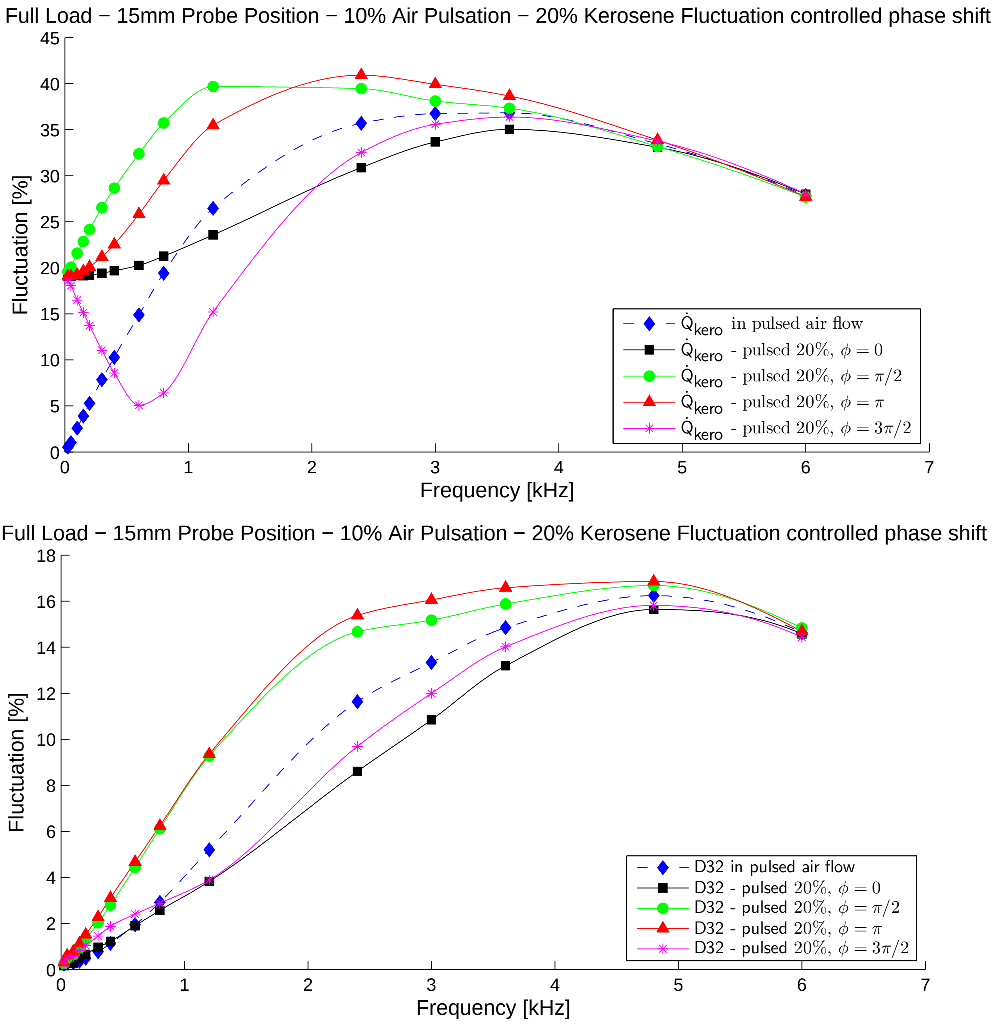


Figure 9.17: *Combining a spray modulated by a 10 % air pulsation with a kerosene pulsation for four different phase-shifts. Probe at 15 mm.*

[Gajan et al., 2007] Gajan, P., Strzelecki, A., Platet, B., Lecourt, R., and Giuliani, F. (2007). Experimental investigation of spray behavior downstream of an aeroengine injector with acoustic excitation. *Journal of Propulsion and Power*, 23(2):390–397.

[Giuliani, 2002] Giuliani, F. (2002). *Analysis on the Behaviour of an Aeroengine Air-Blast Injection Device with Forced Entries*. PhD thesis, ENSAE No 346, Toulouse, France.

[Giuliani et al., 2004] Giuliani, F., Berthoumieu, P., Becker, J., and Hassa, C. (2004). The effect of ambient air pressure on planar liquid sheet disintegration at gas-turbine conditions. In *19th Annual Meeting of the Institute for Liquid Atomization and Spray Systems (ILASS Europe), Nottingham, UK*, pages 68–75.

[Giuliani et al., 2007] Giuliani, F., Bhayaraju, U., and Hassa, C. (2007). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine conditions using laser infra-red absorption. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 2008] Giuliani, F., Bhayaraju, U., and Hassa, C. (2008). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine combustor inlet conditions using laser infra-red absorption. In *32nd International Symposium on Combustion*. Montreal, Canada, The Combustion Institute.

[Giuliani et al., 2005] Giuliani, F., Gajan, P., and Diers, O. (2005). A physical model on air-blast atomisation with modulated air inlet flow. In *Trends in Numerical and Physical Modeling for Industrial Multiphase Flows*. Cargèse, France.

[Giuliani et al., 2002] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2002). Influence of pulsed entries on a spray generated by an air-blast injection device - an experimental analysis on combustion instability processes in aeroengines. *Proceedings of the Combustion Institute*, 29(1):91–98.

[Giuliani and Hennig, 2010] Giuliani, F. and Hennig, C. (2010). Evaluation of active control strategies regarding airblast atomisation. In *23rd European Conference on Liquid Atomization and Spray Systems - ILASS*, Brno, Czech Republic. Submitted Jan. 10.

[Giuliani et al., 2009] Giuliani, F., Hennig, C., Leitgeb, T., and Hassa, C. (2009). Effect of the initial droplet size distribution of the liquid phase combined with transport phenomena on the resulting airblast spray in the far field. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-133.

[Hennig et al., 2009] Hennig, C., Giuliani, F., Freitag, S., and Hassa, C. (2009). Image particle sizing of an air blasted liquid sheet of kerosene at intermediate pressure. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-093.

Chapter 10

Progresses on the physics of pulsed flames

10.1 Methane-air premixed flame observed with supporting measurement techniques

10.1.1 Jet and flame dynamics with PIV

To establish the capacity of laser vibrometry to monitor combustion instabilities, a test case which is known was used which is similar to the experiment realised in the previous chapter. The ONERA siren was provided by our ONERA colleagues to reproduce a vortex-driven modulated flame. The difference is that for this very section the injector is different (a combined venturi-axial swirler designed for premixed air-methane combustion, engineered at TU Graz [Wagner, 2005]). This is the reason why the jet aerodynamics had to be characterised again, this time with the help of PIV. Another difference is the use of a resonator tube to amplify specific eigenfrequencies.

The pulsed jet dynamics (figure 10.1) of the air-methane premix injector are analysed with phase-averaged PIV measurement. On these vector plots, the superimposed contours correspond to the presence of vortical structures identified with the λ_2 criterion. Remarkable here is the detachment of ring vortices surrounding the main jet developing at the burner front plate, detaching and being transported by the flow. These are generated by the mass flow modulation at the injector outlet. In the meantime, the internal recirculation zone performs a back-and-forth motion. The advection velocity of these structures is usually about half of the injection velocity [Panda and McLaughlin, 1990]. This fact was also observed during the present experiments.

The same experiment with flame is shown in the same figure. Due to the burning of the seeding (DEHS oil), the valid velocity measurements take place in the flame periphery. The velocity vectors placed along the flame expansion cone indicate a redundant bottleneck shape, at the shoulder of which a pair of clockwise (line contours on the vorticity maps, unit is 2π rad/s and anticlockwise (filled contours) ring vortices are evolving - one down the flow inside the jet envelope and one up the flow outside of the jet. By comparison with the schlieren visualisation from Fig. 10.2, these vortices work as quadripoles placed around the major flame instability.

10.1.2 Flame dynamics with schlieren technique

The flame dynamics was observed with help of schlieren visualisation (so that density gradients are visible). This is a qualitative measurement where the flame envelope is clearly visible. The shots were obtained with the high speed camera Kodack Motion Corder. The sequence presented in figure 10.2 shows successive images taken at 1 kHz. First, the flame is attached forming a "tube" at the tip of the injector. After that, a mushroom-shaped pattern appears around this tube, with the development of a 2D axisymmetric Kelvin-Helmholtz instability. By comparison with figure 10.1, the flame rolls up around the external ring vortices. This roll-up structure is advected while the flame roll-up closes, and so on. The siren excitation frequency drives the mixing layer instability.

10.2 Flame dynamics description using laser vibrometry

Applying the process of figure 8.21, one derives with DLV not only the ρ' phase-defined values, but also the dynamics of deformation of the flame front (Fig.10.3). The description of the mushroom-like roll-up motion is remarkable, and observable within the depth of the flame where both schlieren and DEHS-seeded PIV techniques are blind.

The zone where the mushroom-shaped flame appears consists of a negative density fluctuation (light contours on the plots), due to the local sudden heat release. This zone seems to be pushed by the arrival of a positive density fluctuation zone (filled contours), that coincides in time and space with the outer vortex ring from figure 10.1. The negative ρ' zone expands around the positive ρ' zone (roll-up and closing of the flame) while the positive density zone drops in intensity. The further down the flame the more the fluctuations are damped or dissolved. Nevertheless they remain visible up to the end of our measurement area.

To establish the capacity of LV to describe the flame dynamics of a confined flame (under intermediate pressure, here 2 bar) as well as its capacity to describe in details middle range frequency (540 Hz), figure 10.4 displays the latest results presented in [Lang et al., 2008]. The generation, detachment and transport of ring vortices is visible in both cases. With this method, we can expect to observe clearly similar structures up to several kHz - a refined measurement grid is then required.

10.3 Project follow-up

The absolute measurement of density fluctuations in a flame is possible in free-jet configuration with help of the LV technique. Stefan Köberl compares the results obtained on a generic diffusion flame with other measurement techniques in the frame of his PhD [Köberl et al., 2009].

However, the measurement error induced by the presence of windows under pressurised flame conditions is challenging, since it implies a deformation of the interface combined to the vibration of the windows. We showed previously that the qualitative results can still be obtained, mostly by getting rid of the major window reflections. Still, this is not satisfying for quantitative analysis. The signal losses due to light deviation/absorption or artefact due to window vibrations are being at the moment researched, especially in the

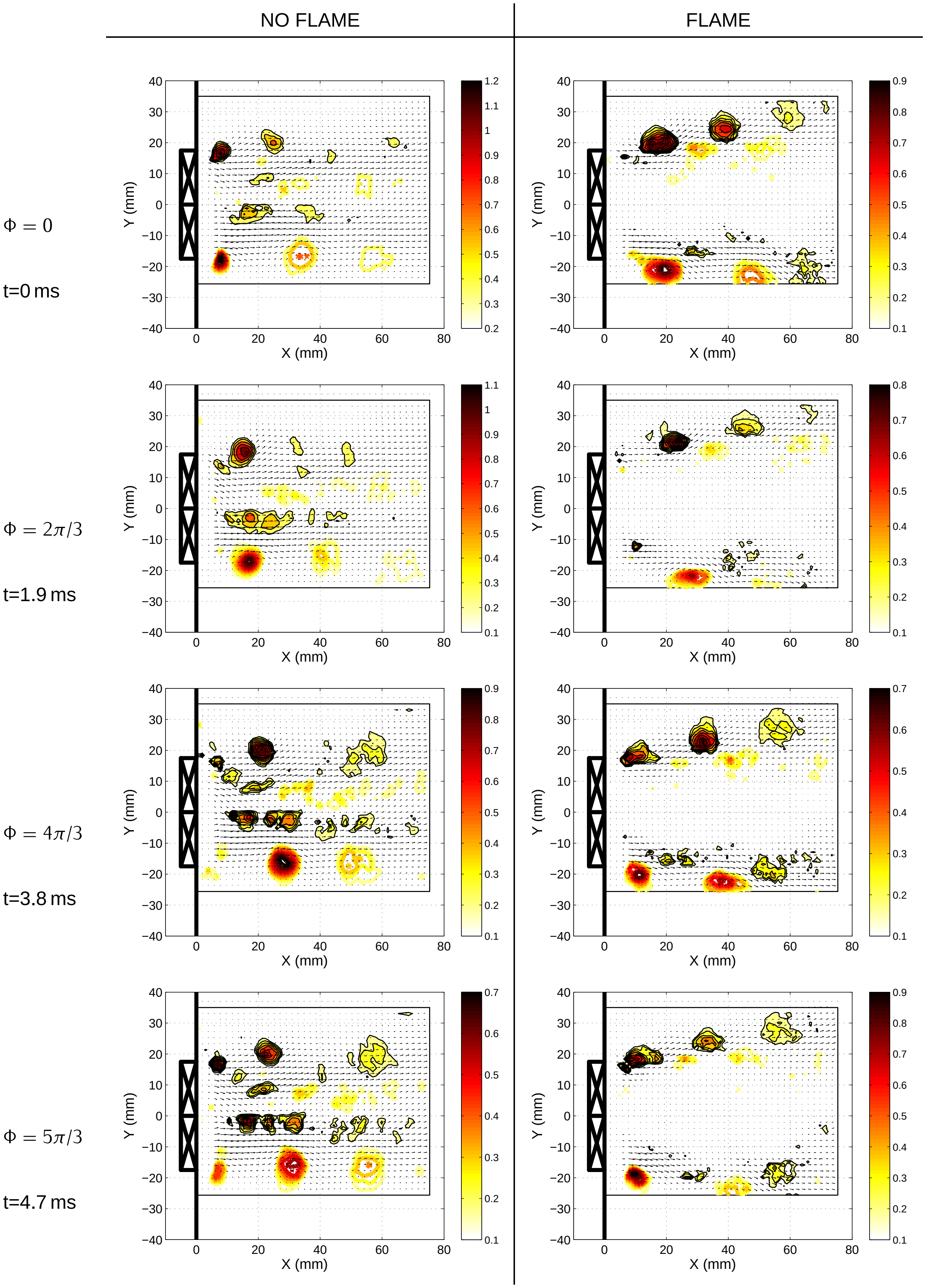


Figure 10.1: *Jet dynamics observed with with PIV in the $Y = 0$ plane in isothermal conditions and in presence of a flame. Siren pulsation frequency 175 Hz. Four phase-locked subperiodes are displayed with incremental time step τ/6=1.9 ms from top to bottom.*

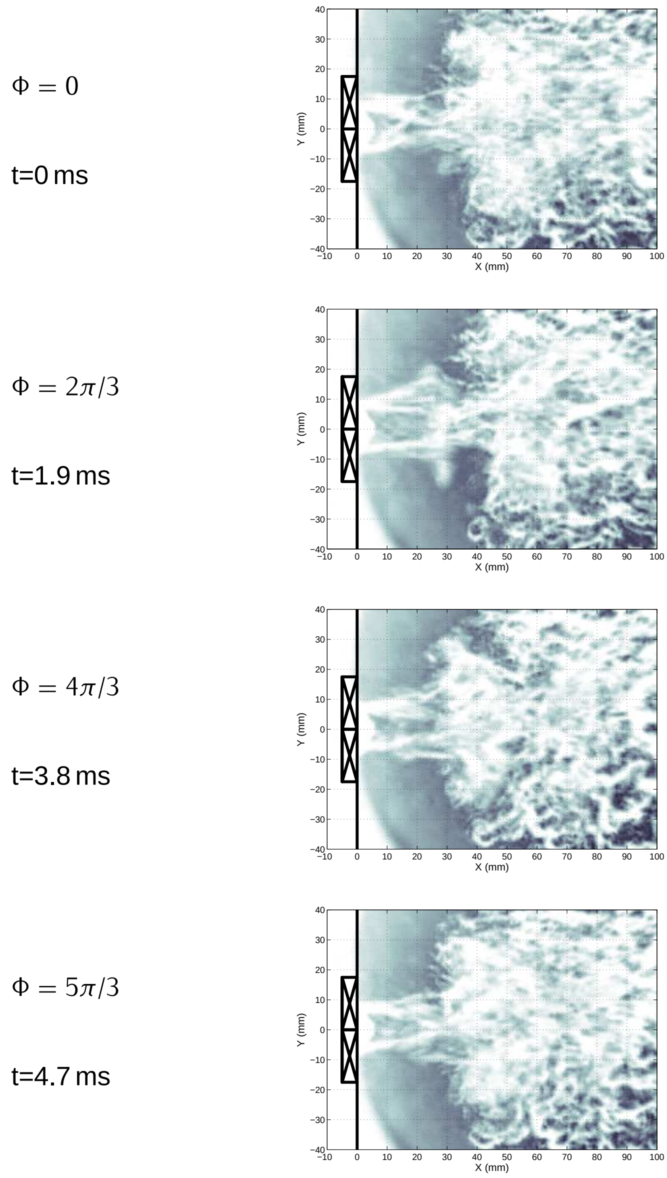


Figure 10.2: *Recurrent mushroom-shaped flame observed with schlieren technique. Siren pulsation frequency 175 Hz. Four phase-locked subperiodes are displayed with incremental time step τ/6t=1.9 ms from top to bottom.*

frame of the co-operation with the DLR.

The next ambition is the extension of LV to reacting multiphase flows. This would result in a combined approach of both LV and IRA technologies to separate the extinction due to liquid and gaseous phases, or to compensate the IRA weakness in the high frequency domain. The very first test will be performed on a LPP configuration having thus a very diluted spray.

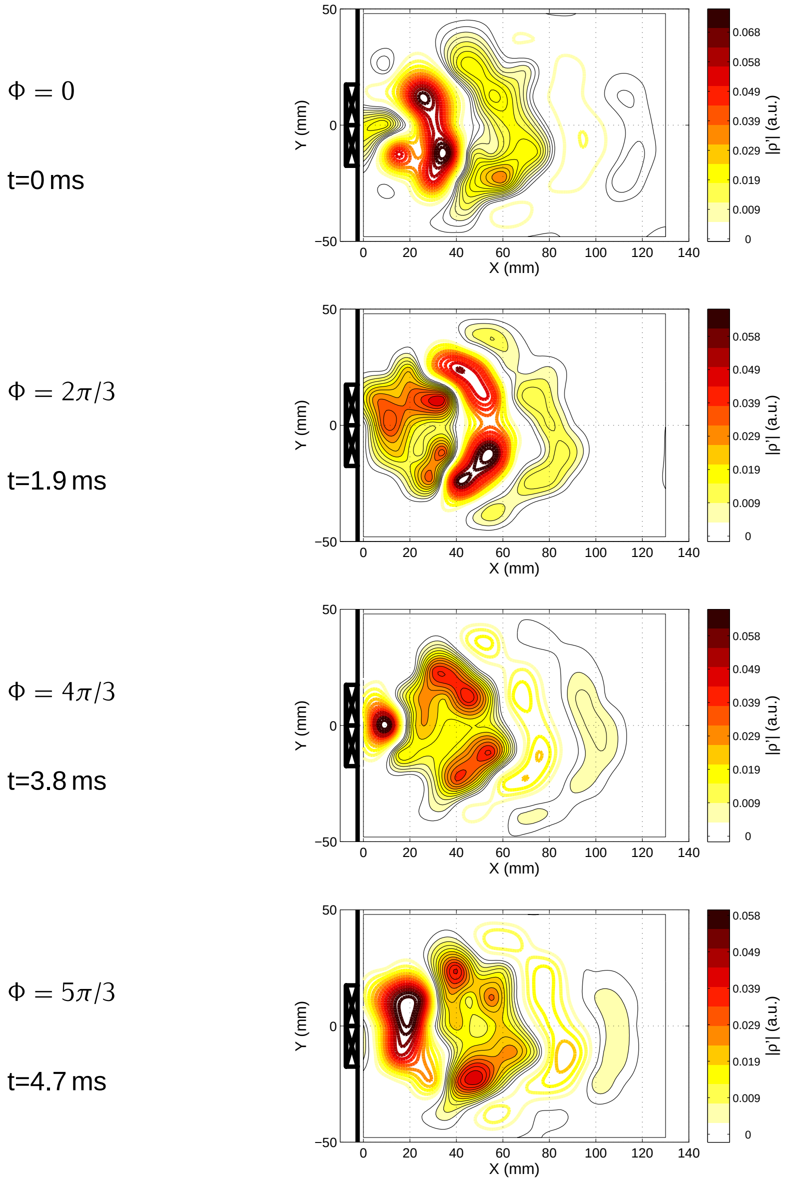


Figure 10.3: *Density fluctuation maps covering one pulsation cycle, based on phase-averaged LV signals, performed on a pulsed flame (free jet, 175 Hz). Relative density fluctuation $\rho'_{f\ LS}(d\tau)$ (line-of-sight, computed with equation 8.6). Filled contours: positive ρ values. Line contours: negative ρ values. Contour colour: absolute value of the density fluctuation $|\rho'|$ (kg/m^3). The plots are synchronous with the ones from figures 10.1 and 10.2.*

Related literature from author

[Diers et al., 2001] Diers, O., Giuliani, F., Biscos, Y., Gajan, P., and Ledoux, M. (2001). Phasenaufgelöste LDA-Messungen in der Gasströmung einer Luftstromzerstäuberdüse. In *Lasermethoden in der Strömungsmesstechnik*, pages 36.1–36.7. Fachtagung der Deutschen Gesellschaft für Laser-Anemometrie GALA e.V.

[Gajan et al., 2007] Gajan, P., Strzelecki, A., Platet, B., Lecourt, R., and Giuliani, F. (2007). Experimental

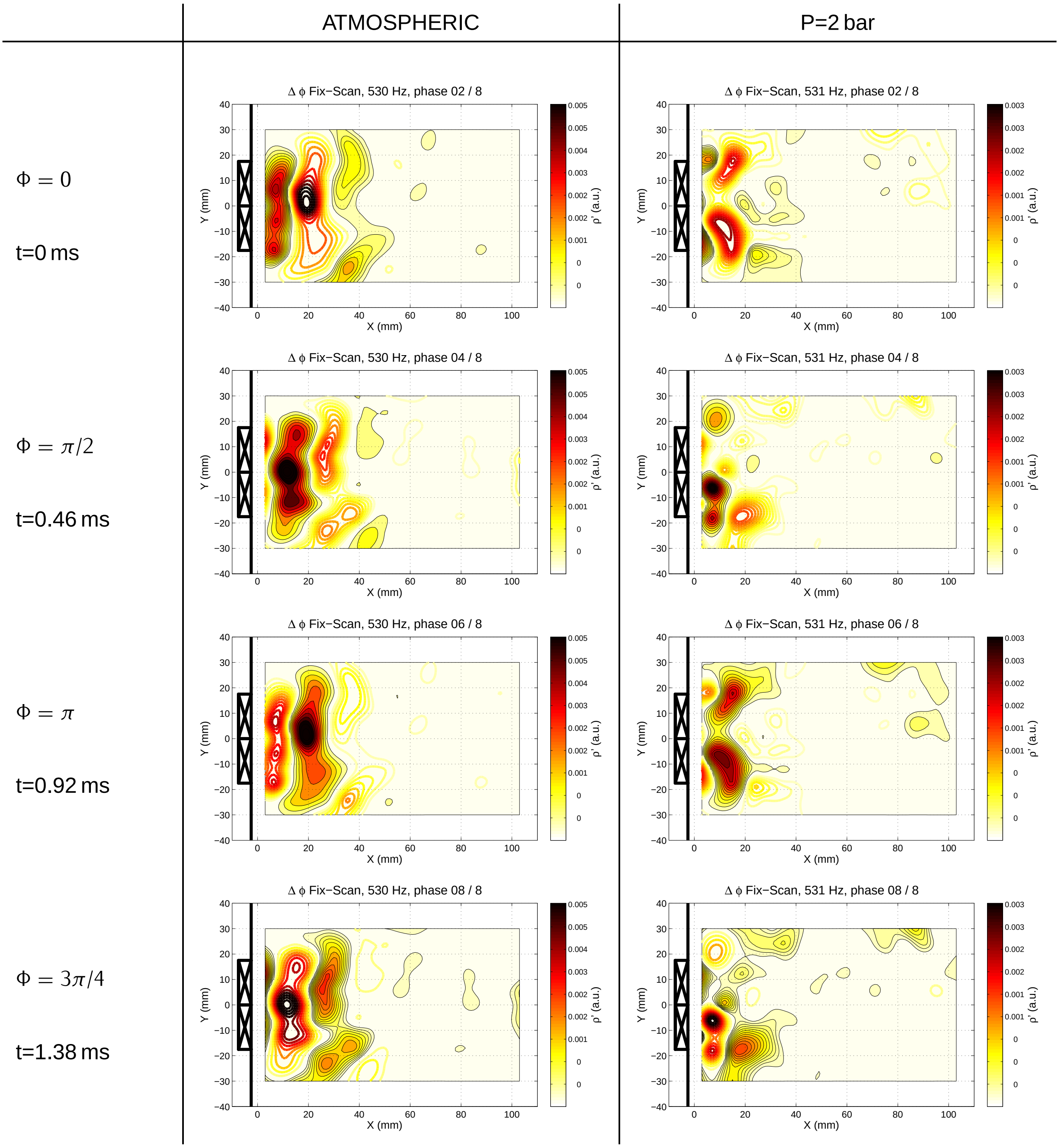


Figure 10.4: *LV measurements for a confined flame at intermediate pressure and at 2 bar*

investigation of spray behavior downstream of an aeroengine injector with acoustic excitation. *Journal of Propulsion and Power*, 23(2):390–397.

[Giuliani, 2002] Giuliani, F. (2002). *Analysis on the Behaviour of an Aeroengine Air-Blast Injection Device with Forced Entries*. PhD thesis, ENSAE No 346, Toulouse, France.

[Giuliani et al., 2002a] Giuliani, F., Diers, O., Gajan, P., and Ledoux, M. (2002a). Characterization of an air-blast injection device with forced periodic entries. In *Proceedings of the IUTAM Symposium on Turbulent*

Mixing and Combustion, Queen's University at Kingston, Canada, June 3-6, 2001 Pollard and Candel (eds) Kluwer Academic Publ., pages 327–336.

[Giuliani et al., 2001a] Giuliani, F., Gajan, P., Biscos, Y., Diers, O., and Ledoux, M. (2001a). Analyse de l'écoulement diphasique généré par un injecteur de type aérodynamique en régime pulsatoire forcé. *Recueil des actes du 9^{e} congrès francophone de visualisation et de traitement d'images en mécanique des fluides, FLUVISU, Rouen, France*.

[Giuliani et al., 2001b] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2001b). Analyse en moyenne de phase du champ de vitesse de l'air issu d'un injecteur aérodynamique en régime pulsatoire forcé. In *Recueil des actes du 15^{e} Congrès Français de Mécanique*, Nancy, France.

[Giuliani et al., 2002b] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2002b). Influence of pulsed entries on a spray generated by an air-blast injection device - an experimental analysis on combustion instability processes in aeroengines. *Proceedings of the Combustion Institute*, 29(1):91–98.

[Giuliani and Hennig, 2010] Giuliani, F. and Hennig, C. (2010). Evaluation of active control strategies regarding airblast atomisation. In *23rd European Conference on Liquid Atomization and Spray Systems - ILASS*, Brno, Czech Republic. Submitted Jan. 10.

[Giuliani et al., 2009a] Giuliani, F., Hennig, C., Leitgeb, T., and Hassa, C. (2009a). Effect of the initial droplet size distribution of the liquid phase combined with transport phenomena on the resulting airblast spray in the far field. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-133.

[Giuliani et al., 2007a] Giuliani, F., Lang, A., Leitgeb, T., , Woisetschläger, J., and Heitmeir, F. (2007a). Time-resolved analysis of density fluctuations in a resonant air-methane flame using dual laser vibrometry for gas turbine combustor qualification tests. In *Proc. of the 18th ISABE conference*. International Symposium on Air Breathing Engines, Beijing, China. ISABE-2007-1187.

[Giuliani et al., 2008] Giuliani, F., Lang, A., Leitgeb, T., and Woisetschläger, J. (2008). Phase-defined density fluctuation maps of a resonant air-methane premixed flame using laser vibrometry. In *32nd International Symposium on Combustion*. Montreal, Canada, The Combustion Institute.

[Giuliani et al., 2007b] Giuliani, F., Lang, A., Leitgeb, T., Woisetschläger, J., and Heitmeir, F. (2007b). Using dual laser vibrometry to monitor the stability of gas turbine combustion. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 2010] Giuliani, F., Leitgeb, T., Lang, A., and Woisetschläger, J. (2010). Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry. *Journal of Engineering for Gas Turbines and Power*, 132. GTP-031603.

[Giuliani et al., 2009b] Giuliani, F., Leitgeb, T., and Woisetschläger, J. (2009b). Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry. In *ASME Turbo Expo, Gas Turbine Technical Congress & Exposition*, Orlando, FL USA. GT2009-59682.

[Hennig et al., 2009] Hennig, C., Giuliani, F., Freitag, S., and Hassa, C. (2009). Image particle sizing of an air blasted liquid sheet of kerosene at intermediate pressure. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-093.

[Köberl et al., 2010a] Köberl, S., Fontaneto, F., Giuliani, F., and Woisetschläger, J. (2010a). Frequency resolved interferometric measurement of local density fluctuations for turbulent combustion analysis. *Measurement Science and Technology*. Submitted Sept. 2009.

[Köberl et al., 2010b] Köberl, S., Fontaneto, F., Heimel, M., Giuliani, F., and Woisetschläger, J. (2010b). Measurement of local density fluctuations for combustion diagnostics of different flames using dual laser vibrometry. In *AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*.

[Köberl et al., 2009] Köberl, S., Giuliani, F., and Woisetschläger, J. (2009). Energy spectra measurements for the density fluctuation in a jet flame using dual laser vibrometry. In *Proc. of the 4th ECM*. European Combustion Meeting, Vienna, Austria, The Combustion Institute.

[Lang et al., 2008] Lang, A., Leitgeb, T., Woisetschläger, J., Strzelecki, A., Gajan, P., and Giuliani, F. (2008). Analysis of a pulsed flame at intermediate pressure. In *ISFV13 - 13th International Symposium on Flow Visualization / FLUVISU12 - 12th French Congress on Visualization in Fluid Mechanics*, Nice, France.

Part IV

Works in progress, and perspectives of research

Chapter 11

Perspectives on Advanced Combustion Management for Gas Turbines at TU Graz

11.1 Development of the Combustion Unit

11.1.1 Experimental facilities

11.1.1.1 Test rigs under development

A spray test facility was also lately built (work of A. Lechner [Lechner, 2008]) to characterise the spray nozzles at atmospheric conditions, and prepare the 2-phase flow measurement techniques. The next spray test rig planned 2010 for fuel spray analysis at realistic GT operating conditions, but without flame, is displayed in figure 11.1. This facility is designed for the analysis of real fuels or replacement fuels, and dimensioned so that the fuel injection is observable for a large palette of operating conditions, with securities versus auto-ignition. The exhaust gases are cooled down with help of a heat exchanger/recuperator and the rest gases are reduced with help of an atmospheric afterburner, so that the exhaust gases are not flammable.

The high-pressure, high-temperature test rig is tested since autumn 2008, and used for the NEWAC program. This facility has an advanced automated system (work of T. Leitgeb [Leitgeb, 2007, Leitgeb et al., 2009a]) and a versatile and flexible air system. At the horizon 2010, we should possess an equipment able to run a full-annular combustor for Auxiliary power units (APUs), small-size helicopter turbines or aeroengines. Other applications such as analysis of cooling technologies is also an issue.

Experiments on pulse combustion for educational use are a topic under development, related to the institute's experience with the old V1-Schmidt-tube pulse combustor. That would also prepare basic experiments on pulse detonation that were already proposed during the informal discussions on a NEWAC II project. The incentive in that case would be to catch-up with the pulse detonation technology at experimental level, expand our understanding on the physics that are involved, and validate and refine the pulse detonation combustor model that was developed during NEWAC.

Figure 11.2 shows two AV designs to be soon investigated. The first one is a flat prefilmer spray facility

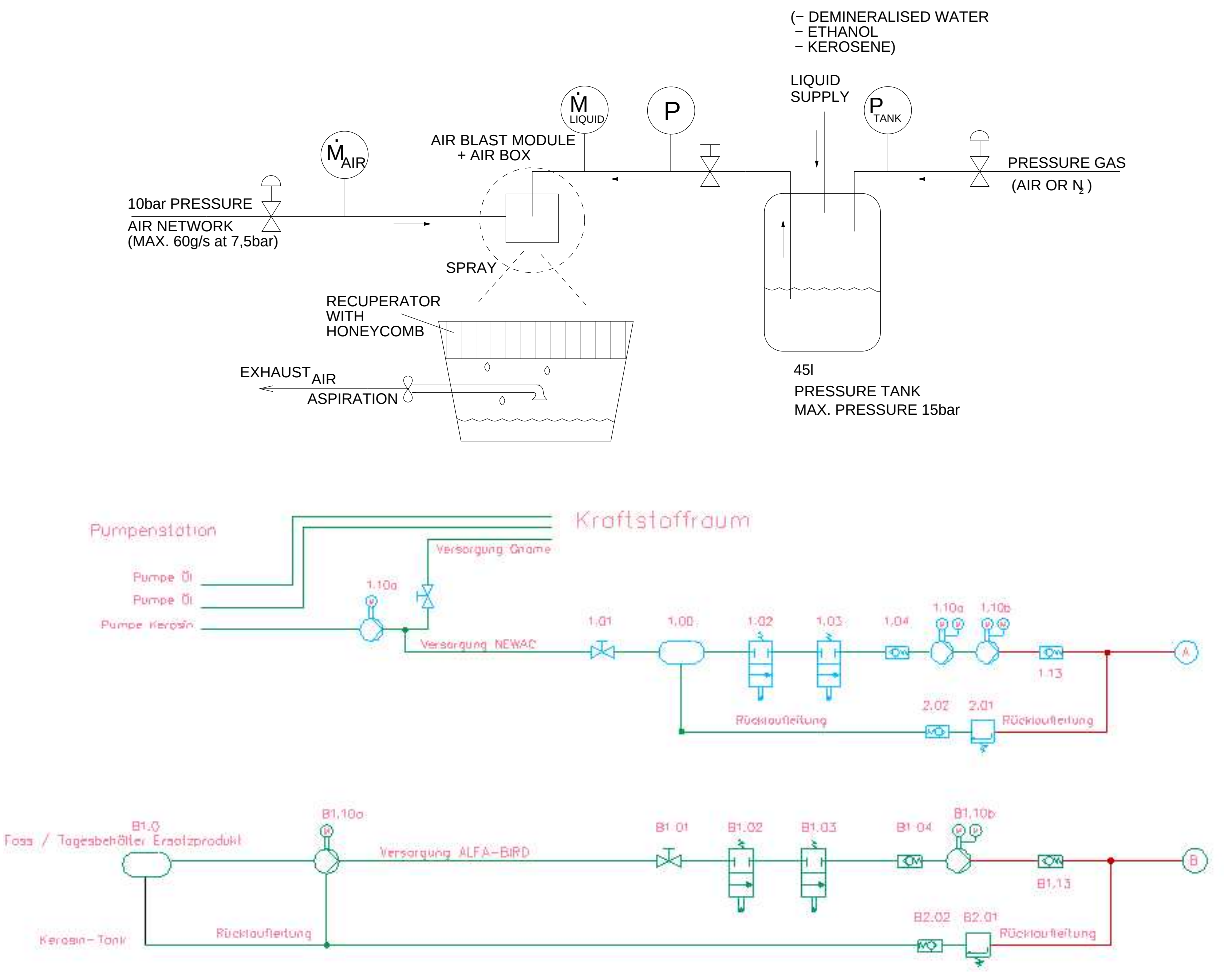


Figure 11.1: *Fuel spray test rig for refined analysis on real fuel atomisation, vaporisation and vapour diffusion. Top: portable version for small tests. Bottom: large facility with two lines (line A is for kerosine, line B is for replacement or surrogate fuel) designed for pressures up to 100 bar*

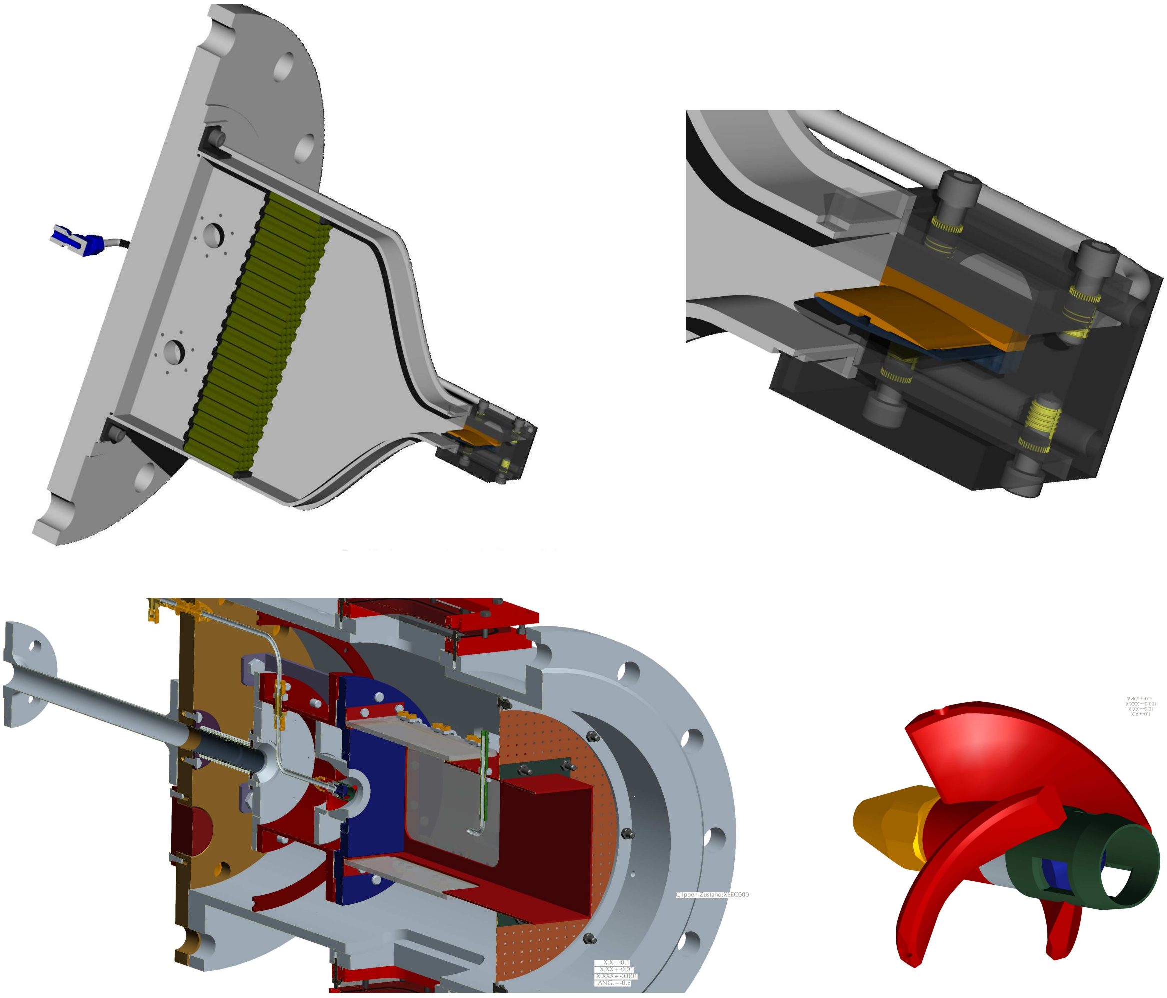


Figure 11.2: *New designs for two-phase flow investigation to be tested in 2011*

with well-defined boundary conditions (with a special effort put on the air boundary layer), and the possibility to pulsate the fuel flow in the frame of the FWF3 programme. The second one was developed for educational purpose, as a design exercise for air blast atomiser, with a strong flow analogy to the Wagner burner. This design was also offered as a generic burner for a EU project. Both models are designed to operate at realistic injection conditions, with surrogate and real fuels.

11.1.1.2 Power systems under construction

- A flexible fuel supply system is under construction, in co-operation with GuT. Two lines for kerosene and surrogate or alternative fuels (water, ethanol, biofuel) with flow rates up to 500 l/h and pressure up to 100 bar are drawn between the fuel station (a room near the tank pumps, that will be reorganise to this purpose). Commissioning is planned at the first semester 2010.

- Sound isolation of the thermal air heater. Commissioning first semester 2010.

11.1.2 Education and dissemination

11.1.2.1 Lectures

- The E-Learning project on the group's lecture plans in 2008-2009 the creation of an homepage, with an interactive exercise on combustor dimensioning
- The spectrum of educational activities of the unit should extend with the development of workshops in the lab (2010), the merging of several lectures concerning thermodynamics (2010). A common work with the faculty for chemistry will be done regarding thermochemistry of kerosene and replacement fuels, including the aspect "fuel design". A new lecture on aerospace propulsion will be proposed, with extension to pulse detonation propulsion, ramjet, scramjet, rocket engines and affiliated. This supports the opening of a aerospace branch at the TU Graz.
- Academic exchanges are planned with Chalmers (Sweden), and our usual partners at ONERA and DLR. A contact was also established lately with Ecole Centrale de Paris for fundamental research purpose.

11.1.2.2 Dissemination 2010

The journal articles and conferences we aim at in 2010 are the following:

- The ICLASS 2009 conference article [Hennig et al., 2009] was recommended for journal publication, and will be resubmitted for "Atomisation and Sprays", ensuring Christoph Hennig a Journal publication
- The works of Stefan Köberl will shortly be submitted to "Measurement Science and Technology" under the title "Frequency- and space resolved measurement of local density fluctuations in a methane jet flame by laser vibrometry". Another article is planned for the AIAA joint conference.
- The ILASS 2010 conference on liquid atomisation systems will be held in Brno, Czech Republic. This is an option for Christoph Hennig and Johannes Fritzer.
  - Results on atomisation control (Giuliani and Hennig)
- The ASME Turbo Expo Conference 2010 will be held in Glasgow, Scotland. This is the opportunity to present the following works:
  - Report on the ECCOMET activities concerning ignition (Lang)

11.2 Combustion management activities: towards the next calls on aeroengine combustion activities 2010-2013

11.2.1 Advanced sensing and acting techniques

2008-2009 were the years where gathered experiences with liquid-fuelled combustion under pressure, as well as soft ignition. We already have acquired in the previous seasons a fair experience in terms of pulsed combustion of air-methane flames at intermediate pressure conditions.

The research effort will be put in 2010 on the development of diagnostic techniques and actuators, in a similar way as we proceeded so far with combustible gases. The common work with PIEZOCRYST will be continued.

The FWF3 programme will consider the actuation of the liquid phase. The objective is the amelioration of air-blasted spray at part-load with active methods involving a minimal input of energy, through perturbation of the liquid input, at the level of the nozzle or at the level of the prefilmer.

A new siren designed by Andreas Lang will offer the possibility to vary the amplitude of pulsation at a given frequency. In comparison with the ONERA siren, the electrical motor will be actively controlled so that the pulsation frequency is steadied with a less than 1 % standard deviation. A prototype for cold flow tests in under development, with aim to develop a similar device for hot flows.

Concerning the actuation on the air, a program of basic thermoacoustics involving a Rijke tube will shortly be started under the supervision of T. Leitgeb. The aim is to investigate "simple" control loops (e.g. opened loop), and try something else than the adaptive and phase-controlled response that has been extensively studied so far [Blonbou et al., 2000,Yang, 2001,Dowling and Morgans, 2005,Garay et al., 2006]. Fundamental research on the Rayleigh criterion analysis in real-time with LV is an option of a common work with Ecole Centrale de Paris.

11.2.2 Combustor with enlarged operation range

This exercise is currently studied theoretically in the frame of the NEWAC project. The main idea is to maintain a steady flame at constant pressure conditions but with a strong variation of primary air (up to 30 %), due to the deviation of primary air in the compressor combined to the action of variable turbine inlet guide vanes that throttle the combustor. We currently analyse this point with help of simulations.

The development of adaption strategies on the injection, swirl number and cooling holes, the choice of effective actuators and the development of a demonstrator will be proposed in the frame of the next EU call in 2010.

11.2.3 Future fuels

The results of ALFA-BIRD will be decisive, whether we invest or not on the development of burners adapted to replacement fuels. Among the tasks to be performed, the aspect "fuel design" is an issue on finding the right compromise between a low-emission fuel, and a fuel that atomises correctly in order to avoid losses. This is an aim for after 2012.

11.2.4 Unsteady combustion

This last point concerns the use of unsteady combustion, with the aspects pulse combustion and pulse detonation. We already have a know-how concerning how to get an unsteady flame, with actuation, resonator, or though the enhancement of thermoacoustics. Our instrumentation is prepared for the observation of rapid - but cyclic - phenomena.

A dimension exercise on the integration of PDE's in gas turbine is currently performed in the frame of NEWAC, with help of simulations. The next step, for instance in the programm of the call 2010, is to experiment and quantify the PDE technology.

Even if in the near future, the application PDE in aeroengine cores is a no-go, the development of sensing and actuating required for this technology is also of great importance for combustion management of "classical" deflagration flames.

11.2.5 Ignition

Adaptive ignition for cold start, hot start or emergency restart is an issue for future projects that was lately discussed with AVIO, since we presented our ignition test bench TALI-2. Andreas Lang did also a successful 3-months academic exchange in the frame of ECCOMET on ignition at ONERA Centre du Fauga Mauzac [Lang et al., 2010].

The igniter may also evolve in the sense that it can be instrumented and provide real-time information, due to its proximity to the flame. It may also be used as an actuator for control purpose.

11.3 Future of the Combustion Division

The Combustion Division at TU Graz / TTM (2004-2010) not only exists, but becomes more and more visible because of the effort on dissemination and thanks the dynamism of the team. It also continuously expands, in 2010 the feedback from the lecture sessions brings us at least two diploma theses and three trainees.

The short-term deadlines are important:

- AV is about to produce results within NEWAC, and establish its capacity as a European lab to analyse / simulate HPT combustion

- The project extensions / new projects 2010 will decide of the work plan and development of AV during the coming half-decade

- The successful EFRE grant application for large facilities will provide the unit with a unique "firepower", opening the doors towards financing dedicated to a club of happy fews.

However, the current situation of AV is very fragile, and its near future uncertain. A dissolution could happen because of:

- The leave of key personnel

- The lack of third-party financing at the outcome of the current projects

- A bad feedback from the student’s side

- A critical facility breakdown

A support of TU Graz is extremely important, to cover the periods of financial gap the follows the 2008 crisis. If long-term is planned in the branche of aeronautics, then the following for the future of AV is suggested.

11.3.1 Status quo: AV as an academic entity

This would be the freeze of the current situation, where AV concentrates on the student's education and performs mostly ground research. A plateau on the AV personnel number may be required during the period 2010-2014, so that the first set of objectives is well brought to an end, without suffering from the problems inherent to frantic expansion.

A team of three permanent staff (academic, in charge of education, facilities, modelling), plus the same of turn-over staff is indicated to ensure a high-quality level of teaching and research.

11.3.2 Major developments: AV as a joint academic-industrial entity

Let us assume we want to position ourselves with a strong orientation on applied research, and get on with combustion diagnostics at elevated pressure and temperatures (for instance up to 20 bar). This is the chance to take to develop up-to-date and unequaled test facilities in Europe. These would include:

- Elevated pressure combustion facility
- Advanced controls in combustion and injection
- Exhaust gases diagnostics, optical and sampling methods

The current needs in development for GT combustion support the creation of such an entity. The personnel requirement would be about 10 permanent staff (3 academic, 3 engineers, 2 technical, 2 administration and finance) and ten turn-over (PhD and post-doctorate level). Third-party financing would come from research projects, service towards the industry (GT partners, specialised instrumentation, air force), and specialised seminars.

11.4 Conclusion: towards a pole of excellence on GT combustion in Graz, and a valuable project partner

Over the last four years, we participated actively in the promotion of gas turbine activities, and observed a genuine feedback and sincere interest from the students. Propulsion technologies are definitely sexy - and the demand is growing fast. Our level of competitiveness in comparison with the emerging countries relies on our ability to keep the technological lead, and our capability to reinvent ourselves. We have one unique chance to make of TU Graz a recognised pole for aerospace, and a valuable project partner.

The AV group is motivated to help in achieving this goal, and participate actively step by step to the progress in GT combustion.

Figure 11.3: *An internationally recognised competence on propulsion technologies at the TU Graz. Why not? Illustration by Barbara Fuchs*

Bibliography

[ica, 1993] (1993). *Annex 16 (environmental protection) to the Convention on International Civil Aviation*, volume 2: Aircraft engine emissions. ICAO CAEP-2, 2 edition.

[aca, 2005] (2005). Strategic Research Agenda 1 and 2. Search term NOx, URL valid in June 2006.

[ozo, 2006] (2006). Environmental Effects of Ozone Depletion and its Interactions with Climate Change: 2006 Assessment. Technical report, United Nations Environment Programme (UNEP).

[weo, 2006] (2006). World energy outlook. Technical report, OECD / International Energy Agency.

[Atthassit et al., 2001] Atthassit, A., Biscos, Y., Giuliani, F., and Lavergne, G. (2001). Mesure de la température des gouttes en évaporation et en combustion par la technique arc-en-ciel. In *Recueil des actes du 9^e congrès francophone de visualisation et de traitement d'images en mécanique des fluides, FLUVISU*, pages 79–84. Rouen, France.

[Becker, 2003] Becker, J. (2003). Characterisation of the temporal and spatial homogeneity of the fuel placement in a swirl cup: non-reacting flow investigation by light sheet imaging, LDA and PDA. LOPOCOTEP deliverable 4.13. Internal report DLR-IB-325-03-03, Institute of Propulsion Technology, DLR Cologne, Germany.

[Becker, 2005] Becker, J. (2005). *Spray-Dispersion in einem generischen Vormischmodul für Flugtriebwerks-Brennkammern*. FB 2004-37, Fakultät für Maschinenbau der Ruhr-Universität Bochum, Institute of Propulsion Technology, DLR Cologne, Germany.

[Becker and Hassa, 2004] Becker, J. and Hassa, C. (2004). Experimental investigation of spatial and temporal aspects of the liquid fuel placement in a swirl cup at elevated pressure. In *ASME Turbo Expo*. Vienna, Austria. GT2004-53524.

[Beér and Chigier, 1972] Beér, J. and Chigier, N. (1972). *Combustion Aerodynamics*, pages 100–146. Applied Science publishers Ltd, London.

[Berthoumieu, 2002] Berthoumieu, P. (2002). Image v5.0: real-time image processer for liquid film disintegration analysis. Technical report, ONERA-CT. Author Pierre.Berthoumieu@onecert.fr.

[Berthoumieu and Carentz, 2000] Berthoumieu, P. and Carentz, H. (2000). Experimental study of a thin planar liquid sheet desintegration. In *8th international conference on liquid atomisation and spray systems*. Pasadena, CA, USA.

[Bhayaraju, 2007] Bhayaraju, U. (2007). *Analysis of Liquid Sheet Breakup and Characterisation of Plane Prefilming and Nonprefilming Airblast Atomisers*. PhD thesis, Technische Universität Darmstadt, Fachbereich Maschinenbau.

[Bhayaraju and Hassa, 2006] Bhayaraju, U. and Hassa, C. (2006). Surface Wave Propagation and Breakup in Planar Liquid Sheets of Prefilming Airblast Atomisers. In *ICLASS*. Kyoto, Japan. ICLASS06-06-073.

[Bhayaraju et al., 2005] Bhayaraju, U., Hassa, C., and Giuliani, F. (2005). A study of planar liquid sheet breakup of prefilming airblast atomisers at high ambient air pressures. In *20th Annual Meeting of the Institute of Atomisation and Spray systems (Europe)*. ILASS 2005 (20th Annual Meeting), Orléans, France.

[Bissières, 1997] Bissières, D. (1997). Modélisation du comportement de la phase liquide dans les chambres de combustion de statoréacteurs. *PhD Thesis, Ecole Centrale Paris, France*.

[Blonbou et al., 2000] Blonbou, R., Laverdant, A.and Kuentzmann, P., and Zaleski, S. (2000). Active adaptive combustion control using neural networks. *Combustion Science and Technology*, 156:25–47.

[Borghi, 1999] Borghi (1999). Multiphase flow combustion. In *Introduction to turbulent combustion*. VKI Lecture Serie 99-04.

[Brandt, 1999] Brandt, M. (1999). *Lasermesstechnische Untersuchung der Kerosinverdampfung und -mischung für die magere Vormischverbrennung unter erhöhtem Druck*. DLR -FB 1999-25, Universität Heidelberg., Institute of Propulsion Technology, DLR Cologne, Germany. ISSN 1434-8454.

[Brandt et al., 1998] Brandt, M., Schmitz, G., and Rachner, M. (1998). An experimental and numerical study of kerosene spray evaporation in a premix duct for gas turbine combustors at high pressure. *Combustion Science and Technology*, 138:313–348.

[Camps, 2008] Camps, A. (2008). Automated ignition for safe start at intermediate pressure conditions. Technical report, TU Graz / TTM / AV.

[Chraplyvy, 1981] Chraplyvy, A. (1981). Nonintrusive measurements of vapor concentrations inside sprays. *Applied Optics*, 20(15):2620–2624.

[Culick, 1988] Culick, F. (1988). Combustion instabilities in liquid-fueled propulsion systems - an overview. In *AGARD Conference Proceedings No. 450*.

[Diers et al., 2001] Diers, O., Giuliani, F., Biscos, Y., Gajan, P., and Ledoux, M. (2001). Phasenaufgelöste LDA-Messungen in der Gasströmung einer Luftstromzerstäuberdüse. In *Lasermethoden in der Strömungsmesstechnik*, pages 36.1–36.7. Fachtagung der Deutschen Gesellschaft für Laser-Anemometrie GALA e.V.

[Dowling and Morgans, 2005] Dowling, A. and Morgans, A. (2005). Feedback control of combustion oscillations. *Annu. Rev. Fluid Mech.*, 37:151–182.

[Drallmeier and Peters, 1991] Drallmeier, J. and Peters, J. (1991). Experimental investigation of fuel spray vapor phase characterization. *Atomization and Sprays*, 1:63–88.

[Dwyer et al., 2000] Dwyer, H., Stapf, P., and Maly, R. (2000). Unsteady vaporization and ignition of a three dimensional droplet array. *Comb. And Flame*, 121:181–194.

[Eckstein et al., 2003] Eckstein, J., Freitag, E., Hirsch, C., Sattelmayer, T., von der Bank, R., and Schilling, T. (2003). Forced low-frequency spray characteristics of a generic airblast swirl diffusion burner. In *ASME Turbo Expo 2003*. Atlanta, USA. GT-2003-38646.

[Einstein, 1940] Einstein, A. (1940). Science and Religion. *Nature*, 9(3706):605–607.

[Evesque et al., 2004] Evesque, S., Park, S., Riley, A., Annaswamy, A., and Dowling, A. (2004). Adaptive combustion instability control with saturation: theory and validation. *Journal of propulsion and power*, 20(6).

[Foucart, 2007] Foucart, S. (2007). Le réchauffement est dû aux activités humaines. LE MONDE.

[Frackowiak, 2007] Frackowiak, B. (2007). *Approche experimentale et simulation numerique des effets d'interactions entre gouttes en évaporation. DOC482*. PhD thesis, ENSAE-SUPAERO. (Clickable version).

[Frackowiak et al., 2005] Frackowiak, B., Strzelecki, A., and Lavergne, G. (2005). Tridimensional direct numerical simulation of droplet evaporation. In *2nd International Symposium on Non Equilibrium Processes, Combustion and Atmospheric Phenomenon*.

[Gajan and Giuliani, 2001] Gajan, P. and Giuliani, F. (2001). Caractérisation d'un système d'injection de turbomachine en régime pulsatoire forcé. *Rapport ONERA RF 3/06107 DMAE*.

[Gajan et al., 2007] Gajan, P., Strzelecki, A., Platet, B., Lecourt, R., and Giuliani, F. (2007). Experimental investigation of spray behavior downstream of an aeroengine injector with acoustic excitation. *Journal of Propulsion and Power*, 23(2):390–397.

[Garay et al., 2006] Garay, M., Kokanovic, S., Guidati, G., Torchalla, S., and Schuermans, B. (2006). Active control system for reduction of nox and pulsation levels in gas turbines. In *ASME Turbo Expo 2006: Power for Land, Sea and Air*. Barcelona, Spain. GT2006-90895.

[Gardiner Jr., 1981] Gardiner Jr., W.C., H. Y. T. T. (1981). Refractivity of combustion gases. *Combustion and Flame*, 40(C):213–219.

[Giuliani, 1997] Giuliani, F. (1997). Experimental study on rainbow interferometry using a pulse laser. Technical Report VKI SR 1997-14, von Karman Institute.

[Giuliani, 1998] Giuliani, F. (1998). Rainbow thermometry: droplet temperature measurement in a spray using a Nd:YAG laser. Technical Report VKI PR 98-11, von Karman Institute.

[Giuliani, 2002] Giuliani, F. (2002). *Analysis on the Behaviour of an Aeroengine Air-Blast Injection Device with Forced Entries*. PhD thesis, ENSAE No 346, Toulouse, France.

[Giuliani et al., 2004a] Giuliani, F., Becker, J., and Hassa, C. (2004a). Investigation of vapour phase, LOPOCOTEP deliverable 4.15. In *EU FP6 - GROWTH Project*. DLR-IB-325-04-04.

[Giuliani et al., 2004b] Giuliani, F., Berthoumieu, P., Becker, J., and Hassa, C. (2004b). The effect of ambient air pressure on planar liquid sheet disintegration at gas-turbine conditions. In *19th Annual Meeting of the Institute for Liquid Atomization and Spray Systems (ILASS Europe), Nottingham, UK*, pages 68–75.

[Giuliani et al., 2007a] Giuliani, F., Bhayaraju, U., and Hassa, C. (2007a). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine conditions using laser infra-red absorption. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 2008a] Giuliani, F., Bhayaraju, U., and Hassa, C. (2008a). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine combustor inlet conditions using laser infra-red absorption. In *32nd International Symposium on Combustion*. Montreal, Canada, The Combustion Institute.

[Giuliani et al., 1999] Giuliani, F., Corieri, P., Buchlin, J.-M., and Olivari, D. (1999). Influence du vent sur un toit de maison: Mesure expérimentale de coefficients de pression en soufflerie. Technical Report VKI EAR 9812, VKI-CSTC Contract Report 1999-25.

[Giuliani et al., 2000] Giuliani, F., Diers, O., Gajan, P., and Biscos, Y. (2000). Caractérisation d'un système d'injection de turbomachine en régime pulsatoire forcé. *Rapport ONERA RF 4/05103-01F DMAE*.

[Giuliani et al., 2002a] Giuliani, F., Diers, O., Gajan, P., and Ledoux, M. (2002a). Characterization of an air-blast injection device with forced periodic entries. In *Proceedings of the IUTAM Symposium on Turbulent Mixing and Combustion, Queen's University at Kingston, Canada, June 3-6, 2001 Pollard and Candel (eds) Kluwer Academic Publ.*, pages 327–336.

[Giuliani et al., 2002b] Giuliani, F., Gajan, P., Biscos, Y., and Diers, O. (2000-2002b). Caractérisation d'un système d'injection de turbomachine en régime pulsatoire forcé. Technical Report RF 4/05103-01F-DMAE, ONERA, PEA TITAN-DGA.

[Giuliani et al., 2001a] Giuliani, F., Gajan, P., Biscos, Y., Diers, O., and Ledoux, M. (2001a). Analyse de l'écoulement diphasique généré par un injecteur de type aérodynamique en régime pulsatoire forcé. *Recueil des actes du 9e congrès francophone de visualisation et de traitement d'images en mécanique des fluides, FLUVISU, Rouen, France*.

[Giuliani et al., 2005] Giuliani, F., Gajan, P., and Diers, O. (2005). A physical model on air-blast atomisation with modulated air inlet flow. In *Trends in Numerical and Physical Modeling for Industrial Multiphase Flows*. Cargèse, France.

[Giuliani et al., 2001b] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2001b). Analyse en moyenne de phase du champ de vitesse de l'air issu d'un injecteur aérodynamique en régime pulsatoire forcé. In *Recueil des actes du 15e Congrès Français de Mécanique*, Nancy, France.

[Giuliani et al., 2002c] Giuliani, F., Gajan, P., Diers, O., and Ledoux, M. (2002c). Influence of pulsed entries on a spray generated by an air-blast injection device - an experimental analysis on combustion instability processes in aeroengines. *Proceedings of the Combustion Institute*, 29(1):91–98.

[Giuliani and Hassa, 2003] Giuliani, F. and Hassa, C. (2003). Measurement of Prefilming Airblast Atomisation: Droplet Size Measurement. Internal report DLR-IB-325-11-03, Institute of Propulsion Technology, DLR Cologne, Germany.

[Giuliani and Hassa, 2009] Giuliani, F. and Hassa, C. (2009). Analysis of air-blasted kerosene vapour concentration at realistic gas turbine conditions, using pda and ira measurements. *Measurements in Fluids*. (in preparation).

[Giuliani and Hennig, 2010] Giuliani, F. and Hennig, C. (2010). Evaluation of active control strategies regarding airblast atomisation. In *23rd European Conference on Liquid Atomization and Spray Systems - ILASS*, Brno, Czech Republic. Submitted Jan. 10.

[Giuliani et al., 2009a] Giuliani, F., Hennig, C., Leitgeb, T., and Hassa, C. (2009a). Effect of the initial droplet size distribution of the liquid phase combined with transport phenomena on the resulting airblast spray in the far field. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-133.

[Giuliani and Köberl, 2009] Giuliani, F. and Köberl, S. (2009). Time- and space-resolved analysis of density fluctuations in a resonant air-methane flame. *Combustion and flame*. (Submitted, reviewed, under revision).

[Giuliani et al., 2009b] Giuliani, F., Lang, A., Irannezhad, M., and Grönstedt, T. (2009b). Effect of a controlled phase-shift on the outlet conditions of a set of pulse detonators. In *19th ISABE Conference*, Montreal, Canada. ISABE-2009-1315.

[Giuliani et al., 2007b] Giuliani, F., Lang, A., Leitgeb, T., , Woisetschläger, J., and Heitmeir, F. (2007b). Time-resolved analysis of density fluctuations in a resonant air-methane flame using dual laser vibrometry for gas turbine combustor qualification tests. In *Proc. of the 18th ISABE conference*. International Symposium on Air Breathing Engines, Beijing, China. ISABE-2007-1187.

[Giuliani et al., 2008b] Giuliani, F., Lang, A., Leitgeb, T., and Woisetschläger, J. (2008b). Phase-defined density fluctuation maps of a resonant air-methane premixed flame using laser vibrometry. In *32nd International Symposium on Combustion*. Montreal, Canada, The Combustion Institute.

[Giuliani et al., 2007c] Giuliani, F., Lang, A., Leitgeb, T., Woisetschläger, J., and Heitmeir, F. (2007c). Using dual laser vibrometry to monitor the stability of gas turbine combustion. In *Proc. of the 3rd ECM*. European Combustion Meeting, Chania, Greece, The Combustion Institute.

[Giuliani et al., 2010] Giuliani, F., Leitgeb, T., Lang, A., and Woisetschläger, J. (2010). Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry. *Journal of Engineering for Gas Turbines and Power*, 132. GTP-031603.

[Giuliani et al., 2007d] Giuliani, F., Schricker, A., Lang, A., Leitgeb, T., and Heitmeir, F. (2007d). High-temperature resistant pressure transducer for monitoring of gas turbine combustion stability. In *Proc. of the 18th ISABE conference*. International Symposium on Air Breathing Engines, Beijing, China. ISABE-2007-1111.

[Giuliani et al., 1998] Giuliani, F., van Beeck, J., and Riethmuller, M. (1998). Thermométrie par arc-en-ciel: technique d'acquisition de donnée à l'aide d'un laser Nd:YAG et traitement de signaux 2D. In *Recueil des actes du 6e Congrès Francophone de Vélocimétrie Laser*, pages B.3.1 – B.3.7, Saint-Louis, France. Association francophone de vélocimètrie laser.

[Giuliani et al., 2006] Giuliani, F., Wagner, B., Woisetschläger, J., and Heitmeir, F. (2006). Laser vibrometry for real-time combustion stability diagnostic. In *ASME Turbo Expo 2006: Power for Land, Sea and Air*. Barcelona, Spain. GT2006-90413.

[Grönstedt et al., 2008] Grönstedt, T., Lei, X., Giuliani, F., and Köberl, S. (2008). WP2.3 - 2.3.2. Variable core cycle. Technical Report CHALMERS-DEL-2.3.2.A, EU IP NEWAC - FP6-030876.

[Grönstedt et al., 2009] Grönstedt, T., Lei, X., Leitgeb, T., and Giuliani, F. (2009). WP2.3 - 2.3.2. Final Assessments for Variable Core Cycle. Technical Report CHALMERS-DEL-2.3.2.B, EU IP NEWAC - FP6-030876.

[Hampel and Woisetschläger, 2006] Hampel, B. and Woisetschläger, J. (2006). Frequency- and space-resolved measurement of local density fluctuations in air by laser vibrometry. *Measurement Science & Technology*, 17(10):2835–2842.

[Hennig et al., 2009] Hennig, C., Giuliani, F., Freitag, S., and Hassa, C. (2009). Image particle sizing of an air blasted liquid sheet of kerosene at intermediate pressure. In *11th International Conference on Liquid Atomization and Spray Systems (ICLASS)*, Vail, Colorado, USA. ICLASS2009-093.

[Hermann, 2001] Hermann, J. (2001). Application of active instability control to heavy duty gas turbines. In *Active control of engine dynamics*. RTO AVT - VKI Special Course.

[Hirschberg and Rienstra, 1994] Hirschberg, A. and Rienstra, S. (1994). Elements of aeroacoustics. *Lecture Series notes LS 94-04, Von Karman Institute, Belgium*.

[Hoffert, 2002] Hoffert, M. J. (2002). Advanced technology paths to global climate stability: Energy for a greenhouse planet. *Sci. Mag.*, 238:981–986.

[Hong, 2003] Hong, M. (2003). Atomisation et mélange dans les jets coaxiaux liquide-gaz. *PhD Thesis INPG-LEGI Grenoble*.

[http://unfccc.int, 2005] http://unfccc.int (2005). Kyoto Protocol, full text of the convention. Search term Kyoto Protocol, URL valid in June 2006.

[Jennings and Drallmeyer, 1996] Jennings, P. and Drallmeyer, J. (1996). Pulsed fuel spray vapor phase characterization. *Atomization and Sprays*, 6:537–562.

[Jeong and Hussain, 1995] Jeong, J. and Hussain, F. (1995). On the identification of a vortex. *Journal of Fluid Mechanics*, 285:69–94.

[Jericha et al., 2004] Jericha, H., Gottlich, E., Sanz, W., and Heitmeir, F. (2004). Design optimization of the graz cycle prototype plant. *Journal of Engineering for Gas Turbines and Power*, 126(4):733–740.

[Kawanabe et al., 2000] Kawanabe, H., Kawasaki, K., and Shioji, M. (2000). Gas-flow measurements in a jet flame using cross-correlation of high-speed-particle images. *Meas. Sci. Technol.*, 11:627–632.

[Köberl, 2008] Köberl, S. (2008). Variable Core Geometrien - Literaturrecherche, Auswertung und Vergleich der Strategien. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften.

[Köberl et al., 2010] Köberl, S., Fontaneto, F., Giuliani, F., and Woisetschläger, J. (2010). Frequency resolved interferometric measurement of local density fluctuations for turbulent combustion analysis. *Measurement Science and Technology*. Submitted Sept. 2009.

[Köberl et al., 2009] Köberl, S., Giuliani, F., and Woisetschläger, J. (2009). Energy spectra measurements for the density fluctuation in a jet flame using dual laser vibrometry. In *Proc. of the 4th ECM*. European Combustion Meeting, Vienna, Austria, The Combustion Institute.

[Kjärstad and Johnsson, 2008] Kjärstad, J. and Johnsson, F. (2008). Resources and future supply of oil. *Energy Policy*, In Press, Corrected Proof:–.

[Kurzke, 2006] Kurzke, J. (2006). *GasTurb 11: Design and Off-Design Performance of Gas Turbines*. www.gasturb.de.

[Lang, 2007] Lang, A. (2007). Konstruktion eines Brennkammer-Prüfstandes und Messungen unter mittlerem Druck. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften. Clickable version.

[Lang et al., 2010] Lang, A., Lecourt, R., and Giuliani, F. (2010). Statistical evaluation of ignition phenomena in turbojet engines. In *ASME Turbo Expo 2010: Power for Land, Sea and Air*, number GT2010-23229, Glasgow, UK. Submitted Nov.09.

[Lang et al., 2008] Lang, A., Leitgeb, T., Woisetschläger, J., Strzelecki, A., Gajan, P., and Giuliani, F. (2008). Analysis of a pulsed flame at intermediate pressure. In *ISFV13 - 13th International Symposium on Flow Visualization / FLUVISU12 - 12th French Congress on Visualization in Fluid Mechanics*, Nice, France.

[Lechner, 2008] Lechner, A. (2008). Management der instationären Verbrennung in Gasturbinen. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften.

[Lefebvre, 1989a] Lefebvre, A. (1989a). *Atomization and Sprays*. Taylor & Francis Group.

[Lefebvre, 1989b] Lefebvre, A. (1989b). Drop evaporation - influence of evaporation on drop size distribution. In *Atomization and Sprays*. Hemisphere Publishing Corporation.

[Lefebvre, 1999a] Lefebvre, A. (1999a). *Gas Turbine Combustion, Second Edition*. Taylor & Francis Group.

[Lefebvre, 1999b] Lefebvre, A. H. (1999b). Gas turbine combustion - 2nd edition. *Taylor & Francis Groupe*.

[Leitgeb, 2007] Leitgeb, T. (2007). Brennkammerprüfstand: Anbindung eines Lufterhitzers und Monitoring der Betriebsdaten. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften. Clickable version.

[Leitgeb et al., 2009a] Leitgeb, T., Giuliani, F., and Heitmeir, F. (2009a). Design and adaptation of a versatile test facility for turbines and combustion chambers. In *Proceedings of the 8th European Turbomachinery Conference*. Graz, Austria.

[Leitgeb et al., 2009b] Leitgeb, T., Giuliani, F., and Niederhammer, A. (2009b). Computer aided dimensioning and validation of a versatile test facility for combustion chambers and turbines. In *ASME Turbo Expo, Gas Turbine Technical Congress & Exposition*, Orlando, FL USA. GT2009-59592.

[Lundbladh and Avellán, 2007] Lundbladh, A. and Avellán, R. (2007). Potential of variable cycle engines for subsonic air transport. In *XIIX ISABE Conference*, Beijing, China.

[Macquisten et al., 2006] Macquisten, M., Moran, A., and Rupp, J. (2006). Passive damper LP tests for controlling combustion instability. In *ASME Turbo Expo 2006: Power for Land, Sea and Air*. Barcelona, Spain. GT2006-90874.

[Mailer, 1970] Mailer, N. (1970). *Of a fire on the Moon*. Little, Brown and Company.

[Marmottant and Villermaux, 2004] Marmottant, P. and Villermaux, E. (2004). On spray formation. *J. Fluid Mech.*, 498:73–111.

[Marn, 2004] Marn, A. (2004). Brennkammerversuche für Flugantriebe-Prüfstandaufbau und Versuchsdurchführung unter besonderer Berücksichtigung der konstruktiven Anforderungen. Diplomarbeit, Institut für thermische Turbomaschinen und Maschinendynamik, TU Graz.

[Mayrhofer and Woisetschläger, 2001] Mayrhofer, N. and Woisetschläger, J. (2001). Frequency analysis of turbulent compressible flows by laser vibrometry. *Experiments in Fluids*, 31:153–161.

[Metz et al., 2007] Metz, B., Davidson, O., Bosch, P., Dave, R., and Meyer, L. (2007). Climate change 2007: Mitigation. contribution of working group iii to the fourth assessment report. Technical report, IPCC, 2007: Intergovernmental Panel on Climate Change.

[Müller et al., 2006] Müller, A., Koch, R., Bauer, H., Hehle, M., and Schäfer, O. (2006). Performance of prefilming airblast atomisers in unsteady flow conditions. In *ASME Turbo Expo 2006: Power for Land, Sea and Air*. Barcelona, Spain. GT2006-90432.

[Moesl et al., 2009] Moesl, K. G., Vollmer, K. G., Sattelmayer, T., Eckstein, J., and Kopecek, H. (2009). Experimental study on laser-induced ignition of swirl-stabilized kerosene flames. *Journal of Engineering for Gas Turbines and Power*, 131(021501).

[Moses and Roets, 2008] Moses, C. A. and Roets, P. N. J. (2008). Properties, characteristics and combustion performance of sasol fully synthetic jet fuel. In *Proceedings of ASME Turbo Expo 2008: Power for Land, Sea and Air*. GT2008-50545.

[Niazmand et al., 1994] Niazmand, H., Shaw, B., Dwyer, H. A., and Aharon, I. (1994). Effects of marangoni convection on transient droplet evaporation. *Comb. Sci. and Tech.*, 103:219–233.

[Niederhammer, 2009] Niederhammer, A. (2009). Aufbau und inbetriebnahme des luftsystems für einen brennkammerprüfstand. Master's thesis, TU Graz.

[Pachauri and Reisinger, 2007] Pachauri, R. and Reisinger, A. (2007). Climate change 2007: Synthesis report. contribution of working groups i, ii and iii to the fourth assessment. Technical report, Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland.

[Panda and McLaughlin, 1990] Panda, J. and McLaughlin, K. (1990). Experiments on the instabilities in a free swirling jet. In *28th Aerospace Sciences Meeting*. AIAA 1990-0506.

[Perz, 2008] Perz, E. (2008). *IPSEpro Overview*. SimTech Simulation Technology. http://www.simtechnology.com/.

[Pilch and Erdman, 1987] Pilch, M. and Erdman, C. (1987). Use of the breakup time data and velocity history data to predict the maximum size of stable fragments for acceleration induced breakup of a liquid drop. *Int. J. Multiphase Flow*, 13:741–757.

[Poinsot and Veynante, 2005] Poinsot, T. and Veynante, D. (2005). *Theoretical and Numerical Combustion*, pages 413–430. Edwards, 2d edition.

[Putnam et al., 1986] Putnam, A., Belles, F., and Kentfield, J. (1986). Pulse combustion. *Prog. Energy Combust. Sci.*, 12:43–79.

[Putnam and Dennis, 1953] Putnam, A. and Dennis, W. (1953). A study of burner oscillations of the organ-pipe type. *Trans. ASME*, 75(1):15–28.

[Rachner, 1998] Rachner, M. (1998). Die Stoffeigenschaften von Kerosin Jet A-1. Technical Report ISRN DLR-Mitt.–98-01, ISSN 1434-8462, Institute of Propulsion Technology, DLR Cologne, Germany.

[Rayleigh, 1875] Rayleigh, J. (1875). *The Theory of Sound*, volume 2. Dover, N.Y.C. (2d edition 1945).

[Reynst and Thring, 1961] Reynst, F. and Thring, M. (1961). *The pulsating combustion of pulverized coal*, pages 13–30. Pergamon.

[Roth et al., 1988] Roth, N., Anders, K., and Frohn, A. (1988). Simultaneous measurement of temperature and size of droplets in the micrometer range. In *7th International Congress on Optical Methods in Flow and Particle Diagnostics ICALEO 88*, volume 67, pages 294–304, L.I.A.,Sunnyvale, USA.

[Roth et al., 1989] Roth, N., Anders, K., and Frohn, A. (1989). Mutual interaction between burning aerosol droplets in the micrometer range. *Journal of Aerosol Sciences*, 20(8):991–994.

[Roth et al., 1991] Roth, N., Anders, K., and Frohn, A. (1991). Refractive-index measurements for the correction of particle sizing methods. *Applied Optics*, 30(33):4960–4965.

[Rousseau, 1778] Rousseau, J.-J. (1778). *Promenade d'un rêveur solitaire (Reveries of a Solitary Walker)*. Gallimard.

[Roux et al., 2005] Roux, S., Lartigue, G., Poinsot, T., Meier, U., and Berat, C. (2005). Studies of mean and unsteady flow in a swirled combustor using experiments, acoustic analysis, and large eddy simulations. *Combustion and Flame*, 141(1-2):40 – 54. Large eddy simulation (LES);Exhaust chambers;Processing vortex core (PVC);Acoustic modes;.

[Schennach, 2004] Schennach, O. (2004). Konstruktion und Auslegung eines Brennkammerprüfstandes. Diplomarbeit, Institut für thermische Turbomaschinen und Maschinendynamik, TU Graz.

[Smith et al., 1991] Smith, C. E., Talpallikar, M. V., and Holdeman, J. D. (1991). A cfd study of jet mixing in reduced flow areas for lower combustor emissions. In *Joint Propulsion Conference*. AIAA 91-2460.

[Spalding, 1951] Spalding, D. (1951). Combustion of fuel particles. *Fuel*, 30(121).

[Steele et al., 2000] Steele, R., L.H., C., Cannon, S., and Smith, C. (2000). Passive control of combustion instability in lean premixed combustors. *Journal of Engineering for Gas Turbines and Power*, 122(3):412–419.

[Swithenbank et al., 1976] Swithenbank, J., Beer, J., Taylor, D., Abbot, D., and McCreath., G. (1976). A laser diagnostic technique for the measurement of droplet and particle size distribution. In *14th Aerospace Sciences Meeting*. Washington, D.C., USA. AIAA 1976-69.

[Tishkoff et al., 1980] Tishkoff, J., Hammond, D., and Chraplyvy, A. (1980). Diagnostic measurements of fuel spray dispersion. *ASME publication 80-WA/HT-35*.

[Trontin et al., 2008] Trontin, P., Vincent, S., Estivalezes, J.-L., and Caltagirone, J.-P. (2008). Detailed comparisons of front-capturing methods for turbulent two-phase flow simulations. *International Journal for Numerical Methods in Fluids*, 56(8):1543–1549.

[van Beeck, 1997] van Beeck, J. (1997). *Rainbow phenomena: development of a laser based non-intrusive technique for measuring droplet size, temperature and velocity*. PhD thesis, Eindhoven University of Technology.

[van Beeck et al., 1999] van Beeck, J., Giannoulis, D., Zimmer, L., and Riethmuller, M. (1999). Global rainbow thermometry for droplet-temperature measurement. *Optics letters*, 24(23):1696–1698.

[Van Beeck et al., 1999] Van Beeck, J., Giuliani, F., and Riethmuller, M. (1999). Rainbow interferometry: principles & developments. In *Optical Diagnostics of Particles and Droplets*, volume VKI LS 1999-01, Rhode-St-Genèse, Belgium. von Karman Institute. VKI RP 1999-27.

[Vetrano et al., 2006] Vetrano, M., Gauthier, S., van Beeck, J., Boulet, P., and Buchlin, J. (2006). Characterisation of a non-isothermal water spray by global rainbow thermometry. *Experiments in fluids*, 40:15–22.

[Wagner, 2005] Wagner, B. (2005). Anpassung von Messmethoden an die stationäre und instationäre Verbrennung. Master's thesis, TU Graz, Fakultät für Maschinenbau und Wirtschaftswissenschaften. Clickable version.

[Walsh and Fletcher, 2004] Walsh, P. and Fletcher, P. (2004). *Gas Turbine Performance*. Blackwell Publishing. Second edition.

[Wilms, 2005] Wilms, J. (2005). *Evaporation of multicomponent droplets*. PhD thesis, Institut für Thermodynamik der Luft- und Raumfahrt der Technische Universität Stuttgart.

[Wintenberger, 2004] Wintenberger, E. (2004). *Application of Steady and Unsteady Detonation Waves to Propulsion*. PhD thesis, California Institute of Technology.

[Woisetschläger and Giuliani, 2006] Woisetschläger, J. and Giuliani, F. (2006). Experimental investigation of flame-flame interaction in gas-turbine model combustors with forced flow instabilities. P19955 Flammenwechselwirkung in einer Gasturbinenbrennkammer. FWF project with peer-review process. F Giuliani co-supervisor.

[Yang, 2001] Yang, V. (2001). Stability characteristics and control approaches. In *Active control of Engine Dynamics*. RTO AVT - VKI Special Course, Brussels, Belgium.

[Yu et al., 1991] Yu, K. H., Trouve, A., and Daily, J. W. (1991). Low-frequency pressure oscillations in a model ramjet combustor. *Journal of Fluid Mechanics*, 232:47–72.

[Zheng et al., 2008] Zheng, F., Ordon, R., Scharton, T., Kuznetsof, A., and Roberts, W. (2008). A new acoustic model for valveless pulsejets and its application to optimisation of thrust. *Journal of Engineering for Gas Turbines and Power*, 130(4). Trans. ASME 041501.