# INVESTIGATION OF THE STATIC ELECTRIFICATION PHENOMENON IN POWER TRANSFORMERS WITH THE STREAMING MODEL TEST SETUP

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**Abstract**: Several insulation damages of large high voltage power transformers in the past were attributed to static electrification. Since the first failures occurred lots of investigations were done. Most of the research concentrated on the conventionally for insulation in power transformers used mineral oil-cellulose couple. The goal of the presented research activity is the investigation of the electrostatic charging behaviour of not so well studied liquid-solid couples, which are also used in transformers for insulation. This paper presents the streaming model test setup which was built up for the simulation and the measurement of the static electrification phenomenon in power transformers. Additionally first results are shown concerning the electrostatic charging behaviour of mineral oil-aramid in comparison to that of mineral oil-cellulose as a function of flow velocity and system temperature. For both investigated liquid-solid couples electrostatic charging tendency increased with rising flow velocity and reached highest values for a combination of high temperature and high flow velocity. The mineral oil-cellulose couple showed higher charging than the mineral oil-aramid couple which is linked to the higher surface roughness of the investigated cellulose.

## 1 INTRODUCTION

High voltage power transformers play a key role in electrical energy distribution. The applied insulation systems have to meet high demands to ensure a secure operation. High voltage power transformers are usually equipped with a mineral oil-cellulose insulation system. Beside its insulating function, the oil also serves as a coolant, which is used to convey heat out of the winding system. For this purpose usually forced oil circulation is installed. The forced oil flow through the cellulose cooling channels in a power transformer results in electrostatic charging between the oil and the cellulose. Charge separation occurs: charges of one polarity are conveyed by the liquid flow and charges of the other polarity remain in the solid and are accumulated [1]. This phenomenon can lead to electrical discharges and result in an outage of a large power transformer. In the past several insulation damages in large high voltage power transformers were attributed to the static electrification phenomenon, see [2, 3]. Damages on power transformers occurred first in Japan in the 70ies of the last century. Most failures were reported in the United States [3]. Since the first incidents occurred, a lot of investigations were done on the static electrification phenomenon in transformers. The main goals of these research activities were to investigate the influence of various parameters, to evaluate the risk of an electrostatic hazard (e.g. [1]) and to find possibilities to decrease the amount of electrostatic charging (e.g. [4]). Most of the research activities concerning static electrification in power transformers concentrated on the conventionally applied insulation system of a power transformer consisting of mineral oil and cellulose. Within a running project at the Institute of High Voltage Engineering and System Management at Graz University of Technology the electrostatic charging behaviour of not so well studied liquid-solid couples should be researched and compared with the mineral oil-cellulose couple. For this purpose a test setup for the simulation and the measurement of the static electrification phenomenon taking place in a cooling channel of a power transformer was built up. In this paper the test setup, named streaming model test setup, is described. Furthermore results of first measurements are shown. Within these first measurements the electrostatic charging behaviour between mineral oil and cellulose was measured as a function of the flow velocity and the system temperature. The same investigations were done for the not so well studied mineral oil-aramid couple. The charging behaviour of the mineral oil-cellulose couple and the mineral oil- aramid couple as a function of flow velocity and system temperature are described and also compared. In this way the impact of the three parameters solid material, flow velocity and system temperature for the same type of mineral oil on the static electrification phenomenon is presented. The obtained results are also compared with the findings and conclusions documented in literature to demonstrate the functionality of the new built test arrangement.

# 2 EXPERIMENTAL INVESTIGATIONS

## 2.1 Streaming Model Test Setup

In the nineties of the last century intensive research has been done on static electrification in power transformers at the Institute of High Voltage Engineering and System Management at the University of Technology in Graz using a test setup with a duct model, see [5]. The streaming model test setup was built following this prior setup and includes improvements in construction and in the measuring system. In the following section an overview of the structure and the function of the streaming model test setup are given. A detailed description of the test setup can be found in [6].

A sketch of the streaming model test setup is shown in Figure 1. The test setup represents a closed metal loop, where the oil under investigation circulates. The main parts of this setup are the streaming model, a flow smoothing duct, two charge relaxation tanks, a main oil vessel, a heating and cooling system, a gear pump and the measuring system. For the tests it is possible to adjust the system temperature, the moisture of the oil and the flow velocity of the oil in the model. In this way different conditions can be simulated.

The streaming model simulates a cooling channel in a power transformer. It is made out of the solid material under investigation. In the tests presented in this paper models made out of pressboard and aramid were investigated. The streaming model has a rectangular cross section. The electrification process in a cooling channel is replicated by the oil flow through the model. A sketch of the model is shown in Figure 2.

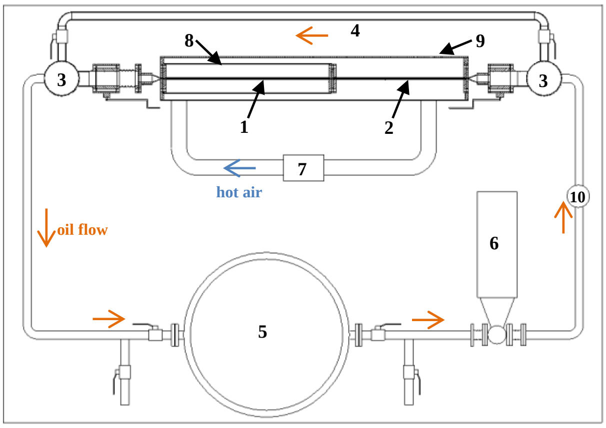

**Figure 1:** Streaming model test setup [6]
1: streaming model; 2: flow smoothing duct; 3: charge relaxation tank; 4: bypass; 5: oil vessel; 6: gear pump; 7: circulating air heating; 8: shielding covering; 9: thermally insulated covering; 10: flow meter

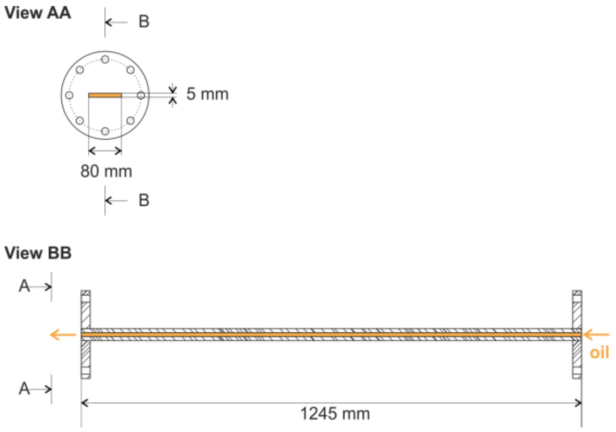

**Figure 2:** Streaming model [6]

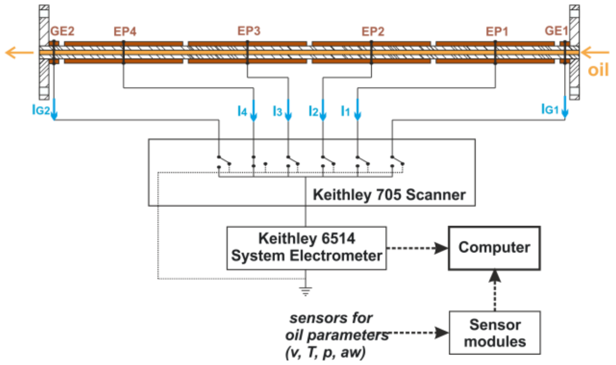

**Figure 3:** Measuring system [6]
EP: electrode pair; GE: guard electrode
$I_1$ – $I_4$: leakage currents from electrode pairs
$I_{G1}$, $I_{G2}$: leakage currents from guard electrodes

The oil has to pass through a flow smoothing duct, before it gets into the model. This duct has the same cross section as the streaming model and serves as a run-up distance. It is needed to create a stationary flow profile before the oil enters the model. Additionally the oil has to pass through two charge relaxation tanks. One charge relaxation tank is placed before and the other one after the streaming model. Inside these tanks charges in the oil can relax. The main oil vessel serves as a storage tank. The heating and the cooling system for the oil are integrated in this vessel. Before and during tests made at higher temperatures the streaming model is also heated up by an air heating system. A speed controlled gear pump makes it possible to regulate the flow velocity inside the streaming model. The oil flow through the streaming model causes electrostatic charging. To evaluate the ECT (electrostatic charging tendency) leakage currents are measured that are flowing via electrodes to the earth. For this purpose four plate electrodes are mounted along the outer surface of each of the two broad sides of the model. Facing electrodes are connected electrically to each other and constitute in total four electrode pairs. Moreover there are guard electrodes fixed on the inlet and the outlet of the duct around the outer surface, see Figure 3. They have the task to prevent an impact on the plate electrodes by surface currents. The measuring system records during an experiment continuously the leakage currents of the six electrodes and the oil parameters (moisture, temperature, flow velocity and pressure). The model is surrounded by a shielding covering to prevent measuring errors because of noise fields, see Figure 1.

## 2.2 Investigated Parameters

In the tests presented in this paper the impact of the following three parameters on the static electrification phenomenon was investigated:

- the material of the solid
- the flow velocity of the oil in the model
- the system temperature

Tests were done with streaming models made out of two different solid materials. The tested solids were aramid and pressboard. The studied aramid was Nomex® 994 and the examined pressboard was Transformerboard type B 3.1A. Figure 4 and Figure 5 show microscope images with a magnification of four times of the surface of the two investigated solid materials. In Figure 4 the mesh structure on the surface of Transformerboard B 3.1A can be seen clearly.

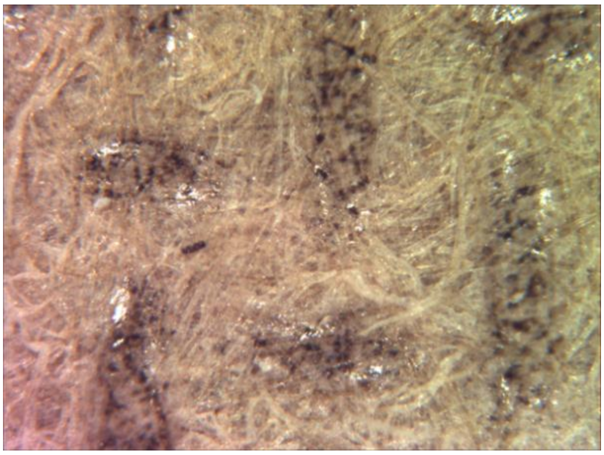

**Figure 4:** Surface of Transformerboard B 3.1A

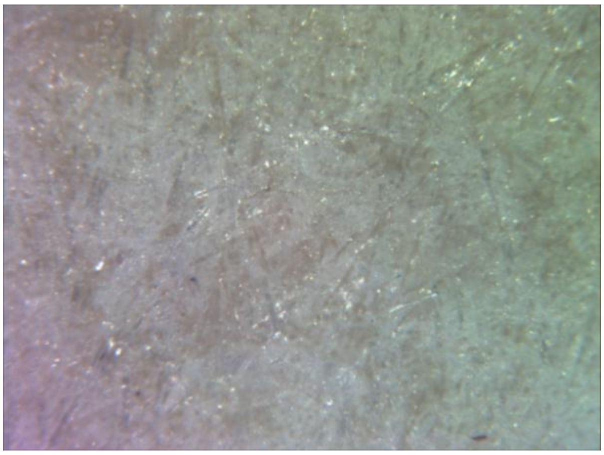

**Figure 5:** Surface of Nomex® 994

The dark brown areas are indentations, which give the surface a high roughness of about 100 microns. The surface of the model made out of Nomex® 994 was grinded off so that the surface was smooth. This can be seen in Figure 5. For the tests four flow velocities were adjusted in the model: 0.5 m/s, 1 m/s, 2 m/s and 4 m/s. The investigated system temperatures have been 20 °C and 60 °C. For the tests always the same type of mineral oil was used.

## 2.3 Test Procedure

Before a test the oil in the test setup and the streaming model had to be prepared. The tested oil was filtered, degassed and dried by an oil treating machine. This machine was connected directly to the streaming model test setup by the connections at the left and at the right side of the main oil vessel, see Figure 1. The streaming model was dried and impregnated.

During a test the four flow velocities under interest were set and measured in ascending order: 0.5 m/s – 1 m/s – 2 m/s – 4 m/s. At the end of the test the lowest flow velocity was repeated to check if the conditions were the same at the end of the test as they have been at the beginning. There was always a break maintained between the measurement of two different flow velocities. During this break the oil circulated in the closed metal circuit over a bypass, which is installed in parallel to the model and the flow smoothing duct, see Figure 1. During this break charges in the oil had time to relax. The typical result of the measured leakage current at the second electrode pair during a test is shown in Figure 6. The described test procedure was performed at a system temperature of 20 °C and 60 °C. Tests at both temperature levels were done for the model made out of Transformerboard B 3.1A and for the model made out of Nomex® 994. For the evaluation of the electrostatic charging tendency the steady state leakage current measured at the second electrode pair was determined.

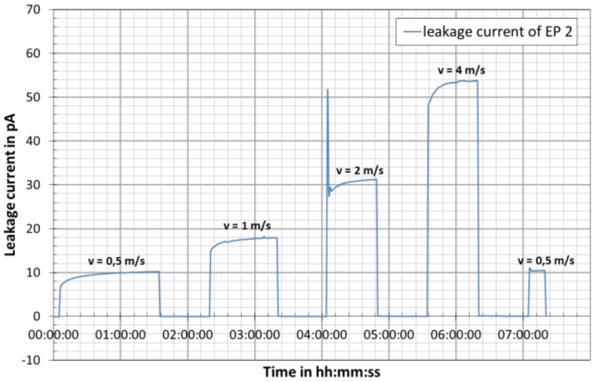

**Figure 6:** Typical evaluation of the measured leakage current at the second electrode pair [6]

After every test an oil sample was taken and the oil parameters breakdown voltage, dissipation factor, relative permittivity, resistivity and moisture content were determined. [6]

## 3 RESULTS AND DISCUSSION

### 3.1 Impact of flow velocity and system temperature

Figure 7 and Figure 8 show the steady state leakage current at the second electrode pair versus flow velocity for the two temperatures 20 °C and 60 °C. In Figure 7 the results of the measurements with a streaming model made out of Transformerboad B 3.1A are presented. Figure 8 shows the results for Nomex® 994. Because of a polarity change of the leakage current at 60 °C, Figure 8 shows the absolute values.

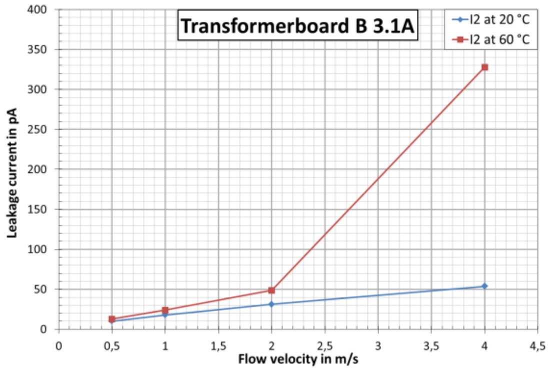

**Figure 7:** Steady state leakage current $I_2$ versus flow velocity for 20 °C and 60 °C measured at Transformerboard B 3.1A [6]

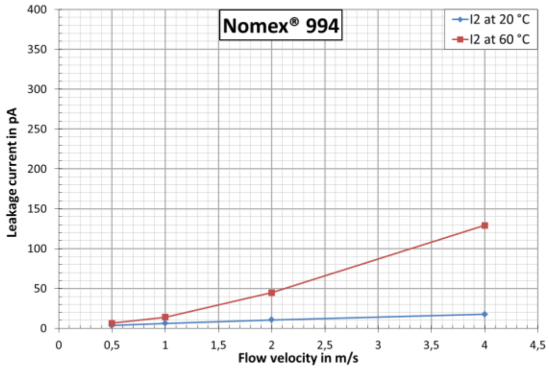

**Figure 8:** Steady state leakage current $I_2$ versus flow velocity for 20 °C and 60 °C measured at Nomex ® 994 (absolute values)

The behaviour of the leakage current as a function of flow velocity and temperature was the same for the two investigated solid materials:

The leakage currents increased with rising flow velocity. For the investigated temperature range there was marginal temperature dependence in the magnitude of the leakage currents at low flow velocities (0.5 m/s, 1 m/s). At higher flow velocities (2 m/s, 4 m/s) the leakage currents increased obviously for higher temperature. This increase can be explained by the change of the flow condition from laminar to turbulent flow. More information about that can be found in [6]. The measured behaviour is in good accordance with the behaviour described in literature [7].

### 3.2 Impact of solid material

In Figure 9 the steady state leakage current measured at Transformerboard B 3.1A and at Nomex® 994 is compared for different flow velocities at 20 °C. In Figure 10 the same comparison is made for 60 °C. The diagrams show, that for all investigated flow velocities and system temperatures Transformerboard B 3.1A showed a higher electrostatic charging tendency than Nomex® 994. This behaviour is also documented in [5] and can be related to the higher surface roughness of Transformerboard B 3.1A. At 20 °C the leakage currents were about 3 times higher for Transformerboard B 3.1A. At 60 °C the leakage currents were up to 2.5 times higher for Transformerboard B 3.1A.

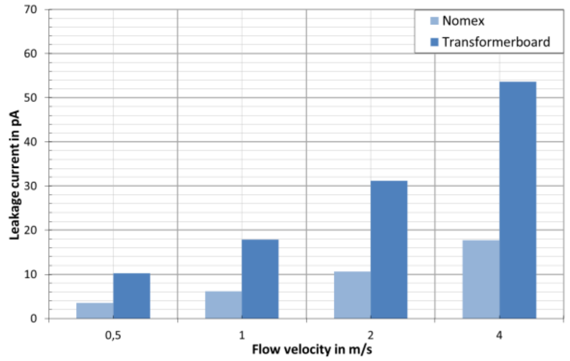

**Figure 9:** Comparison of the leakage current $I_2$ measured at Transformerboard B 3.1A and Nomex® 994 for different flow velocities at 20 °C

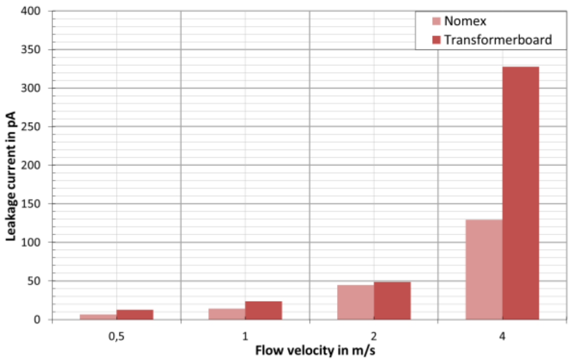

**Figure 10:** Comparison of the leakage current $I_2$ measured at Transformerboard B 3.1A and Nomex® 994 for different flow velocities at 60 °C (absolute values)

### 3.3 Oil parameters

Table 1 and Table 2 contain the results from the measurements of the oil samples taken after the experiments. The breakdown voltage was measured corresponding to IEC 60156. The dissipation factor, the relative permittivity and the resistivity were determined corresponding to IEC 60247. The water content was measured with Karl Fischer titration. The values in the tables show that the oil parameters didn't differ obviously for the compared measurements.

**Table 1:** Oil parameters for the tests with Transformerboard B 3.1A

| Oil parameter | 20 °C | 60 °C |
|---|---|---|
| Breakdown voltage (kV) | 94,4 | 79,5 |
| Resistivity at 90°C ($10^9$ Ωm) | 585 | 627 |
| Dissipation factor at 90°C | 0,00078 | 0,0007 |
| Relative permittivity at 90°C | 2,1 | 2,1 |
| Water content (ppm) | 2,4 | 3,5 |

**Table 2:** Oil parameters for the tests with Nomex® 994

| Oil parameter | 20 °C | 60 °C |
|---|---|---|
| Breakdown voltage (kV) | 84,6 | 85,5 |
| Resistivity at 90°C ($10^9$ Ωm) | 665 | 649 |
| Dissipation factor at 90°C | 0,0005 | 0,0007 |
| Relative permittivity at 90°C | 2,1 | 2,1 |
| Water content (ppm) | 2,1 | 2,6 |

## 4 CONCLUSION AND OUTLOOK

This paper presents the streaming model test setup that was built at Graz University of Technology for the simulation and the measurement of the static electrification phenomenon, which takes place in the cooling channels of a power transformer. Additionally results of first measurements are shown. The investigations concentrated on the impact of the solid material, the temperature of the system and the flow velocity on the electrostatic charging tendency. The measurements showed that electrostatic charging increases with increasing flow velocity. A combination of high temperature and high flow velocity generates the highest charging values. Additionally two solid materials, Transformerboard B 3.1A (pressboard) and Nomex® 994 (aramid), in combination with the same mineral oil were compared concerning their charging behaviour. The measurements showed higher charging for Transformerboard B 3.1A for the temperatures 20 °C and 60 °C and for the flow velocity range of 0.5 m/s – 4 m/s. This behaviour is linked to the higher surface roughness of Transformerboard B 3.1 A. The results are in good accordance with the behaviour described in literature. This shows the functionality of the new built test setup. In future works the investigation of the charging behaviour of further liquid-solid couples, which are used in transformers but not so well studied, is considered. An actual topic is the replacement of the conventionally used mineral oil by alternative, biodegradable fluids [8]. The investigation of these fluids in combination with pressboard and aramid are future research objectives.

## 5 ACKNOWLEDGMENTS

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