Elecrical Conduction Phenomena through impregnated pressboard submitted to a thermal gradient

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ABSTRACT

For the last twenty years, flow electrification has been suspected to be responsible of failures in high power transformers.
In order to understand the phenomenon and to avoid incidents, several research programs have been undertaken in different countries. Our laboratory is involved in one of this program in collaboration with the French Electricity Company (E.D.F.).
From this research in terms of velocity, pipe geometry, temperature and moisture content it seems that the transverse thermal gradient play a fundamental role in the process.

INTRODUCTION : THE CHARGE TRANSFER AT SOLID-LIQUID INTERFACE

Electrical insulation in a high power transformer is obtained with pressboard and oil. The oil flows inside the transformer as it is also used as a cooler of the system.
Like with other liquid-solid interfaces, at the oil-pressboard interface it exists a preferential adsorption of negative ions coming from the oil (impurities) into the pressboard. This leads to a space charge in the oil and in the pressboard Moreau (1). Under the effects of diffusion, electric forces and convection the space charge organises itself in a distribution called electrical double layer.
When the oil is in motion viscous forces induce a continuous removing of the space charge existing near the wall in the double layer. These charges are transported by the oil flow. Consequently, at the interface the equilibrium of electrical species is modified and new ions are created to restore those convected. As a result a current (wall current) takes place from the interface to the earth. This process in the literature is usually called flow electrification.
The creation of new ions is determined by an electrochemical phenomena taking place at the interface. This reaction is rather unknown and gives rise to many assumptions and models. ie : Walmsley (2), Touchard (3).

As the liquid and pressboard are highly resistive it may appear an accumulation of charges in some places of the transformer. This space charge may be so high to produce dielectric breakdown of the oil or of the pressboard.

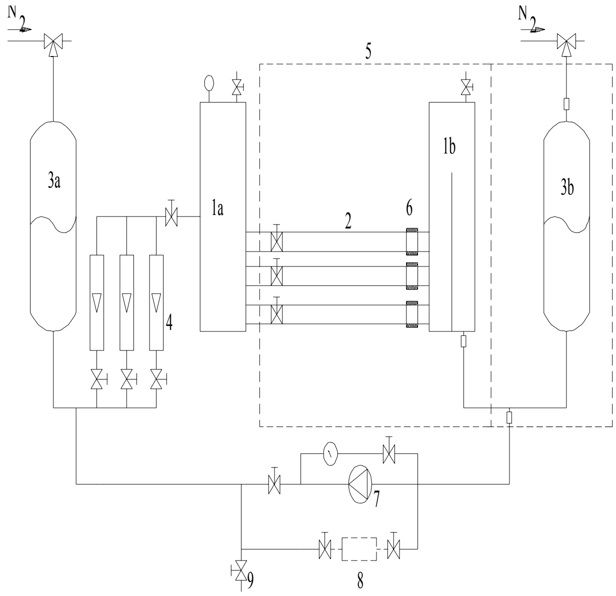
Many failures have occurred when a transformer initially cold is energised. This seems to indicate that a crucial phenomena takes place when there is an important thermal gradient through the pressboard which exists between the windings and the oil.
This paper relates a recent experimental study we have undertaken in our laboratory to obtain more information in order to better analyse this transient state.

EXPERIMENTAL STUDY

We describe here two different group of experiments. The first group deals with the wall current response of a pressboard duct submitted to a heat transfer step produced from the outer side of the duct. In the second one the top and the bottom of a stack of oil-impregnated pressboard is submitted to a voltage and temperature difference. Inserted electrodes enable to measure the voltage and capacitance at different levels of the stack.

Experimental Arrangement For Experiment n°1

This experimental arrangement enables to simulate the oil path in a transformer.
It consists in a loop where the oil passes through pressboard ducts and through grounded metallic pipes and reservoirs.
A general diagram of the equipment is given in figure 1. From the reservoir (1a) oil flows through pressboard ducts placed in the stainless steel channels (2). Then, the oil enters in reservoir (1b) and gets back to the pump (7) that enables to a adjust the flowrate. This last reservoir (1b) is electrically insulated from the rest of the circuit and we can ground it directly or through an ammeter to measure the current **I1** that flows out from the ducts into the vessel. As the flow velocities are rather low, the charge generated upstream can relax easily through the vessel's wall and the oil at the outlet of this reservoir can be considered electrically neutral or at least very weakly charged. The vessels (3a) and (3b) have membranes separating gas from oil. We can sample oil with a bypass and measure its resistivity in a cell (8).



1 Stainless steel vessel, **2** Channels, **3** Vessels under pressure, **4** Flowmeter, **5** Faraday cage, **6** Insulators, **7** Adjustable Pump, **8** Conductivity measurement system, **9** Oil sampler.

Figure 1 : Experimental Equipment

The pressboard duct is of rectangular cross section The dimensions are 6 mm high, 60 mm wide and 750 mm long and it is made of a 4 mm thick pressboard.

Figures 2 and 3 are general diagrams of this duct. We have placed stick heating resistor on the two outer faces of the duct. The whole is pressed between duralumin and then inserted in a stainless steel channel.
The pressboard duct is in fact divided in three identical parts which can be heated separately. One of this part is shown figure 3.
At the inner pressboard surface, three different electrodes collect at different points the wall current **Io**. We can measure with thermocouples **T1** the temperature at the pressboard surface in contact with the heating resistors and **T2** the temperature at the surface of pressboard in contact with the liquid.

Oil can be sampled in order to analyse oil's moisture content evolution with a moisture detector Panametrics.

We study with this device the effect of a heat transfer step on the wall current.
The evolution with time of temperatures at both sides of pressboard **T1** and **T2** are obtained with a Digital Data Recorder.
The evolution of the currents **Io** collected from one electrode in the duct and **I1** collected from the vessel (1b) are measured with Keithley electrometers 642.

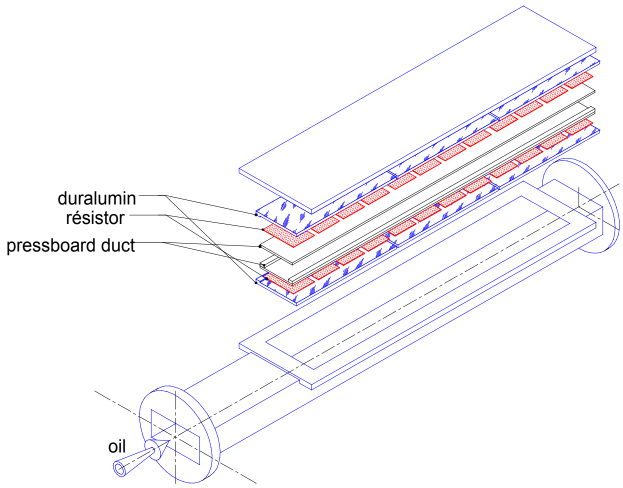


Figure 2 : General Diagram of Duct N°2

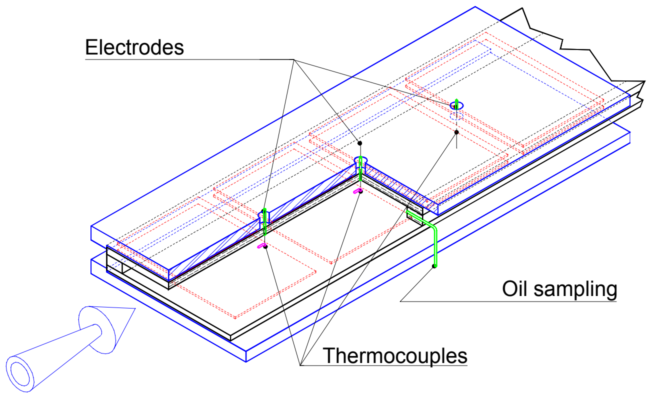


Figure 3 : Diagram of one part of the Duct N°2

Experimental Arrangement For Experiment n°2

A general schema of this experiment is shown in figure 4. We have performed a measuring cell with a body in Teflon inside which we have placed a stack of pressboard impregnated with transformer oil existing in an upper and lower reservoir.
The stack of pressboard is composed of 10 circular discs of 50 mm of diameter and 1.5 mm thick.
The whole is pressed between two brass porous electrodes between which we apply a voltage difference with a voltage source Nobraton QRB 40-2 to the stack. The lower one is grounded through a Keithley electrometer 642 that measures the current flowing through the stack.
At the 8 levels corresponding with the planes of separation of the pressborad discs we have inserted circular perforated electrodes. These electrodes are made of copper, they have a diameter of 30 mm and are 100µm thick. A schema of each electrode can be seen in figure 5.
The electrodes are connected either to a device to measure the electrode voltage or to a capacitance bridge 1615 GenRad. So, we can obtain the voltage at the 8 different levels and to measure the capacitance existing between two adjacent electrodes.

The device to measure electrode voltage consists on a battery of adjustable voltage in series with an electrometer Keithley 642. The battery provide a system of voltage opposition to obtain a null current through the electrometer. When the equilibrium is reached then we measure the potential delivered by the battery with a voltmeter.
We can fix the temperature of the oil of the upper and lower reservoir with heat exchangers. The secondary circuit of this heat exchangers is composed of a water loop and thermostats Lauda RM6 and RK20.
The pressure of the system may be adjusted and remains constant during the experiences as both oil reservoirs are connected through a by pass with small tubes to the loop of experience 1.
To avoid external noise the cell is placed in a Faraday pale.

Measurement Protocols and Results

Experiences n°1. Touchard (4) described the results with this duct heated with the resistors when the steady states are reached. Now, in this paper we present our study of the transient phenomena.
In this experience the pressboard and the oil were initially at rest and at the same temperature (about 20°C). Then, pump is operated to obtain the desired flow rate and all the heating resistors of our system are connected at time t=0 to an auto transformer working at 600 Watts. After 20 minutes we switch off power of the heating resistors.
We have observed that the temperature recorder may interfere in the current measurements. So both measurements are not undertaken simultaneously and in a first test temperature is recorded and in a second at the same experimental conditions the current is measured.
In figures 6-9 we show these evolutions for different flow rates.

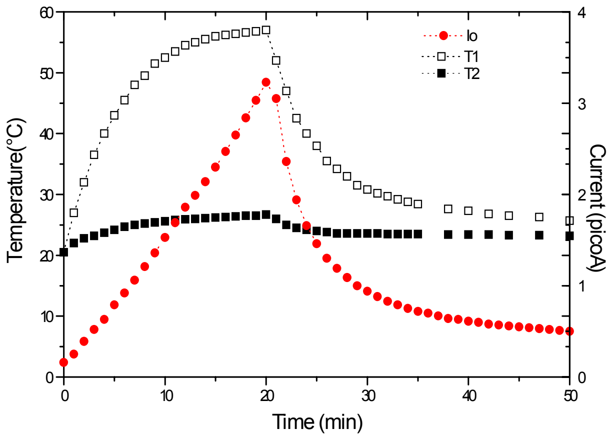


Figure 6 : Temperatures and current collected with an electrode. Flow rate 168 l/h

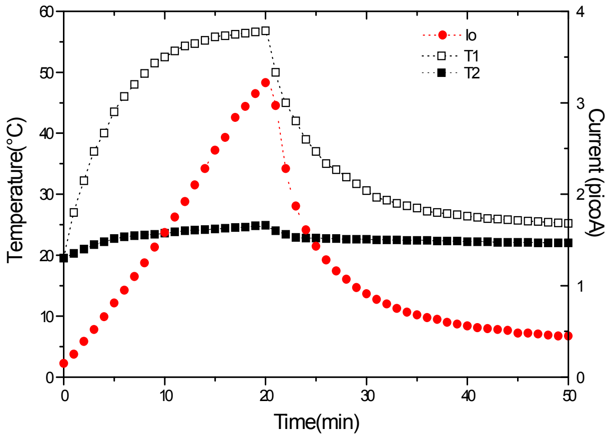


Figure 7 : Temperatures and current collected with an electrode. Flow rate 288 l/h

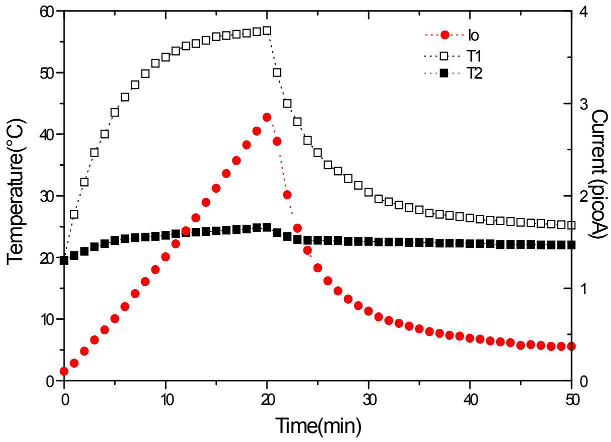


Figure 8 : Temperatures and current collected with an electrode. Flow rate 384 l/h

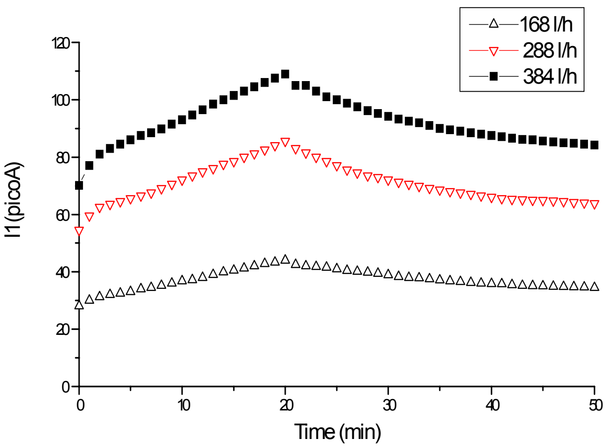


Figure 9 : Current collected in the vessel (1b) for different flow rates

Another experiment has been undertaken that shows the behaviour of the system during a long time when heating is not interrupted. A typical result is shown in figure 10.

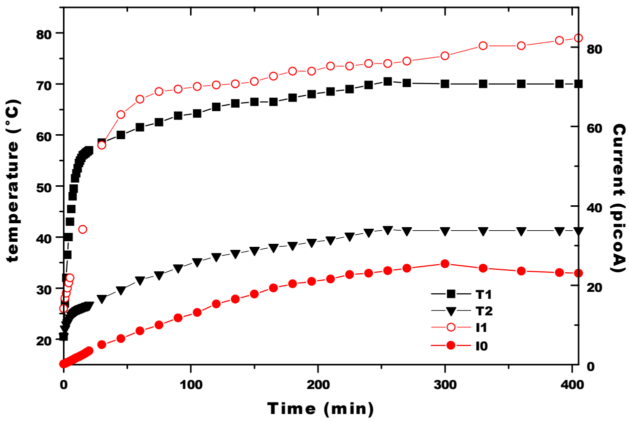


Figure 10: Current and temperature as a function of time

During our experiences, we sampled oil at different time intervals to measure water contents and conductivity. No important changes have been observed during the experiences and this values remain almost constant about 4 ppm and 1.5 $10^{-11}(\Omega^{-1}m^{-1})$ respectively

Experiences n°2. We start our experiences with the oil of both reservoirs and pressboard stack at the same temperature (20 °C). At time t=0 we open a valve of the heating system and water at a desired temperature circulates inside the upper heat exchanger of the measurement cell. The lower one operates always at 20°C.
Then at different time intervals we measure at each level the voltage and the capacitances between adjacent electrodes. A positive voltage of 30V is applied to the upper porous electrodes continuously during this experience. The lower one is earthed.
In figure 11 and 12 we can see respectively the evolutions in terms of time of the distribution between the two porous electrodes of potential and of capacitance. The upper liquid temperature is 70°C.

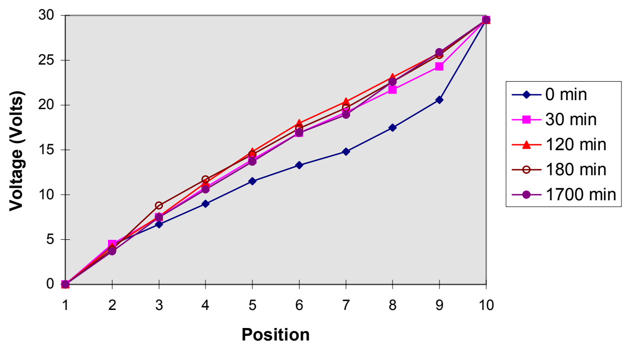


Figure 11 : Voltage distribution at different time

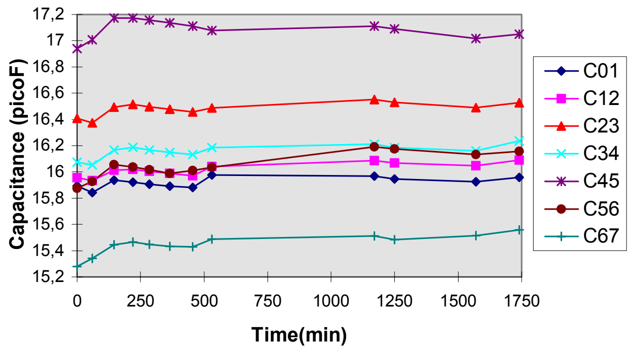


Figure 12 : Capacitance between different electrodes as a function of time

Finally in figure 13 we present the same experiment for a reversed potential difference (lower electrode is at 30V) but at the same thermal gradient (upper electrode at 70°C).

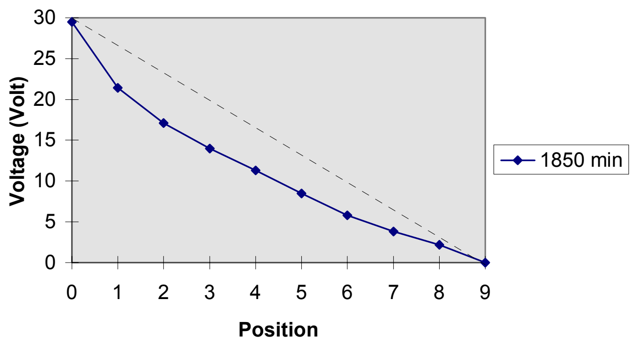


Figure 13 : Voltage distribution at different time. Reversed voltage.

DISCUSSION

Experiences n°1 : These experiences indicate that flow electrification is highly increased in the thermal transient regime when the "cold" pressboard duct is heated from the outer side.

We see in figure 9 that **I1** depends strongly on the flow rate (roughly it is proportional) and on the heat transfer process. Also we observe that after 10 minutes even though temperatures **T1** an **T2** do not increase too much (see fig 6-8), **I1** continues increasing almost at the same rate that during the first part of the experience until time t=20min when we stop the heating phase.
In figure 10 we can see that the evolution of both currents **Io** and **I1** seem not to be coupled with the thermal gradient (almost constant after 10 minutes) but with the evolution of temperatures **T1** and **T2**.
In figures 6-8 we observe that currents **Io** are slightly dependent on the flow velocity. Though the trend of **Io**

with heat transfer is coincident with current **I1**, it is not with flow rate and it seems that other phenomena are present in this measurement.

Experiences n°2 : The analysis of the distribution of voltage through the porous electrodes gives an important information about the charge distribution. Liu (5) has reported space charge patterns in oil impregnated pressboard at high electric fields (1.5MV/m). Our results concerns low electric fields (2 kV/m).

From the distribution of potential for t=0 min of figure 11, it seems that heterocharges exists near the upper electrode (the positive electrode) thus negative charges exists in the oil impregnated pressboard. As time increases and so temperature of this region does, the heterocharges disappear probably due to a reaction at the interface. This evolution of the potential difference is really due to the temperature evolution and not a time effect as the same experiment at 20° for the whole system made at the end of the set of experiments give the same result that for t=0 min.

In the experiment shown .in figure 13 the potential differences is reversed and not the thermal gradient. We observe from the potential distribution that the charges appearing near the upper electrode are negatives. This process may be due to the same physicochemical reaction at the interface than the previous one.

Another observation from this experiment is that the oil impregnated pressboard resistivity distribution (fig. 11) as well as the dielectric permittivity distribution (fig. 12) do not evolve in terms of time when the thermal gradient is stabilised. So, it seems that moisture migration is not detected in the stack at least during a long period of time.

CONCLUSION

Our experiences shows that the phenomenon of flow electrification highly increases in the transient regime of heating a "cold" pressboard and oil system.

It is deducted from voltage distribution that near the positive electrode negative charges accumulate. If the temperature of the region close to this electrode is increased the amount of charge decreases.

The distribution of capacitance and resitivity in the stack is quite constant for long time intervals. This tends to prove that when heating not a high rate change of moisture content inside the pressboard occurs and so the evolution of flow electrification current with a thermal gradient observed in experiences n°1 is more related with an interface phenomena than with a bulk evolution of moisture content inside the pressboard.

References

1. O. Moreau, P. Plion, G. Touchard, 1995 ,"Modelling of Flow Electrification in a 3D Computational Fluid Dynamic Software : Application to Power Transformers" Annual Report CEIDP, 424-427.
2. H. L. Walmsley, 1983, "The Generation of Electric Currents by Turbulent Flow of Dielectric Liquids: Pipes of Finite Length", J. of Phys. D : Appl. Phys., 16, 553-572.
3. G. Touchard, T. W. Patzek, C. Radke, 1996, "A physiscochemical explanation for flow electrification in low conductivity liquids in contact with a corroding wall", IEEE IAS, SO 10-96.
4. G. Touchard, O. Moreau, H. Romat, S. Watanabe, J. Borzeix, 1995 "Electric behaviour of pressboard submitted to an oil flow electrification", Annual Report CEIDP, 612-615,.
5. R. Liu, C. Tornkvist, 1995, "Charge storage in oil-impregnated pressboard at polarity reversal under HVDC", Annual Report CEIDP, 33-37.