A Contribution To Modelling And Experimental Studies Of Flow Electrification In Transformers

O. Moreau[1], G. Artana[2], H. Romat[2], G. Touchard[2]

[1]Electricité de France, Etudes et Recherches, Service ERMEL, 1av. Général de Gaulle, 92141, CLAMART FRANCE
[2]Operation n°9 du L.E.A., URA CNRS N°191, Université de Poitiers, 40 Av du Recteur Pineau, 86022, Poitiers, FRANCE

Abstract

As part of the research program of Electricité de France on static electrification in power transformers, on one hand an experiment has been carried out at the university of Poitiers to simulate the oil path in a transformer and on the other hand the 3D Computational Fluid Dynamics software ESTET developed at the R&D centre of Electricité de France has been extended to the modelling of the phenomena. The experimental devices has enabled us to study in a pressboard duct the wall current reponse to a heat transfer step produced from the outer side of the duct and to calibrate the interfacial charge transfer laws used in our simulation. So we can characterise the influence of parameters such as velocity, temperature, moisture, transient and steady states on the phenomena.
This paper shows that some parameters sets lead to important dielectric stresses in the pressboard which might be the cause of the hazardous discharges observed in power transformers.

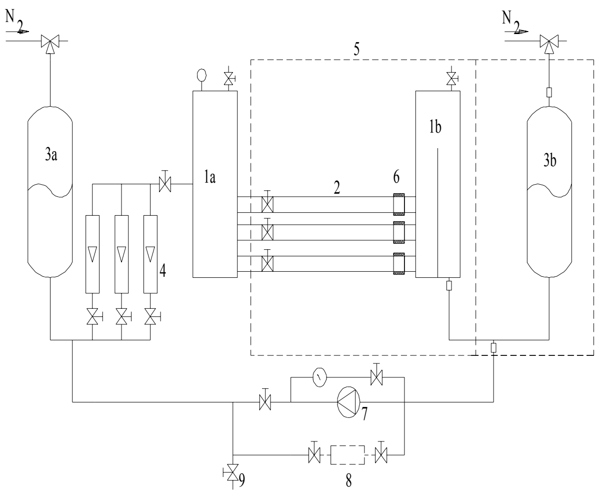
Introduction : the charge transfer at solid-liquid interface

A high power transformer is composed of different metallic parts electrically insulated one from each other by pressboard and oil. The oil is also used to cool the system. So, by the help of a pump the oil flows past the pressboard and through a heat exchanger.
For the last twenty years, static electrification has been suspected to be responsible of failures in power transformers (electric "tree" paths, "worms holes"...). The phenomena consists in a preferential adsorption of negative ions coming from the oil (impurities) into the pressboard. This yields on one hand a space charge in the oil which can relax in contact with grounded metallic walls and on the other hand a space charge in the pressboard which can accumulate depending on the leakage paths [1]. Under the effects of diffusion, electric forces and convection the space charge in the two media organises itself in a distribution called double layer. Unfortunately the physico chemical phenomena taking place at the interface is rather unknown and gives rise to many assumptions and models. The charge transfer boundary condition used in our simulation is derived from the H. Walmsley's model [2], developed for grounded metallic pipes, and applied to insulated pressboard (see section "Governing equations" for further details).
If on one hand all the parameters of influence seem to be clearly identify on the other hand their critical combination has not been put in evidence. Numerical modelling and experiments have been chosen to investigate the phenomena in the transformer conditions in order to determine a critical context which might explain the observed incidents.

Experimental Apparatus

An experiment has been carried out at the University of Poitiers to simulate the oil path in a transformer [3]. It consists in a loop where the oil flows alternatively through grounded metallic pipes and pressboard ducts and so two kinds of interface are present.
A general diagram of the equipment is given in figure 1. From the reservoir (1a) oil may flow through three different types of channels (2) where we have placed electrodes. Then oil passes through reservoir (1b) and gets back to the pump (7) which can be operated to obtain different flow rates. This last reservoir (1b) is electrically insulated from the rest of the circuit and we can ground it or measure the current **I1** that flows out from the ducts in the vessel. In our experiments as the flow velocities remain rather small, at the outlet of this reservoir the charge generated upstream has relaxed and the oil can be considered electrically neutral or at least very weakly charged. The vessels (3a) and (3b) have membranes separating gas from oil. They dampen

pressure fluctuation in the circuit and enable to circulate oil without operating the pump. We can sample oil with a bypass and measure its resistivity in a cell (8).



1 Stainless steel vessel
2 Channels
3 Vessel under pressure
4 Flowmeter
5 Faraday cage
6 Insulators
7 Pump
8 Conductivity measuring sy
9 Oil sample
Valves

Figure 1 : Experimental Equipment

We worked on two different kind of channels made of stainless steel. In them, oil only flows inside a duct of rectangular cross section constructed with a 4 mm thick pressboard.

The geometry of the duct n° 1 (shown in figures 2 and 3) corresponds to a 600 mm length which cross section dimensions are 4 mm height and 40 mm width. In this duct a sheet of teflon is wrapped around the duct and electrodes are placed on the teflon. Another sheet of teflon is wrapped around the electrodes. With this device we can study how the pressboard can accumulate electric charges measuring the capacitive current on the electrodes.

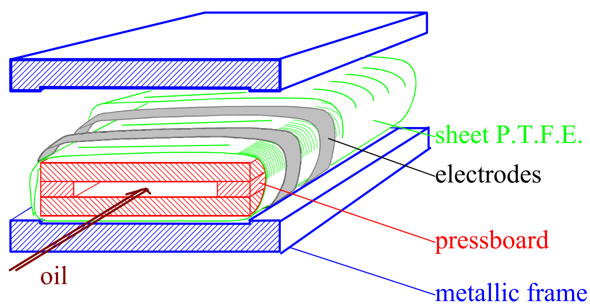


Figure 2: General Diagram of Duct N°1

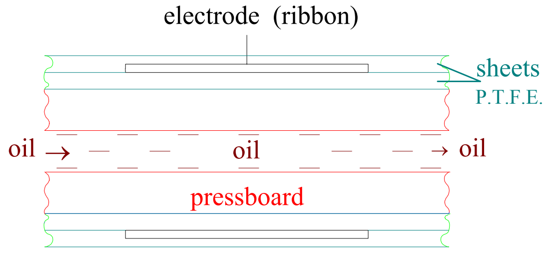


Figure 3: Section of Duct N°1

Figures 4 and 5 are general diagrams of the duct n°2. This one is 6 mm high, 60 mm wide and 750 mm long. We have stick heating resistor on the two faces of the press board duct and the whole is pressed between duralumin and then inserted in the 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 5. At the pressboard surface, three different electrodes collect at different points the wall current **Io**. We have placed thermocouples to measure **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. We can study with this device the effect of a heat transfer step on the wall current. This study aims to give some information about the phenomena occurring when a cold transformer is energised.

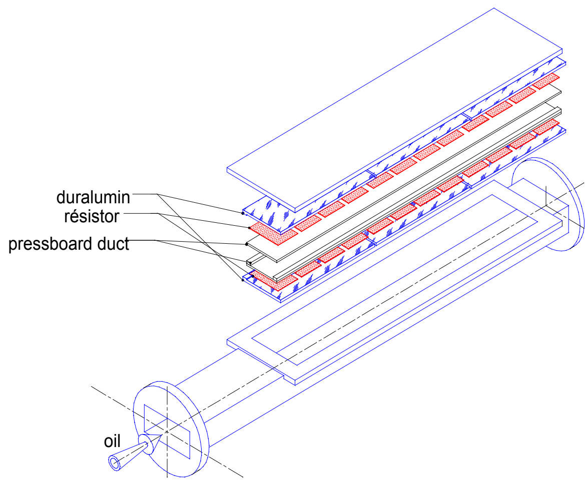


Figure 4 : General Diagram of Duct N°2

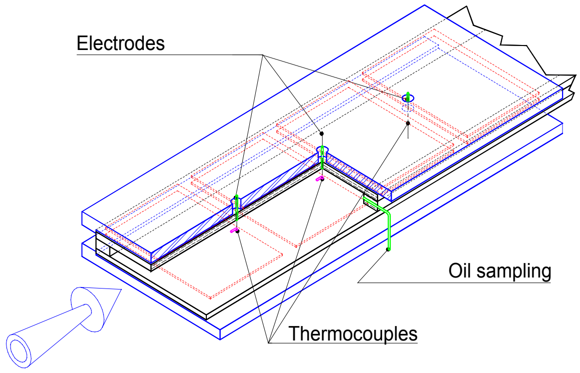


Figure 5 : Diagram of one part of the Duct N°2

Modelling of flow electrification in Duct N°1

When the flow starts, the static equilibrium may only be partially reached. Depending on whether the pressboard is well insulated or not two kinds of operating state can be considered:
- if the pressboard is not insulated, the leakage current may lead to a time independent charge distribution in the system without the interface being in equilibrium (fluxes non equal to zero) because the too small residence time does not allow the diffuse layer to completely develop. So the charge distribution in a material volume of fluid oscillate during its circulation between the two equilibrium profiles associated with the two interfaces pressboard and metallic wall. The difference between leakage and adsorption fluxes determines the accumulation rate in the pressboard.
- if there is no leakage flux, the accumulation in the pressboard can only be limited by a possible saturation of the adsorption sites at the interface or discharges due to gradients of potential becoming too important in relation to the dielectric strength of the pressboard or of the oil. In next paragraphs we show how we simulate the flow electrification according to this most constraining case.
The experimental results we have already obtained with duct n°1 [4] enable us to calibrate the interfacial charge transfer laws used in the modelling.

Governing equations

Let us consider a dielectric fluid (medium 1) in contact with a dielectric solid (medium 2) facing a grounded electrode insulated from the pressboard (fig. 6).

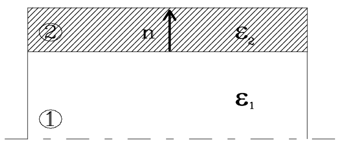


figure 6

medium 1

The fluid is assumed to contain one type of neutral specie which can dissociate in two ions according to the following equilibrium :

$$\gamma C \Leftrightarrow A^+ + B^-$$

If we note:

$\Gamma^{\pm}$, Γ^{n}: flux densities of ionic and neutral species,
$n^{\pm}$, n: concentrations of ionic and neutral species,
$D^{\pm}$, D: diffusion coefficients of species,
K_d, K_r: dissociation and recombination coefficients,
$\mu^{\pm}$, Φ: ionic mobilities, electric potential,
v: fluid velocity,
q, ε: elementary charge, permittivity,

we obtain the flux densities of chemical species written as the summation of a diffusion flux, a migration flux in an electric field and a convected flux :

$$\Gamma_1^+ = -D_1^+ \nabla n_1^+ - n_1^+ \mu_1^+ \nabla \Phi_1 + n_1^+ \mathbf{v}$$
$$\Gamma_1^- = -D_1^- \nabla n_1^- + n_1^- \mu_1^- \nabla \Phi_1 + n_1^- \mathbf{v}$$
$$\Gamma_1^n = -D_1^n \nabla n_1 + n_1 \mathbf{v}$$

then the conservation equations of each species :

$$\frac{\partial n_1^+}{\partial t} + \nabla.\Gamma_1^+ = \quad K_{d1} n_1^{\gamma} - K_{r1} n_1^+ n_1^-$$
$$\frac{\partial n_1^-}{\partial t} + \nabla.\Gamma_1^- = \quad K_{d1} n_1^{\gamma} - K_{r1} n_1^+ n_1^-$$
$$\frac{\partial n_1}{\partial t} + \nabla.\Gamma_1^n = -\gamma\left[K_{d1} n_1^{\gamma} - K_{r1} n_1^+ n_1^-\right]$$

and the Poisson equation :

$$\nabla.\left(\varepsilon_1 \nabla \Phi_1\right) = -|q|\left(n_1^+ - n_1^-\right)$$

The space charge in the fluid interfering with the electric field induces a Coulombic force, so that the Navier Stokes equation for a incompressible Newtonian fluid with a constant dynamic viscosity becomes :

$$\rho\frac{d\mathbf{v}}{dt} = -\nabla p + \rho\mathbf{g} + \mu\Delta\mathbf{v} - |q|\left(n_1^+ - n_1^-\right)\nabla\Phi_1$$

with:

ρ: mass density $\quad\mu$: dynamic viscosity $\quad$ p: pressure

medium 2

The pressboard is considered as a very viscous fluid medium with no velocity. The same equations as above govern the charge distribution in the medium 2, but with different chemical parameters (diffusivity, mobility, dissociation recombination coefficients) and no convection term.

interface oil-pressboard

The interfacial charge transfer law is derived from the H. Walmsley's model but involves ionic concentrations at both sides of the interface:

$$\mathbf{\vec{n}}.\mathbf{\Gamma}_1^+ = C_a^+ \left(1 - \frac{n_{adj2}^+}{n_t^+}\right) n_{adj1}^+ - C_d^+ n_{adj2}^+$$

$$\mathbf{\vec{n}}.\mathbf{\Gamma}_1^- = C_a^- \left(1 - \frac{n_{adj2}^-}{n_t^-}\right) n_{adj1}^- - C_d^- n_{adj2}^-$$

with

$n^{\pm}_{adj}$: ionic concentrations adjacent to the interface

$n^{\pm}_{t}$: available sites number

C_a, C_d: adsorption and desorption constants

according to the interface conditions:

$$\begin{cases} \mathbf{\vec{n}}.(\varepsilon_1 \nabla \Phi_1 - \varepsilon_2 \nabla \Phi_2) = 0 \\ \mathbf{\vec{n}} \times (\nabla \Phi_1 - \nabla \Phi_2) = 0 \\ \mathbf{\vec{n}}.(\Gamma_2^+ - \Gamma_1^+) = 0 \\ \mathbf{\vec{n}}.(\Gamma_2^- - \Gamma_1^-) = 0 \end{cases}$$

surface of the pressboard facing the electrode

As this face of the pressboard is insulated from the electrode, the boundary conditions are:

$$\mathbf{\vec{n}}.\mathbf{\Gamma}_2^+ = 0$$
$$\mathbf{\vec{n}}.\mathbf{\Gamma}_2^- = 0$$

Results of the Simulation

The experimental results we have obtained with duct n°1 [4] has enabled us to calibrate the interfacial charge transfer laws used in the modelling. The determination of the physical constants is detailed in [1].

In order to separate the chemical reaction, the interface interaction and the influence of the convection, the simulation is decomposed into two phases : research of the static equilibrium then starting of the flow. This way of proceeding enable us to control how react the model according to each phenomena. In addition a real transformer is first filled up before starting the pumps.

The results we have obtained with our model are shown in figures 7-9.

Figure 7

Figure 8

Figure 9

Static equilibrium

When starting with the initial conditions corresponding to chemical equilibrium, the simulation points out :

• The kinetic of the phenomena is very slow. The equilibrium is in fact not totally reached : the wall fluxes are weak but not equal to zero.
• The transient state is complex: the global process is controlled by the overlapping establishment of the two ionic species equilibrium which present kinetic of different order.

Flow state:

The state at 8000s is used as initial condition for the convected state in a laminar flow (Reynolds number equal to 60). The figures 7, 8 and 9 depict: the potential at t=2s, the potential and charge at t = 170 s.
The calculation shows :
• the initial charge is swept up by the convection what induces important gradient of potential,
• The interface fluxes get back to the initial values of the static case. The charge in oil, after a first passage (t>resident time) reached a steady state whereas the pressboard does not stop from charging.
• The gradients of potential in the pressboard become more and more important.
The simulation time did make possible to find the final state corresponding to the saturation of the site number.

Experimental Study with Duct N°2

We have described in [5] our 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 the experiences we have carried out the pressboard and the oil where 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 determine the evolution with time of temperatures at both sides of pressboard **T1** and **T2** with a Digital Data Recorder, and with Keithley electrometers 642 we study the evolution of the currents **Io** and **I1** collected with one electrode in the duct and with the vessel (1b) respectively. In figures 10-13 we show these evolutions for different flow rates.
We sampled oil at different time intervals during our experiences to measure water contents with a moisture detector Panametrics. No evolution of moisture with time was detected. The measurement of oil conductivity gives 1.5 $10^{-11}(\Omega^{-1}m^{-1})$ and also no important change has been observed during the experiences.

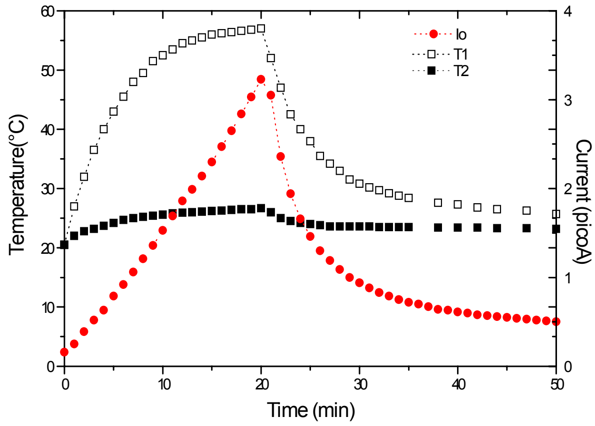


figure 10 : Temperatures and current collected with an electrode. Flow rate 168 l/h

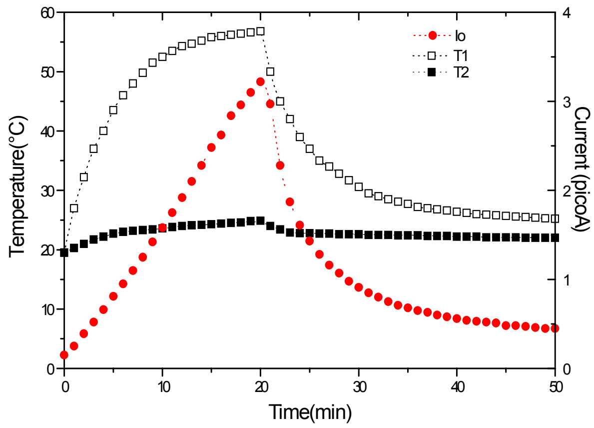


Figure 11 : Temperatures and current collected with an electrode. Flow rate 288 l/h

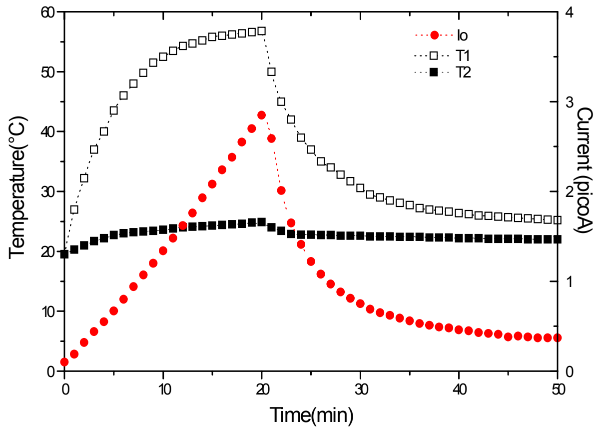


Figure 12 : Temperatures and current collected with an electrode. Flow rate 384 l/h

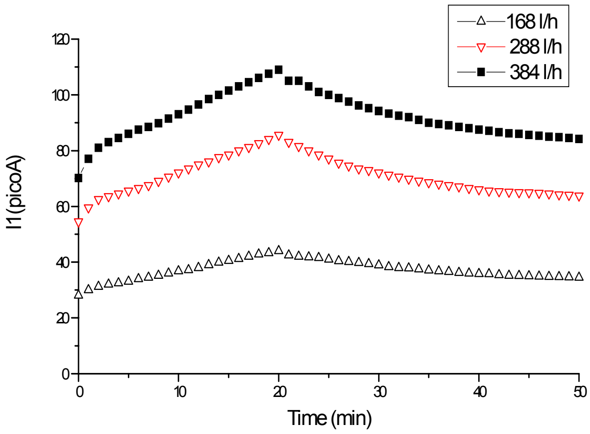


Figure 13 : Current collected in the vessel (1b) for different flow rates

Discussion

These experiences shows that flow electrification is highly increased in the transient regime when the "cold" pressboard duct is heated from the outer side.
We see in figure 13 that **I1** depends strongly on the flow rate (roughly it is proportional) and on the heat transfer process. Though after 10 minutes **T1** an **T2** do not increase too much, **I1** continues increasing at the same rate and this process goes on during a long time. An increase of the diffusion of some species through the pressboard that change the electrochemical reaction at the interface or an increase of the adsorption sites associated with pressboard dilatation may be some keys to understand this strange behaviour.
Now, we carry out other complementary experiences to better understand this phenomenon.
In figures 10-12 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.

Conclusion

The ESTET software environment provides a powerful investigation tool to study the flow electrification phenomena in its most complete form according to the present state of our knowledge. The experimental results of the simulated benchmark made possible to determine one set of parameters for the model. But the tool has the ability to consider other combinations giving the same reachable variables (average oil charge, capacitive electrode currents) but leading to different charge distributions more or less critical in term of dielectric strength.

Our experiences shows that the phenomenon of flow electrification highly increases in the transient regime of heating a "cold" pressboard and oil system. We hope that the new set of experiences we are now undertaking will give much more information about these phenomena.

References

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