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Flow electrification due to the flow of a perpendicular jet on a flat plate

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This paper deals with the phenomena of flow electrification due to an immerged jet impinging perpendicularly onto a pressboard plate. The experimental results are analysed taking into account some hydrodynamic predictions of the jet behaviour. They give a rough estimation to describe the whole phenomena.

1. INTRODUCTION

The phenomena of flow electrification on a pressboard-oil system has received recently special attention [1-2] due to the failures of large power transformers that occurred in different countries. Our laboratory has undertaken a large research program in association with EDF, the French Electricity Company, to obtain a better understanding of this complex phenomena. In the past, most of the studies we have undertaken were concerned to analyse the flow electrification phenomena of the pressboard-oil system in ducts [2]. However as in some parts of the transformers the flow is perpendicular to pressboard plates, we were interested to look at the phenomena in this configuration. Thus we have analysed previously the case of a non immerged impinging jet with different impact angles [3] and this paper relates to the case of an impinging immerged jet perpendicular to the plate.

2. EXPERIMENTAL STUDY

In this paragraph we describe the experimental device we have used to analyse the process of flow electrification of an immerged liquid jet impinging on a flat pressboard plate. The liquid we have used is a transformer oil supplied by EDF and used by French manufacturers.

2.1. Experimental equipment

2.1.1. Description

A general schema of the device is shown in figure 1

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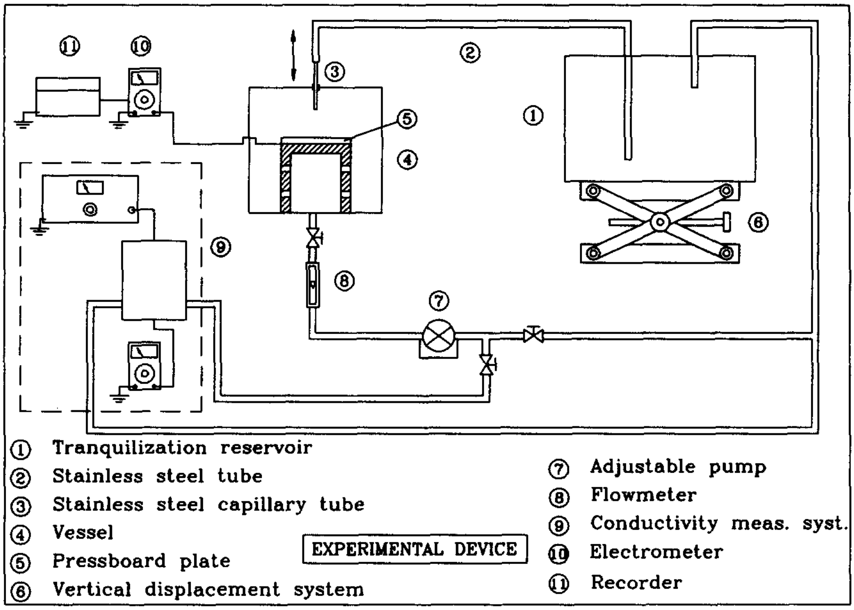

Figure 1: General schema of the flow loop

In this loop the liquid flows from a tranquilization reservoir ①, through a stainless steel tube ②, then through a stainless steel capillary tube (ϕ_{int}=2.5mm) ③ into the vessel full of transformer oil ④ where the pressboard plate ⑤ is located. A vertical immerged jet is obtained when the flow exits from the capillary that is directed perpendicular to this plate. The distance tip of the capillary-plate can be changed by the system of vertical displacement ⑥. An adjustable flow is obtained with the pump ⑦ measured with a flowmeter ⑧ placed between the pump and the vessel ④. A by-pass enabled us to measure the oil resistivty with a conductivity measurement system ⑨ composed of a cell, a stabilised voltage source and an electrometer Keithley 610C. All the experiments were made with the same oil which has shown a resistivity of 2.5 10^{11} Ωm.

A more detailed schema of the pressboard plate ⑤ can be seen in figure 2. The plate is composed of a thin pressboard disc of 0.2 mm thick, where the jet impinges, and then another pressboard disc of 3 mm thick. The whole is fixed to the vessel by a Teflon support. Between both discs of pressboard we placed 5 concentric electrodes that enabled us to measure the image of the wall current at different radial positions. These currents are measured with an electrometer Keithley 642 schematised in figure 1.

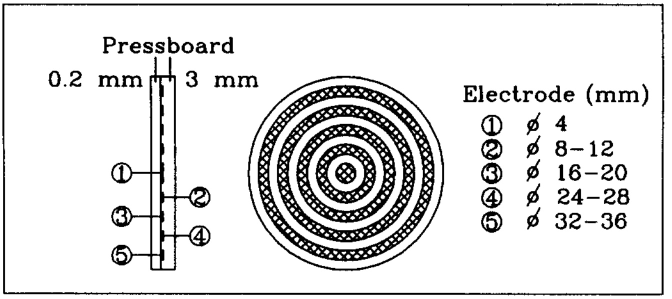

Figure 2 : Schema of the pressboard plate

2.2 Experimental results

The experimental results are summarised in the following paragraphs.

2.2.1. **Flow electrification as a function of velocity**

We have analysed 5 different velocities that leads to Reynolds number in the range of 10.4 - 52. A typical result for a fixed distance capillary-plate H is shown in figure 3 for the five different electrodes. In this figure electrodes are numbered subsequently with increasing diameter from the central one as shown in figure 2.

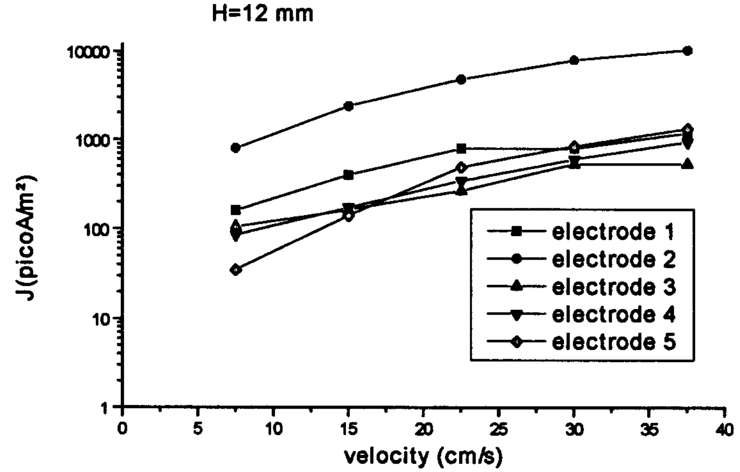

Figure 3: Flow electrification as a function of jet velocity for the different electrodes

2.2.2. Flow electrification as a function of radial position

We show in figure 4, a typical result of flow electrification as a function of radial position for a fixed distance capillary-plate H and for different jet velocities. The values observed at each electrode are associated to the mean radius of the electrode.

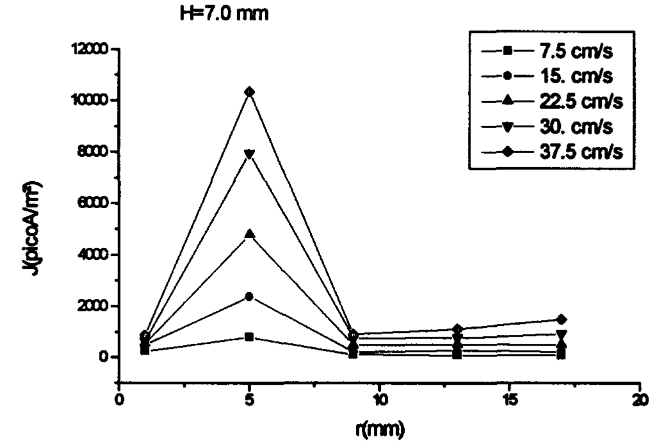

Figure 4: Flow electrification as a function of radial distance for different jet velocities

2.2.3. Flow electrification as a function of the plate-tip of the capillary distance H.

We have made experiments for 5 different distances plate-tip of the capillary. A typical result for a fixed electrode and for different jet velocities is shown in figure 5.

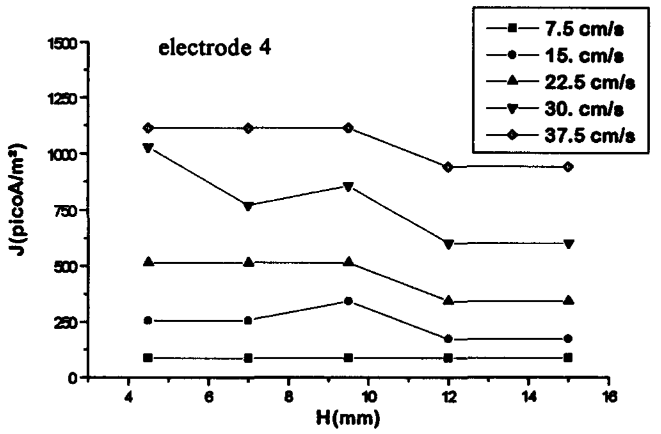

Figure 5: Flow electrification as a function of the distance plate-tip of the capillary H for different jet velocities

3. DISCUSSION

The analysis of figure 3-4-5 leads to the following remarks :

1-For all electrodes the flow electrification increases as a function of the jet velocity. This observation is valid for all the distances H that we have tested.
2-For all jet velocities the flow electrification is dependent on the radial distance, and the highest signal is detected at the electrode 2 (mean radius =5mm). This is valid for all heights.
3-The current measured in each electrode has a slight tendency to decrease as we increase the distance H. This is valid for all jet velocities.

In the following paragraph we try to have some theoretical insight using the existing theories to analyse our results.

3.1. Theoretical insight

The flow electrification process for an oil-pressboard interface has been relied to the wall shearing stress [2]. So to analyse this phenomenon we need to know this velocity gradient. In the usual case of pipes or flat plates this gradient is well known, however this is not the case in all positions for a jet that impinges perpendicular to a flat plate.

In general for an impinging jet we can divide the flow field into three regions 1) the free jet region, at heights approximately greater than two jet diameters above the ground, 2) the impingement region, in which flow turns through 90° and 3) the wall jet region usually at radii greater than approximately one diameter [4].

As a result of the industrial applications of these jets, most of the theoretical efforts to describe the flow fields has been concentrated in non immerged jets and in turbulent immerged jets (or radial turbulent jet). The case we study is a laminar radial jet and has received less attention. Glauert [4] arrived to the following expression for the shearing stress τ_0, that seems at least adequate to describe the behaviour at the wall jet region.

$$\tau_0 = \rho\, \nu \left.\frac{\partial u}{\partial y}\right|_{y=0} = \rho \left(\frac{125\, F^3}{216\, \upsilon\, r^{11}} \right)^{1/4}$$

with ρ liquid density, υ dynamic viscosity, u velocity in the radial direction, y vertical co-ordinate, r radial co-ordinate, and

$$F = \int_0^\infty r\, u \left(\int_y^\infty r\, u^2\, dy \right) dy$$

that can be roughly estimated with $F \approx \frac{1}{2} U_0\, Q_L^2$. being U0 the initial velocity of the jet and Q_L the initial flowrate. Using this expression the shearing stress will be of the form :

$$\tau_0 = A\, U_0^{9/4}\, r^{-11/4}$$

with A being constant. If we consider the wall current proportional to the shearing stress then we can write

$$J(U_0, r) = \beta\, U_0^{9/4}\, r^{-11/4}$$

We can see from this formula that the dependency of the wall current on the velocity is larger than that of the wall current in a duct usually at a power belonging to the interval 1-2. With this theoretical framework we have calculated for all our experiments the values of $B = \frac{J}{\tau_0}$ that we show in table 1

Table 1 :
Values of the coefficient B (picoA/N) of the different electrodes for different H

H(mm)	B(electrode 1)	B(electrode 2)	B(electrode 3)	B(electrode 4)	B(electrode 5)
4.5	17.4	5607.4	3010.4	8355.1	9820.4
7.0	6.8	3770.4	1441.3	4917.6	6620.0
9.5	4.2	2933.7	1111.8	3667.7	7975.7
12.0	2.8	2427.5	1071.0	3323.0	7844.2
15.0	2.4	1949.0	994.7	2726.4	7581.1

The analysis of this table shows that electrode 1 is quite different from the others and these results should not be included in the analysis as they belong to the impinging region and not to the wall region.

As far as the other electrodes, we observe that using Glauert's expressions we can not obtain the same constant for all electrodes but they differ by less than a magnitude order.

So for the pressboard-oil system in an impinging jet a suitable value for the constant B seems to be in the range 1-10 nanoA/N. When comparing the values of these constants to those for a rectangular pressboard duct with a fully established flow ($B \approx 0.25$ nanoA/N) [2], this difference in about one order of magnitude is associated to the difference between the two hydrodynamic configurations.

Table 1 also shows a dependence of B with H, that is not predicted by the theory.

As a result, accepting that the flow electrification is proportional to the velocity gradient at the wall, Glauert's theory seems to give only a rough estimation of the wall current behaviour. Much more effort needs to be done to achieve a model for the impinging region and a better description of the wall region.

4. CONCLUSIONS

The experimental work we have undertaken shows the dependency of the wall current on different parameters. The most important are the initial velocity of the jet and the distance to the axis. Though we have obtained some initial theoretical predictions, more effort needs to be accomplished to obtain a global description of the whole process.

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