Flow Electrification Behavior: A New Parameter Involved

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Abstract—Flow electrification is a complex phenomenon and, in spite of extensive researches for many years by several groups all over the word, the origin of the process is not totally clarify. Indeed, even if the influence of many parameters has been established. However, the physicochemical process at the interface solid/liquid remains rather difficult to clearly understand because it is often controlled by impurities which are not well identified. Concerning the influence of the flow characteristics, it has been pointed out in various experiments that the wall shearing stress plays an important role on the ionic exchanges at the interface which control the wall current density. In this paper we analyze this behavior comparing the different experimental results that we previously obtained. Finally, we discuss the relation between the wall shearing stress and the wall current density.

Keywords—Flow electrification, wall shearing stress, wall current, Reynolds number

I. Introduction

The phenomenon of flow electrification has been investigated for more than fifty year [1]–[5]. Thus, the influence of different parameters is now well understood. This is the case of the flow regime influence (specially the jump from laminar to turbulent flow), the influence of the Reynolds number and radius of the pipe, the influence of roughness [6], the influence of the shape of the tube [7]. The influence of the electrical characteristics of the liquid is predictable as well. Nevertheless, one important mechanism is still unpredictable and it strongly governs the phenomenon. This mechanism is the physicochemical process occurring at the interface between the liquid and the solid. This process is responsible of the development of the electrical double layer. Moreover, the influence of the wall shearing stress on this process, even if it has been pointed out to play an important role has never been fully clarified.

The goal of this paper is to analyze different previous experiments made at the laboratory showing the possible influence of this parameter, After that, we describe a possible model taking into account this parameter. First, we are going to briefly describe the flow electrification phenomenon.

II. Flow electrification phenomenon

The flow electrification phenomenon (Fig. 1) is the convection, due to a flow, of a part of the electrical double layer appearing at the inner wall of a pipe or a channel. Indeed, when a liquid is in contact with a solid, a physicochemical reaction appears which leads to an electric charge in the solid (one part of the double layer) and the opposite charge in the liquid (the other part of the double layer). In fact, the charges in the liquid are generally separated in two zones: one very close to the solid wall which is called the compact layer and

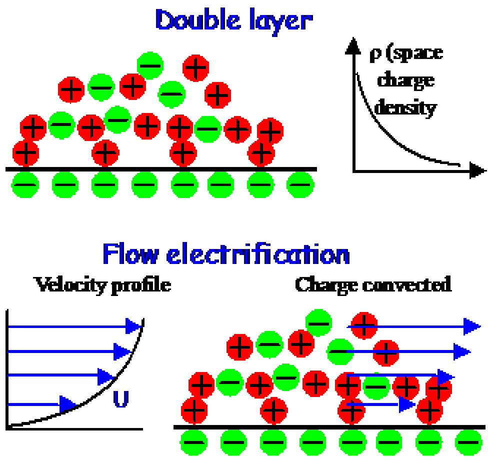

Fig. 1. Flow electrification phenomenon.

the thickness of which is so small that it cannot be affected by the flow; the other one, called the diffuse layer, has a thickness proportional to the square root of the electrical resistivity of the liquid (thus in the case of insulating liquid this layer can be rather thick ∼tens of microns).

The flow electrification is the convection of the diffuse layer. Then, even if the current generated by this convection is rather small, often in the order of pA, the voltage reached by some insulated parts could be important due to the high resistivity of the liquid which implies very small charge dissipation. These high voltages can under certain conditions generate electrical discharges which can lead to electrostatic hazards. This is mainly the reason of the importance to understand the phenomenon for industrial applications.

III. Flow electrification parameters

In the case of a fully developed double layer, the influence of the flow parameters is now well known, (i.e. flow velocity, effect of turbulence, jump from laminar to turbulent flow). However, in the case of a non-fully developed double layer

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(which is common in industry), the process which governs the double layer development is still not well understood. Our experiments over the years show that the wall shearing stress plays an important role. Concerning the chemical aspect of the flow electrification, the diffuse layer thickness (the Debye length) is now well known, but the chemical reaction on the wall, leading to the creation of the double layer is badly understood. Indeed, in the case of dielectric liquids, for which the flow electrification may be responsible of electrostatic hazards, the double layer behavior is greatly affected by impurities, which are generally very difficult to control. This means that the intensity of the wall reaction at the interface between the solid and the liquid is generally not known, thus the amount of charge in the diffuse layer and as well the space charge density on the wall or the zeta potential remain difficult to predict in the case of dielectric liquids. This is the worst point in the prediction of the flow electrification phenomena in industry leading to electrostatic hazards. Indeed, in spite of numerous researches undertaken for a long time concerning petroleum industry, transport and transfer of dielectric liquids, chemical industry, aeronautic industry, or degradations of electrical and electronic devices due to the flow of cooling liquids, this parameter needs still to be determined experimentally for the same liquid/solid interface of the industrial application.

The influence of wall shearing stress on the wall current appearing during the development of a double layer was first suspected in the case of experiments concerning flow electrification in high power transformers. After presenting the wall current model generally used during these last decades, we are going to describe previous experiments, made at the laboratory, in which the wall shearing stress seems to have had an influence.

IV. Wall Current for a Double Layer in Development

Walmsley, Zahn and Touchard proposed models of wall current during the development of the double layer [8]–[10]. Even if some differences exist in their respective models, globally they are very similar and the main point is that only physicochemical reactions independent of the wall shearing stress are supposed to be at the origin of the process. Indeed, in the wall current density equation (Eq. 1), the coefficient K is only function of a physicochemical reaction, ρ_w is the space charge density at the wall during the development, $\rho_{w\infty}$ is the space charge density at the wall for a fully developed double layer (an infinitely long pipe) and i_w is the wall current density.

$$i_w = K(\rho_{w\infty} - \rho_w) \tag{1}$$

Our first interrogation concerning a possible role of the wall shearing stress in the wall current was published in 1994 [11]. We are going to present the reason of this interrogation here.

The research concerned flow electrification in high power transformers. The wall current is measured all along a rectangular channel (Fig. 2) made of pressboard inside which a flow of oil is forced. The channel dimensions are 4 mm height ($2a$), 40 mm wide (l) and 600 mm long.

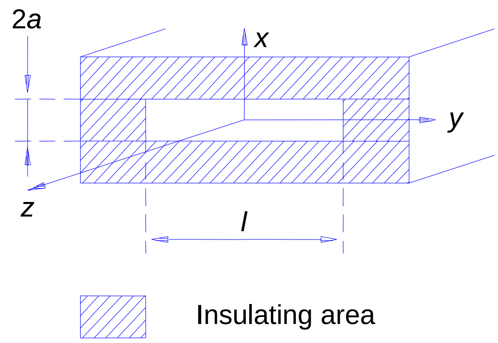

Fig. 2. Cross section schema of the pressboard channel.

In such a channel, where the width is much greater than the height (10 times in our case), it is possible to make the approximation of two infinite parallel plates. Then, in the case of weak space charge density and for a fully developed diffuse layer, the space charge density profile is given by the following equation:

$$\rho_\infty(x) = \rho_{w\infty} \frac{\cosh(x/\delta_0)}{\cosh(a/\delta_0)} \tag{2}$$

δ_0 is the Debye length and a the channel half thickness.

For a slow reaction compared to the relaxation time of the charges, the diffuse layer profile at a distance z from the entrance of the duct, can be expressed by:

$$\rho(x,z) = \rho_w(z) \frac{\cosh(x/\delta_0)}{\cosh(a/\delta_0)} \tag{3}$$

where $\rho_w(z)$ is the space charge density on the wall for a given distance z from the entrance.

Considering that this profile is nearly the same all across the width l of the channel, and that there is no contribution of the two sides to the charge transported, the streaming current (the charge transported by the flow) through a cross section at abscissa z for a laminar flow is given by the following integral:

$$I(z) = l \int_{-a}^{a} \rho(z,x)U(x)\ \mathrm{d}x \tag{4}$$

$U(x)$ being the velocity profile for a laminar flow.

$$U(x) = \frac{3}{2}U_m \left(1 - \frac{x^2}{a^2}\right) \tag{5}$$

After some calculation, we find:

$$I = 2l\rho_w(z)C \tag{6}$$

with

$$C = 3\left(\frac{\delta_0}{a}\right)^2 U_m \left(a - \delta_0 \tanh\left(\frac{a}{\delta_0}\right)\right) \tag{7}$$

Considering now the evolution $\mathrm{d}I$ of the streaming current I between two cross sections, one at z and the other one at $(z+\mathrm{d}z)$, $\mathrm{d}I$ is given by:

$$\mathrm{d}I = 2l\mathrm{d}(\rho_w(z))C \tag{8}$$

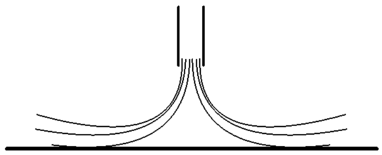

Fig. 3. Impinging jet.

But this variation is due to the wall current arriving from the top and the bottom of this small channel section:

$$\mathrm{d}I = 2l\mathrm{d}zi_w = 2l\mathrm{d}zK(\rho_{w\infty} - \rho_w(z)) \qquad (9)$$

With the assumption that the space charge density at the entrance of the channel (for $z = 0$) is null in the whole section, combination of Eqs. 8 and 9 gives a differential equation for $\rho_w(z)$ which has the following solution :

$$\rho_w(z) = \rho_{w\infty}\left(1 - \exp\left(-\frac{K}{C}z\right)\right) \qquad (10)$$

which can be written in the following form:

$$\rho_w(z) = \rho_{w\infty}\left(1 - \exp\left(-\frac{b}{U_m}z\right)\right) \qquad (11)$$

with

$$b = \frac{K}{3\left(\frac{\delta_0}{a}\right)^2 a\left(1 - \frac{\delta_0}{a}\tanh\left(\frac{a}{\delta_0}\right)\right)} \qquad (12)$$

Finally, the wall current density is given by:

$$i_w = K\rho_{w\infty}\exp\left(-\frac{b}{U_m}z\right) \qquad (13)$$

Near the entrance of the channel, such modeling gives a wall current density nearly constant (for different velocities and for the experimental parameters in [11], as the exponential $\sim$1), but this was not what we observed [11]. Indeed, even very close to the entrance, the wall current density is nearly proportional to the velocity.

Then, on the basis of these experiments, we made others experiments in which the wall shearing stress is strongly varying. These experiments were made on an impinging jet [12], [13]. The jet of oil impinges a piece of pressboard behind which concentric electrodes were placed. An impinging jet (Fig. 3) is a jet striking perpendicularly a plate. This configuration exists at the bottom of a shell high power transformer; the oil flow impinges the pressboard. It is, as well, the region where some evidences of electrostatic discharges have been pointed out. For such flow, the wall shearing stress is strongly varying as we can see in Fig. 4, in which the wall shearing stress has been computed numerically and with an approximate analytical solution. In Figs. 5 and 6 the schema of the impinging jet setup is presented. An example of the current measured on the different electrodes is plotted in Fig. 7. Even, if it does not follow exactly the evolution of the wall shearing stress it has clearly the same behavior.

In light of these experiments we have re-examined experiments made with capillary tubes of several lengths [14]. The experiments were made for laminar flows with a 0.24 mm radius (R) stainless steel capillary. The capillary tube was

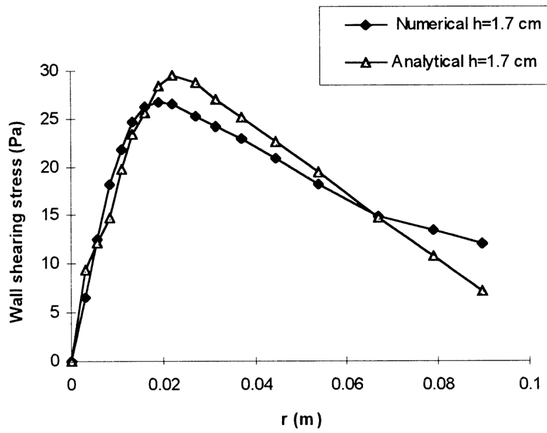

Fig. 4. Wall shearing stress evolution on a plate impinged by a jet.

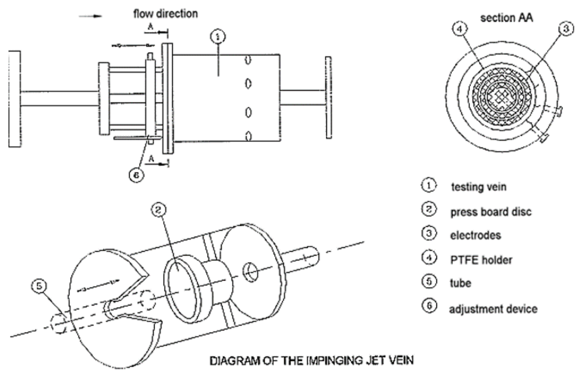

Fig. 5. Schema of the impinging jet vein.

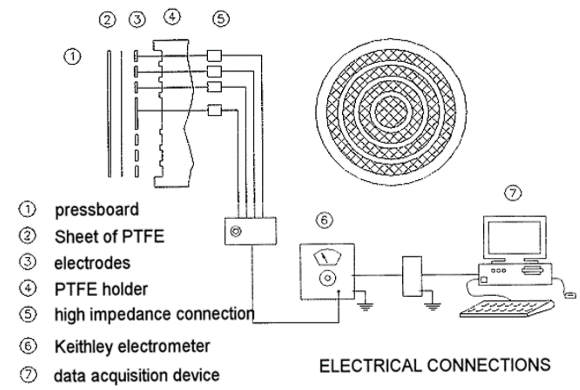

Fig. 6. Diagram of the electrical connections of the impinging jet vein.

initially 4 m long and then shortened. Thus, six capillary lengths of exactly the same material have been tested: 4 m, 3 m, 2 m, 1 m, 0.5 m and 8 cm. The electrical conductivity of the liquid remained constant during all the set of experiments. This means that the amount of impurities inside the liquid has mainly remained constant, but, as the experiment campaign lasted several months, it is possible that some change in impurities concentration occurred which could influence the space charge density at the wall.

For a tube of circular cross section with a radius R, the

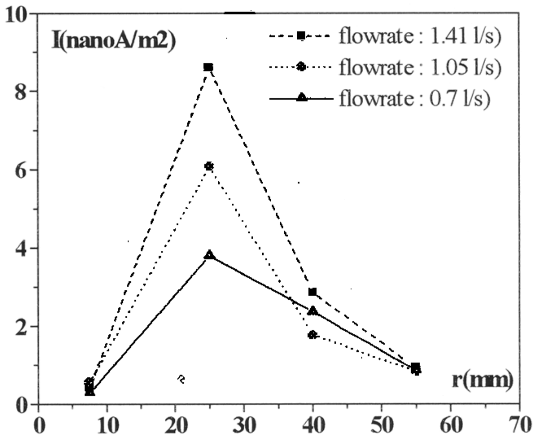

Fig. 7. Wall current on the different concentric electrodes.

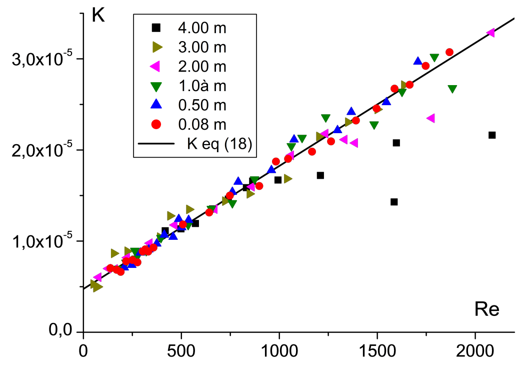

Fig. 8. K evolution in terms of Re and z.

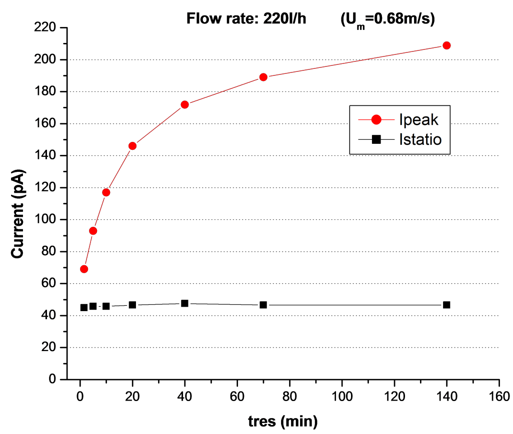

Fig. 9. Evolution of the peak and stationary currents for pressboard.

streaming current at abcisse z for a laminar flow $I(z)$ is:

$$I(z) = 8\pi\rho_w(z)R^2U_m\left(\frac{\delta_0}{R}\right)^2\frac{I_2(R/\delta_0)}{I_0(R/\delta_0)} \tag{14}$$

And the space charge density convected $Q_l(z)$:

$$Q_l(z) = 8\pi\rho_w(z)\left(\frac{\delta_0}{R}\right)^2\frac{I_2(R/\delta_0)}{I_0(R/\delta_0)} \tag{15}$$

Again, $\rho_w(z)$ verifies Eq. (11) with a coefficient b given by:

$$b = \frac{K}{4\left(\frac{\delta_0}{a}\right)^2 R\frac{I_2(R/\delta_0)}{I_0(R/\delta_0)}} \tag{16}$$

I_0 and I_2 being respectively the zero order and second order modified Bessel functions.

Reversing the calculus, experimental value of K, can be computed from the experimental values of the space charge transported

$$K = \frac{-2\nu\mathrm{Re}I_2(R/\delta_0)}{(R/\delta_0)^2 I_0(R/\delta_0)} \times \ln\left[1 - \frac{Q_l(z)}{8\rho_{w\infty}}\left(\frac{R}{\delta_0}\right)^2\frac{I_0(R/\delta_0)}{I_2(R/\delta_0)}\right] \tag{17}$$

ν being the kinematic viscosity of the liquid and $\mathrm{Re} = \frac{2U_mR}{\nu}$ the Reynolds number of the flow. $\rho_{w\infty}$ is obtained experimentally, indeed, when Re is very small the space charge density transported tends to the case of a fully developed diffuse layer and:

$$\rho_{w\infty} = \frac{Q_{l\infty}}{8}\left(\frac{R}{\delta_0}\right)^2\frac{I_0(R/\delta_0)}{I_2(R/\delta_0)} \tag{18}$$

We can see in Fig. 8. The experimental value of $K(\mathrm{Re})$ compared with the following analytical expression:

$$K = 1.35 \times 10^{-8}\mathrm{Re} + 4.75 \times 10^{-6} \tag{19}$$

For the computation of the different values of K from experiments we took the following space charge density on the wall (in μC/m^3), for a developed diffuse layer:

Clearly, in this experiment the coefficient K is not only function of physicochemical reactions but also of the Reynolds number, in other words it is a function of the wall shearing stress.

The last research concerning the dependence of K on the wall shearing stress has been made by Cabaleiro and is the most important [15]. Cabaleiro made experiments in rectangular channels 3 mm height, 30 mm wide and 300 mm long. He used three different materials: pressboard, PVC and stainless steel. He analyzes the streaming current at the exit of the channel for different residence time (t_{res}) of the liquid in the channel, thus for different states of development of the diffuse layer without flow. Then, at the exit of the channel, just after the flow begins, and until the time is equal to the ratio of the channel length divided by the velocity sweeping the charges in the diffuse layer, the streaming current must be constant. Then, it decreases to reach a stationary value (I_{statio}) corresponding to the wall current. Practically, due to the response of the electrometer with the cables, the plateau reached by the streaming current is reduced to a peak (I_{peak}). Fig. 9 corresponds to the pressboard channel, Fig. 10. to the PVC channel and Fig. 11. to the stainless steel channel.

The evolution of the peak current is not so clear for Stainless steel; this is probably due to the fact that the double layer formation in the liquid at rest is faster for this material than for

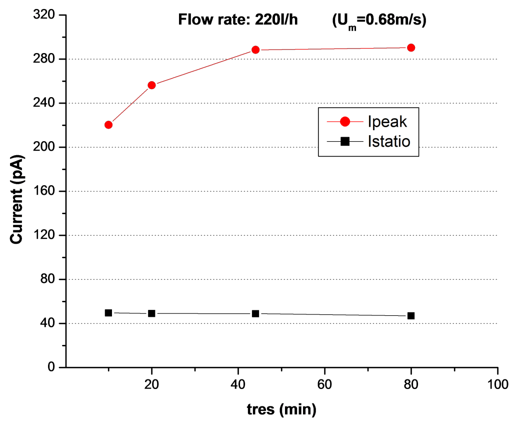

Fig. 10. Evolution of the peak and stationary currents for PVC.

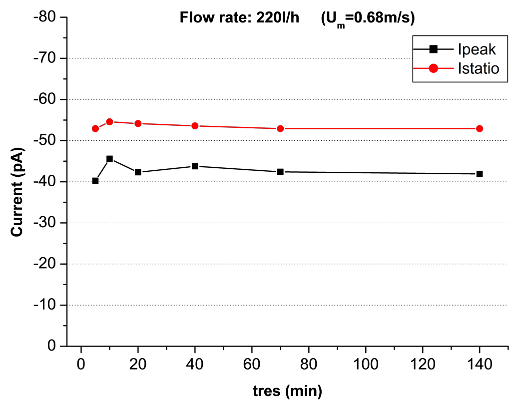

Fig. 11. Evolution of the peak and stationary currents for stainless steel.

pressboard and PVC. In the case of pressboard as the double layer formation seems to be rather slow it seems reasonable to assume that the diffuse layer is quasi in equilibrium inside the channel, thus, assuming also the weak space charge density approximation, the charge profile in the diffuse layer at any time during its development in the liquid at rest can be written:

$$\rho(x,t) = \rho_w(t)\frac{\cosh(x/\delta_0)}{\cosh(a/\delta_0)} \tag{20}$$

The density of charge in the whole diffuse layer facing one wall of the channel (the total charge in the diffuse layer per unit of area of the wall) is given by:

$$\begin{aligned} q &= \int_0^a \rho_w(t)\frac{\cosh(x/\delta_0)}{\cosh(a/\delta_0)}\,\mathrm{d}x \\ &= \rho_w(t)\delta_0 \tanh\left(\frac{a}{\delta_0}\right) \end{aligned} \tag{21}$$

But:

$$i_w = K_0\left(\rho_{w\infty} - \rho_w(t)\right) = \frac{\mathrm{d}q}{\mathrm{d}t} \tag{22}$$

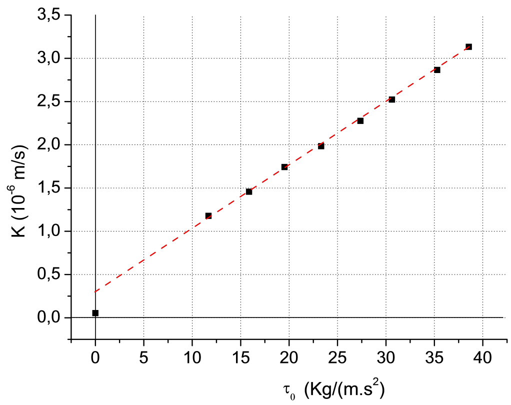

Fig. 12. Evolution of K in terms of the wall shearing stress.

K_0 being the coefficient for a liquid at rest (null velocity). Finally:

$$\rho_w(t) = \rho_{w\infty}\left(1 - \exp\left(-\frac{K_0}{\delta_0 \tanh(a/\delta_0)}t\right)\right) \tag{23}$$

The streaming current I_{peak} is then:

$$I_{peak} = 2l\rho_{w\infty}C\left(1 - \exp\left(-\frac{K_0}{\delta_0 \tanh(a/\delta_0)}t\right)\right) \tag{24}$$

C being the coefficient already defined in Eq. (7). Then, from the experiments shown in Fig. 9, it is possible to compute the value of K_0. It is much smaller than any value of K with a flow; we find $K_0 \approx 10^{8}$ m/s. Finally we present in Fig. 12 all the evolution of the coefficient K in terms of the wall shearing stress τ_0 in the case of the pressboard channel. Again, the coefficient K is strongly dependent on the wall shearing stress, in fact nearly proportional.

V. Model of wall current

From all the experiments described above it seems that the model usually used which does not take into account the wall shearing stress do not correspond to the reality. Thus one part of the model must be modified.

In the previous model [9] we did not suppose any restriction concerning the formation of ion C_S^+ in the liquid. More, in this model we assumed that the concentration of positive ions $[C_S^+]$ at the interface is so large that there is always enough C_S^+ for the reaction:

$$C_S^+ \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} C_S^+ + e^- \tag{25}$$

In other words, the concentration $[C_S^+]$ was not restrictive of the process. But, in fact, it seems that this concentration in the liquid controls totally the wall current, more it is quasi totally proportional to the wall shearing stress.

Thus, we can model as follows: on the wall, atoms C_S^+ exist; even if few of them, due to salvation force, will go to the liquid and become ions C_S^+ (this process corresponds to K_0), the most part of ions C_S^+ in the liquid when it is flowing past the surface is probably due to shear forces applied by the wall shearing stress on the atoms C_S.

VI. Conclusion

In this paper we gathered all the experiments made in our laboratory proving that the process which governs the double layer development in a liquid flowing past a surface cannot be reduced to a simple physicochemical process but is also governed by the wall shearing stress due to the flow. Probably, this parameter is not the only one acting in this process but it plays an important role.

Nevertheless, more experiments of flow electrification dedicated to the analyze of the influence of this parameter are needed to have a better understanding of the phenomenon.

References

[1] A. A. Boumans, “Streaming currents in turbulent flows and metal capillaries,” *Physica*, vol. 23, pp. 1007–1055, 1957.

[2] A. Klinkenberg and J. L. van der Minne, *Electrostatics in the Petroleum Industry*. Elsevier, 1957.

[3] I. Koszman and J. Gavis, “Development of charge in low-conductivity liquids flowing past surfaces. Engineering predictions from the theory developed for tube flow,” *Chemical Engineering Science*, vol. 17, pp. 1013–1022, 1962.

[4] J. C. Gibbings, “Electrostatic charging in the laminar flow in pipes of varying length,” *Journal of Electroanalytical Chemistry*, vol. 25, pp. 497–504, 1970.

[5] G. Touchard, “Streaming currents developed in laminar and turbulent flows through a pipe,” *Journal of Electrostatics*, vol. 5, pp. 463–476, 1978.

[6] G. Touchard, M. Benyamina, J. A. G. Borzeix, and H. Romat, “Static electrification by laminar flows through artificially roughed pipes,” *IEEE Transactions on Industry Applications*, vol. 25, pp. 1067–1072, 1989.

[7] G. Domínguez and G. Touchard, “Streaming current development in a rectangular channel,” *Journal of Electrostatics*, vol. 40-41, pp. 152–159, 1997.

[8] H. L. Walmsley and G. Woodford, “The generation of electric currents by the laminar flow of dielectric liquids,” *Journal of Physics D: Applied Physics*, vol. 14, pp. 1761–1782, 1981.

[9] G. Touchard, T. W. Patzek, and C. J. Radke, “A physicochemical explanation for flow electrification in low-conductivity liquids in contact with a corroding wall,” *IEEE Transactions on Industry Applications*, vol. 32, pp. 1051–1057, 1996.

[10] A. P. Washabaugh and M. Zahn, “A chemical reaction-based boundary condition for flow electrification,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 4, pp. 688–709, 1997.

[11] O. Moreau, P. O. Grimaud, and H. Romat, “Flow electrification in power transformers explanation of the wall-current measurements,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 1, pp. 728–733, 1994.

[12] O. Moreau and G. Touchard, “Experimental study and modeling of static electrification in power transformers,” in *the 1997 IEEE Industry Applications Conference, Thirty-Second IAS Annual Meeting, IAS ’97*, vol. 3, Oct 1997, pp. 1920–1926.

[13] G. Artana, G. Touchard, and O. Moreau, “Flow electrification due to the flow of a perpendicular jet on a flat plate,” *Journal of Electrostatics*, vol. 40-41, pp. 129–134, 1997.

[14] T. Paillat, J. Cabaleiro, H. Romat, and G. Touchard, “Flow electrification process: The physicochemical corroding model revisited,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 16, pp. 359–363, 2009.

[15] J. M. Cabaleiro, T. Paillat, O. Moreau, and G. Touchard, “Flow electrification of dielectric liquids in insulating channels: Limits to the application of the classical wall current expression,” *Journal of Electrostatics*, vol. 66, pp. 79–83, 2008.