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POSSIBILITY OF PRACTICAL USING OF ELECTRIC FIELD IN TRANSPORTATION SYSTEMS

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Abstract - Liquid motion in pipes under electric field action has been theoretically and experimentally investigated for the first time. Essential dependences of liquid properties on electric field are found. Flowrate increase is discovered and viscosity change is estimated. Condition for the effect validity is given. New electric field construction for real transportation system is developed. Using real hydrodynamic diagram, some appropriate pressure gains are calculated

Keywords - electric field, viscosity of liquid, flowrate, cylindric pipe, capacitor.

1. INTRODUCTION

This investigation pattern was realized in accordance with scientific projects N 5800 and 6551 of Kvaerner John Brown Ltd. involving influence of electric and magnetic fields on various liquids properties (first of all oil) in order to improve pumping station functioning for AIOC western route of pipeline. I would like to note beforehand , that some aspects of the pattern which are of sufficient commercial interest are not described here in obvious form.

Because of practical interest of this research, from the beginning it is necessary to elucidate two factors important for liquid transportation in pipeline. These are value of viscosity drop under external agent and liquid "memory"on this agent. As "memory" one considers time for that the liquid conserve its changed state. Having analyzed papers published to present time devoted to influence of physical fields on rheological properties of liquids [1 – 3] , we discriminated the following agents:
a) magnetic field, b) electric field (hereafter e.f.), c) temperature, d) pressure field e) electro-magnetic field (radiation), f) ultrasound.

However, not any from above agents could be used for industrial purposes. For example, agent c) changes liquid viscosity very strongly in the range (-5 $\div$ +20 ^{0}C), but after removal of the agent very rapid reduction of viscosity initial value takes place due to effective heat exchange with surrounding medium. Agents e) and f) prove to be ineffective by the same way, although essential viscosity drop may be acquired by means of them. Agent d) decreases viscosity sharply and has essential "memory", but practical use of it in transportation system is not possible. From the rest of the agents for real transportation systems we did choose e.f. and that′s why :

1. Lorenz force and negative consequences connected with it are absent at any direction of e.f., that gives opportunity to use transverse e.f. as the most convenient from practical point of view.

2. Character of final result does not already depend on magnetic properties of liquids, as e.f. will influence both paramagnetic, and diamagnetic liquids in the same way.
3. From technical point of view, creating e.f. is greatly cheaper and constructurally simpler, than any other agent. In principle, for this task, two metallic plates are enough. Between the plates it is necessary to create potential difference and let liquid pass through them (material and geometric dimensions of plates depend on concrete aim).

2. THEORETICAL APPROACH

Liquid non-stationary isothermal laminar motion in horizontal cylindrical pipe is described by following well-known equation written in cylindrical coor-dinates:

$$\rho\frac{\partial v}{\partial t}=\eta\left(\frac{\partial^2 v}{\partial r^2}+\frac{1}{r}\frac{\partial v}{\partial r}\right)+\frac{\Delta P}{L}+f\,, \qquad (1)$$

where ρ and η are density and viscosity of studied liquid respectively , ΔP / L is the pressure drop ΔP in length L , $v = v(r, t)$ is the velocity of liquid as function of radius and time, f is the force acted on liquid in volume unit (in our case - e.f.). Developed new capacitor construction [4] provides e.f. described by law

$$f=A\cdot e^{-\sigma r},$$

where A and σ are some constant coefficients which characterize external transverse e.f. In practice, applied e.f. may be either direct, or alternating. For real pipeline alternating variant of e.f. is considered as the most profitable due to commercial benefits. So, here we will solve equation (1) taking into account, that e.f. is alternating and changes by time with harmonic law, namely

$$A=A_0\cdot e^{-i\omega t},$$

where ω is the frequency of e.f., A_0 is the initial value (amplitude) of e.f. at time t = 0. Then, equation (1) is written in below form

$$\rho\frac{\partial v}{\partial t}=\eta\left(\frac{\partial^2 v}{\partial r^2}+\frac{1}{r}\frac{\partial v}{\partial r}\right)+\frac{\Delta P}{L}+A_0\cdot e^{-i\omega t}e^{-\sigma r} \qquad (2)$$

with boundary conditions

$$v(r=0,t)=v_{\max}(t)\quad,\quad v(r=R,t)=0\quad,\quad R-\text{radius of pipeline}$$

and time conditions

$$v(r,t=0)=v_{in}\quad,\quad v(r,t=\infty)=v_{fin},$$

where v_{in} and v_{fin} are the initial and final velocities of the liquid respectively. For solving the problem, the below substitution is made first

$$v(r,t)=w(r,t)-\frac{\Delta P}{L\eta}\cdot\frac{r^2}{4}$$

Then , equation (2) is transformed to

$$\rho\frac{\partial w}{\partial t}=\eta\left(\frac{\partial^2 w}{\partial r^2}+\frac{1}{r}\frac{\partial w}{\partial r}\right)+A_0\cdot e^{-i\omega t}e^{-\sigma r} \qquad (3)$$

with the same boundary conditions , but with different time conditions

$$w(r,t=0)=v_{in}+\frac{\Delta P}{L\eta}\cdot\frac{r^2}{4}$$

$$w(r,t=\infty)=v_{fin}+\frac{\Delta P}{L\eta}\cdot\frac{r^2}{4}$$

A solution in below form can be proposed

$$w(r,t)=u(r)\cdot e^{-i\omega t}e^{-\sigma r} \qquad (4)$$

In this case, having subsequently realized all derivatives of function w (r , t) by r and t , after reducing for exponential coefficient $e^{-\sigma r}$ that could never be equal to zero, we obtain

$$(-i\omega)\rho\, u(r)=\eta\left\{\frac{\partial^2 u(r)}{\partial r^2}-\left(2\sigma-\frac{1}{r}\right)\frac{\partial u(r)}{\partial r}+\left(\sigma^2-\frac{\sigma}{r}\right)u(r)\right\}+A_0; \quad (5)$$

this is a non - homogeneous Bessel equation. Solution of the last equation may be given as sum of that of homogeneous equation expressed by Bessel function [5] and partial solution of non - homogeneous equation found by using Lommel function [6]

$$u(r)=\{C_1J_0(\beta r)+C_2Y_0(\beta r)\}\cdot e^{\sigma r}-\frac{A_0}{\eta}S_{1,0}(r)$$

Due to physical matter of the function u (r) and properties of Bessel functions at small values of argument, constant C_2 is accepted to be zero as the liquid velocity cannot be unlimited at r = 0, so at last one arrives at

$$u(r)=C_1J_0(\beta r)\cdot e^{\sigma r}-\frac{A_0}{\eta}S_{1,0}(r), \qquad (6)$$

where

$$C_1=\frac{v_{max}-A_0S_{1,0}(R)/\eta}{1-e^{\sigma r}J_0(\beta R)}\quad,\quad \beta=\sqrt{i\omega\rho/\eta}\,,$$

$J_0(\beta r)$ is the Bessel function of imaginary argument of zero order

$$J_0(\beta r)=ber_0(\beta r)-bei_0(\beta r),$$

$S_{1,0}(r)$ is the Lommel function of zero order. Returning to original function v (r,t), one may define it as

$$v(r,t)=\left\{C_1J_0(\beta r)-\frac{A_0}{\eta}S_{1,0}(r)\cdot e^{-\sigma r}\right\}e^{-i\omega t}-\frac{\Delta P}{L\eta}\cdot\frac{r^2}{4} \qquad (7)$$

To find the flowrate Q through any cross-section of the pipe, one should calculate integral

$$Q=\int_0^R 2\pi r v(r)\,dr$$

without time dependence. The reason of this is the following: We are interested in flowrate increase under e.f. action through any cross - section and want to compare this value with appropriate flowrate through the same cross - section without e.f. For this procedure time dependence of the function v (r , t) may be neglected. From mathematical point of view this corresponds to finding a module of v (r , t) that is complex magnitude. Module of the exponential coefficient $e^{-i\omega t}$ is always 1, so one immediately arrives to the next expression

$$Q_{(E)} = \int_0^R 2\pi r \left\{ C_1 J_0(\beta r) - \frac{A_0}{\eta} S_{1,0}(r) e^{-\sigma r} - \frac{\Delta P}{L\eta} \cdot \frac{r^2}{4} \right\} dr ,$$

where $Q_{(E)}$ is the flowrate under e.f. action. The final result may be given in the following form

$$Q_{(E)} = a_1 J_1(\beta R) R - a_2 H(S, \sigma, R) - a_3 R^4 , \qquad (8)$$

where

$$a_1 = 2\pi C_1 / \beta ,$$
$$a_2 = 2\pi A_0 / \eta ,$$
$$a_3 = \pi \Delta P / 8L\eta ,$$

$J_1(\beta r)$ is the appropriate Bessel function of the first order, the function $H(S, \sigma, R)$ is defined as

$$H(S,\sigma,R) = e^{-\sigma R} \left\{ \sum \frac{\sigma^k}{2(k+1)} \left(S_{k+2,k+1}(R) R + \frac{1}{2} S_{k+3,k+2}(R) \right) \right\} +$$
$$+ \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \frac{\sigma^{j+k+1}}{2(j+2)} S_{k+j+4,k+j+3}(R) e^{-\sigma R}$$

In finding relationship (8), appropriate properties of Bessel and Lommel functions during integrating are used [6]. In this representation, the flowrate is a complex number

$$Q_{(E)} = \operatorname{Re} Q_{(E)} + i \operatorname{Im} Q_{(E)}$$

For calculating the actual flowrate, it is necessary to take the module of $Q_{(E)}$

$$Q_{(E)} = \sqrt{\operatorname{Re}^2 Q_{(E)} + \operatorname{Im}^2 Q_{(E)}} \qquad (9)$$

Now, it is worthwhile to compare the values $Q_{(E)}$ and Q_0, that is well - known flowrate without any external action

$$Q_{(E)} = \sqrt{\pi R^4 \Delta P \big/ 8 L \eta_0} ;$$

where the magnitude η_0 is the liquid initial viscosity. Herein it is necessary to note , in formulae (2) – (8), the value η is accepted as $\eta_{(E)}$ - viscosity under e.f. action. Having compared these flowrates, after non - complex calculations, one may obtain the following ratio for viscosities

$$\frac{\eta_{(E)}}{\eta_0} = \alpha_1 + \alpha_2 \frac{L}{\Delta P} \qquad (10)$$

where α_1 and α_2 are some coefficients which can be found both theoretically and experimentally for any concrete case of liquid and applied e.f.. Since the coefficient α_2

is proportional to A_0 (see expression (2)), we conclude that the more the value of applied e.f., the greater the change of viscosity would be under the action.

If applied e.f. is direct, then one should look for function w (r , t) in (4) without time aspect, namely

$$w(r)=u(r)e^{-\sigma r}$$

because w (r) does not already depend on time; further scheme of the solution will be the same.

3. EXPERIMENTAL

For practical realization of the idea above, it was necessary to develop construction, when e.f. could act on transported liquid. As a base, we accepted the capacitor construction in cylindrical pipe. Two metallic horse-shoe-shaped plates are tightly attached to pipe intrinsic sides. In real conditions of metallic pipeline between plates and sides isolated layer should be installed. But in our laboratory investigations pipeline was substituted for glass and/or plastic pipe with diameter ∅ = (4 ÷ 8) cm, so isolated layer was not created. A pipe length L = (1 ÷ 1.5) m and one pair of plates along the pipe was installed in our experiments. Construction of the platesand dimensions are selected so that maximal quantity of liquid moving through the cross-section was influenced by e.f.

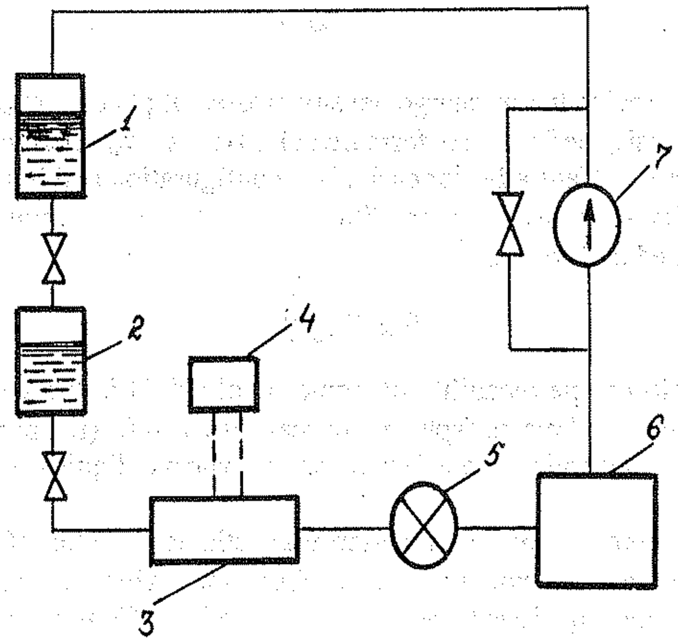

Figure 1. Scheme for experimental observation of e.f. action on liquid viscosity .

Because of liquid viscosity drop, flowrate Q increases under e.f. and pressure drop decreases. In our experiments, initial pressure drop was $\Delta P_0 = (2\div3)$ atm, after influence of e.f., the pressure drop was not measured, but we observed an increase of the flowrate ΔQ due to e.f. action. Scheme of the experiment was shown in fig. 1.

By means of pump 7, liquid is directed from bulb 1 to tank 6 through bulb 2. After all the liquid passes through pipe section 3 (called electric cascade and connected to source 4) where it is acted by "capacitor" which changes the viscosity. Because of this, the liquid flowrate increases which can be read by flowmeter 5.

We theoretically obtained the formula giving an opportunity to calculate the compensation of pressure drop along the length (i.e. negative pressure gradient) due to e.f. action

$$\sigma_{\min} = \frac{\varphi\left(1+\frac{1}{k^2}\right)}{q} \cdot \frac{\Delta P}{L}, \qquad (11)$$

where $\sigma_{\min}$ is the minimal charge surface density at plates necessary for compensating the pressure drop ΔP along section L. Herein, φ is some constant coefficient, q is the total electric charge in liquid volume unit, k is the plate curvature defined as $k = 1 / d$, d is the diameter of plates "sphere". In reality, when plate thickness h is much less than pipeline diameter D ($h << D$) one may consider $d \approx D$.

In order to acquire essential effect of e.f. for moving liquid in capacitor case, the condition to be satisfied would be

$$\sigma_{pl} \geq \sigma_{\min}, \qquad (12)$$

where σ_{pl} is the real value of charge density created at plates , $\sigma_{\min}$ is the threshold value of charge density defined by formula (11). Below $\sigma_{\min}$, effect of e.f. on liquids has not been observed. Naturally, for each plate configuration and liquid type, there will be appropriate value of $\sigma_{\min}$, but condition (12) has to be inevitably satisfied. The value σ_{pl} is defined by formula

$$\sigma_{pl} = \frac{\varepsilon U}{4\pi d},$$

where ε is the dielectric permeability of liquid involved, U is the voltage between the plates, d is the diameter of plates "sphere". In real case $d \approx D$ (D - pipeline diameter).

Some results concerning the effect of e.f. on various liquids are given in figs. 2 and 3 and in table 1.

Temperature range of the investigation was estimated to be $10 \div 25$ ° C. Below 10 ° C, studied liquids did not move by rubber tubes which connect base elements shown in fig.1 , so investigations have not been carried out. Temperature of liquids have been measured in bulb 1. Since the bulb was of great dimensions , we have not been able to thermo - insulate it, so accuracy of the temperature was estimated as 0,1 ° C , which is acceptable for commercial conditions.

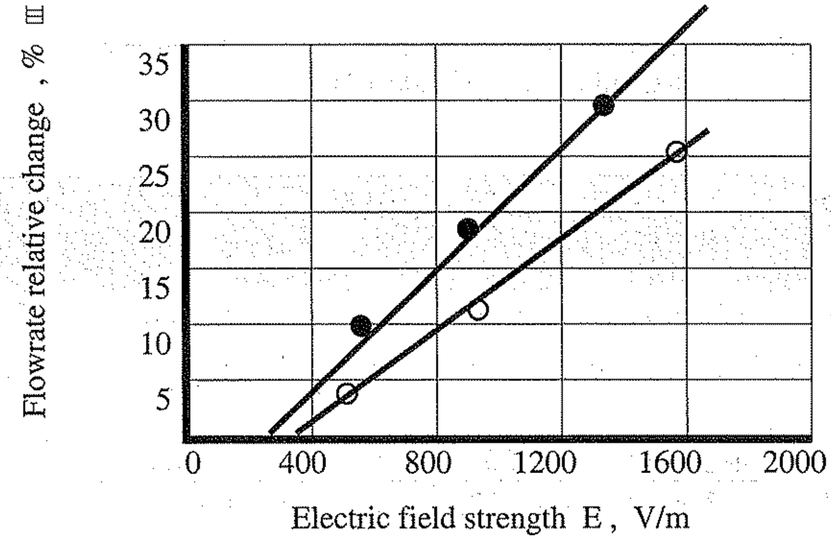

Figure2. Flowrate increase of oil versus e.f. strength at temperature t = 18 ° C. Light circles are for purtified oil, dark ones are for crude. Below 250 V/m for crude oil, and 300 V/m for purified no effect has been observed, as condition (12) has to be valid .

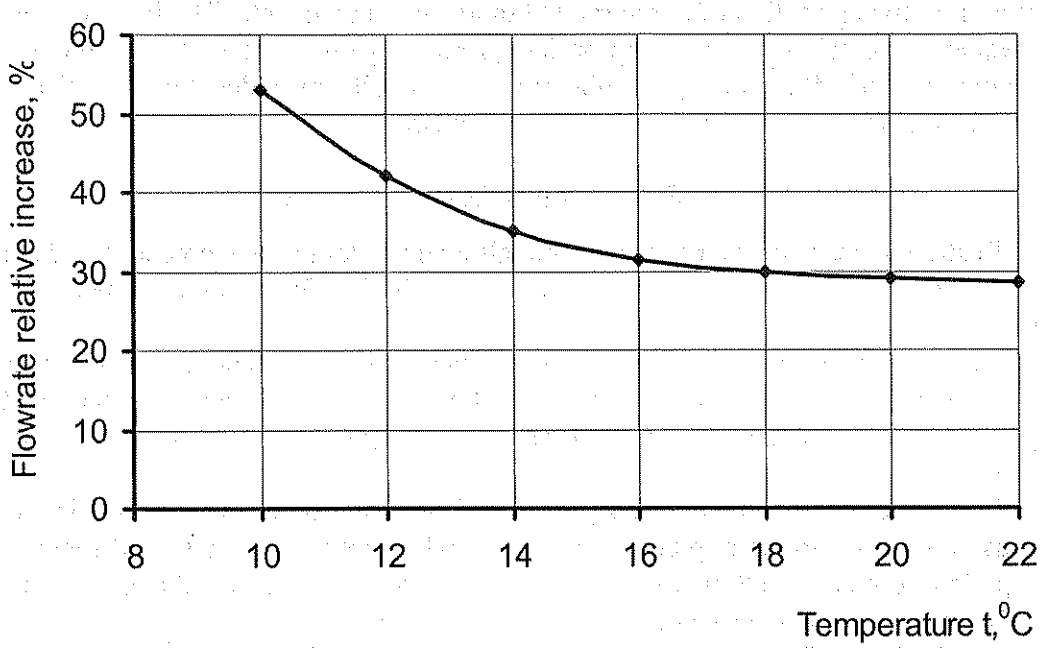

Figure 3. Flowrate increase of crude oil versus temperature under e.f. strength E = 1600 V/m .

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Table 1. Results of measurements under the effect of transverse alternating e.f. E = 1600 V/m.

Type of Liquid	Density kg / m^3	Flowrate change, % t = 10 °C	Flowrate change, % t = 18 °C	Memory, min	Pressure gain , % t = 10 °C	Pressure gain , % t = 18 °C
Oil (crude)	860	+(50÷55)*	+ 35 *	5 ÷ 6	110 ÷ 115	≈ 70
Oil (purified)	750	+(35÷40)	+ 25	5 ÷ 6	70 ÷ 80	≈ 50
Benzine	720	+(25÷30)	+ 20	3 ÷ 4	50 ÷ 60	≈ 40
Machine oil	830	+(35÷40)	+(18÷22)	4 ÷ 5	70 ÷ 80	33 ÷ 41

*) signs " + " in the third and fourth columns mean flowrate increasing under e.f.

From the table one can see that all liquids flowrate increased as it was readily predicted (see item 2 of chapter **1**) . Purified oil has lower flowrate change compared to crude oil . This finding may have been explained by less number of electrically active centres in the first that is the result of purification process. Presence of significant "memory " on e.f. (see the fifth column) allows us to use this effect for practical purposes: in transportation of commercial liquids, in medicine etc. The last two columns are sequences of calculations of appropriate pressure gain , if one takes into account the increasing of flowrate (the diagram was kindly provided by Mr. Roger W. Groombridge, Pipeline Manager, Kvaerner John Brown , Ltd) .

4. RESULTS AND CONCLUSIONS

Restricted space of the paper does not allow us to completely note all the details of the investigation. However, we would like to underline the following obtained sufficient results :

1) Capacitor construction in pipe which enables to sharply decrease liquid viscosity was developed for the first time. There are a few variants of capacitors ; each of them may be applied in dependence on concrete purpose, pipeline route, required viscosity drop etc.

2) We created hydrodynamic theory of liquid moving under e.f. action in pipe in various variants (horizontal pipe , pipe with height - drop , transverse and longitudinal e.f. applied , direct and alternating e.f.). For each case, appropriate change of viscosity and flowrate increase are found.

3) Lower limit of effect of e.f. action on viscosity of liquids is theoretically predicted and experimentally observed. Formula for determining the limiting value σ_{min} is given.

4) A new algorithm for calculating the pressure gain along pipeline is created. A principal model of pipeline without pumping stations is developed. Electric cascades,

e.f. applied to them, distance between the cascades in dependence on liquid " memory " and velocity are estimated.
5) In the paper, we considered non - conducting liquid only, when specific resistance is enormous (in practice , this condition is realized for oil and oil - products which are commercially important for transprotation) . If specific resistance of liquid is low (for example , water) , it is necessary to take into account alternating electric currents arising under e.f. action .
6) Moreover , in moving any liquid under alternating e.f. generated due to electro - magnetic induction, magnetic field should be taken into consideration for complete description of liquid behaviour. However, aspects marked in items 5 and 6 are out of the volume of one paper and will be objects of our further investigations.
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