Electromagnetic Flow Meter Efficiency

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Abstract—A study of electromagnetic flow meter is presented in the paper. Comparison has been made between the analytical and the numerical results by the use of FEM numerical analysis (Quick Field 5.6) for determining polarization voltage through the circle cross section of the polarization transducer. Exciting and geometrical parameters increasing its effectiveness has been examined. The aim is to obtain maximal output signal. The investigations include different variants of the magnetic flux density distribution around the tube: homogeneous field of magnitude B_m, linear distribution with maximal value B_m and trapezium distribution conserving the same exciting magnetic energy as the homogeneous field.

Keywords—Effectiveness, electromagnetic flow meter, finite element method, polarization voltage.

I. INTRODUCTION

THE flow meter is an instrument that measures linear, nonlinear, mass or volumetric flow of a liquid or a gas within a pipe or tube.

Electromagnetic flowmeters work by detecting the induced voltage between two electrodes, situated opposite to one another in the pipe wall, when a magnetic field normal to the flow direction is applied. The accuracy of the measurement is therefore dependent on the existence of processes that can induce a voltage difference between the electrodes apart from the flow signal itself. It is well known [1], that the charged particles situated in a position not symmetrical with respect to the electrodes, will induce an unwanted signal. This trouble is avoided calculating processes in the flow meter numerically.

Measuring the flow rate of liquids is an important industrial application. In some operations, the ability to conduct accurate flow measurements is very significant. There are cases in which inaccurate flow measurements or failure to take measurements can cause not only serious but even disastrous results.

With most liquid flow measurement instruments, the flow rate is determined indirectly by measuring the fluid's velocity [2], [3], or the change in kinetic energy [4] and [5]. Velocity depends on the pressure differential that is forcing the fluid through a pipe or conduit. Because the pipe's cross-sectional area is known and remains constant, the average velocity is an indication of the flow rate. Other factors that affect liquid flow rate are the liquid's viscosity and density, and the friction of the liquid in contact with the pipe walls.

Most velocity-type meter housings are equipped with flanges or fittings to permit them to be connected directly into pipelines. The velocity flow meters include the devices based on the electromagnetic field theory – electromagnetic and magneto-electric flow meters. The obvious advantages of these instruments are due on their contactless transducing and electrical output signals, which discloses great possibilities for automatic control and management [6].

The paper deals with some electromagnetic flow-meter theoretical problems [7] and verification of the obtained analytical results numerically by applying Finite Element Method. Finally-investigations and conclusions show that the distribution and the exciting magnetic field wave front shape are very important in the increasing effectiveness of the device even in the case without changing the quantity of the exciting magnetic energy.

II. COMPARISON AND VERIFICATION OF THE MODELS

A. Analytical Model

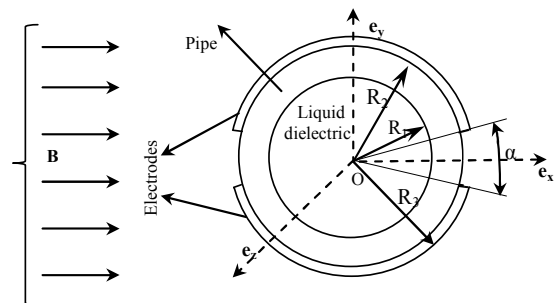The schematized cross section view of the device is presented in Fig. 1.

Fig. 1 Cross section of a polarization transducer

Accepted idealizations in analytical investigation are:
- The length of the pipe is vastly greater than any other linear dimension;
- The pipe is from dielectric material and consequently on the walls are not stored electric charges;
- The two electrodes are conductive, nonmagnetic;
- The dielectric liquid is nonmagnetic;
- The forward motion of the fluid is uniform;
- The processes are stationary;
- The currents of conductivity are neglected;
- The physical characteristics of the medium ε, μ and γ are considered constants.

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The governing equation of polarization transducer is solved with respect to the scalar electric potential φ. Independently of the applied magnetic field characteristics in the moving dielectric fluid is valid the following differential equation

$$\nabla^2 \varphi = \frac{\varepsilon - \varepsilon_0}{\varepsilon} \operatorname{div}(\mathbf{v} \times \mathbf{B}) \ . \tag{1}$$

After a number of transformations a final expressions are obtained [7] with respect to the polarization voltage U_e between electrodes

$$U_e = \frac{\pi}{4 \ln 4/\alpha} \frac{(\varepsilon_r - 1)}{\varepsilon_r} \frac{(1-k)}{R_1^2 - R_2^2} R_1^2 B v_m d \cos \alpha, \tag{2}$$

$$k = \frac{(\varepsilon_1 k_1 - \varepsilon_2)}{(\varepsilon_1 k_1 + \varepsilon_2)} \frac{(1 - k_1)}{(R_1^2 + R_2^2)}, \ k_1 = \frac{R_2^2 - R_1^2}{R_2^2 + R_1^2}, \ d = 2R_1. \tag{3}$$

These expressions include the dielectric permitivities of the fluid and the pipe ε_1 and ε_2, respectively. As could be seen in [7] and [8] and presented as final results here the voltage measured between electrodes, placed on the opposite sides of flow channel, is proportional to the mean velocity of the flow v_m.

Equations (2) and (3) are solved with mean value of the liquid velocity $v_m = 0.5 \text{ m/s}$, the magnetic flux density $B_m = 0.5 T$ and the following values of the other participating magnitudes: $R_1 = 0.025 \text{ m}$ and $R_2 = 0.025 \text{ m}$; the angle between two electrodes $\alpha = 20 \deg$; the relative dielectric permittivities - $\varepsilon_{r1} = 4$ and $\varepsilon_{r2} = 5$ of the liquid and the pipe, respectively.

For the value of the polarization voltage between the electrodes analytically is found $U_e = 2 \text{mV}$. The result differs from this one when the pipe is reduced only to the shell. Then the calculated values are: voltage between electrodes $U_{es} = 2.315$ mV and surface electrode charge $Q_s = 5.6 \cdot 10^{-14}$ C.

B. Description of the Numerical Model

As the governing equation in liquid dielectric is used (1). The real magneto-hydrodynamic distribution term of the velocity in radial direction [9] under the steady state conditions is introduced in the form

$$v = 2v_m (1 - \frac{r^2}{R_1^2}) \cdot \tag{4}$$

The problem being solved consists of finding the voltage between two electrodes and the potential distribution in the channel. The forward problem is solved now by the use of FEM and applying QuickField 5.6 software package. The following boundary conditions are posed:

- $\frac{\partial \phi}{\partial n} = 0$ along the symmetry axis $\mathbf{e}_y$;
- φ=0 - Dirichlet boundary conditions along the axis of electrical anti-symmetry $\mathbf{e}_x$ and on the buffer zone boundary;
- The evaluated value of the potential φ on the upper electrode is equal to the voltage Uwith respect to the plane of anti-symmetry ($\varphi = 0$).

The numerical solution requires the right side of the governing equation to be presented in developed form. The transformations performed in two variants-in Cartesian and in cylindrical coordinate systems give physically analogically results. Because of this the results are presented here in Cartesian coordinates only. Taking into account the aim to be investigated the influence of the exciting magnetic field distribution on the output voltage the analytical expressions are developed in more common form. They correspond to the following assumptions: $\mathbf{v} = \mathrm{v}[r(x,y)]\mathbf{e}_z$, $\mathbf{B} = B(y)\mathbf{e}_x$ and $R_1 = R_2$. In accordance with these relations more universal equation for the member with divergence in the right side of (1) is obtained

$$div(\mathrm{v} \times \mathbf{B}) = div(\mathrm{v} B \mathbf{e}_y) = B \frac{\partial \mathrm{v}}{\partial y} + \mathrm{v} \frac{\partial B}{\partial y} \cdot \tag{5}$$

C. Analytical and Numerical Results Comparison for the Homogeneous Exciting Field

Applying this computational technology the potential of the upper electrode has been found (Fig. 2) as $\varphi = U = 1.378$ mV .
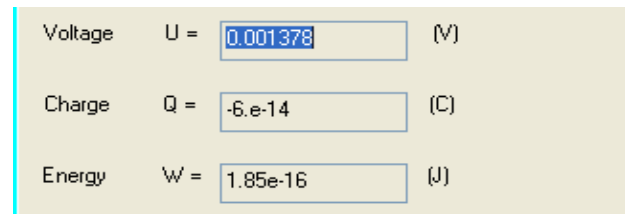
Fig. 2 The main quantities electric voltage, charge and energy

Approximately the same is the scalar electric potential at the point very closed to the electrode (Fig, 3), where is calculated also electric intensity *E*.
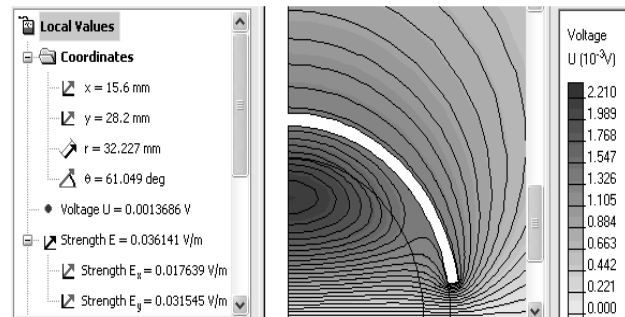
Fig. 3 Distribution of the electric field in the flowing dielectric. The exciting magnetic field is homogeneous

Here is taken into account that the potential of the upper electrode is equal to the voltage U between it and the plane of anti-symmetry. Consequently the voltage between the two electrodes is Ues $= 2U = 2.756$ mV. On the basis of this result the relative error ∇,% between the analytically and the numerically computed values is

$$\nabla,\% = \left| \frac{2.315 - 2.756}{2.315} \right| .100 = 19.0 \% \qquad (6)$$

This error is relatively not very small, but the error with respect to the electrode charge is oppositely rather small. The analytical result for the electric charge is Q=5.6.10^{-14} C and the corresponding numerical result is Q$_n$=6.10^{-14} C (Fig. 2). The relative error is $\nabla_Q,\% = 6.67\%$.

The comparison between the results shows good agreement. The conclusion is that the models adequately describe the real device behavior and it is possible applying them to make additional investigations.

III. NUMERICAL INVESTIGATIONS

A. The Exciting Magnetic Field Distributions

The investigations are implemented for three different cases:

1. $\mathbf{B} = B_m \mathbf{e}_x$, $B_m =$ const.-homogeneous magnetic field (Fig. 1);

This is the basic variant for which the analytical solution is earlier obtained [7].

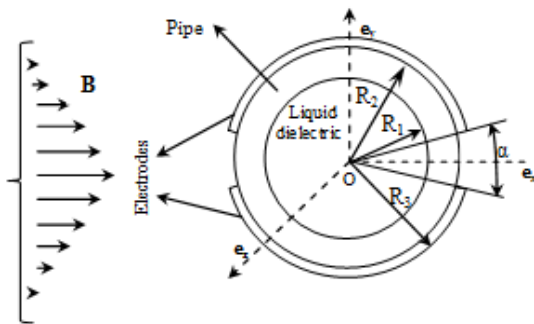2. $\mathbf{B} = B_m(1 - y/R_2)\mathbf{e}_x$ -linear distribution (Fig. 4);

Fig. 4 Linear distribution of the exciting magnetic field

3. $\mathbf{B} = B_m(1.6 - 48y)\mathbf{e}_x$ -trapezium form (Fig. 5).

This distribution characterizes physically total amount of the exciting magnetic field energy the same as in the first case (Fig. 1).

Replacing the B(y) equations and the expression for v from (4) the right side of (1) is circumstantially determined. Now the mathematical analogy between the fields is used. It is known that in the electrostatic field the Poisson's equation is presented as follows

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon}. \qquad (7)$$
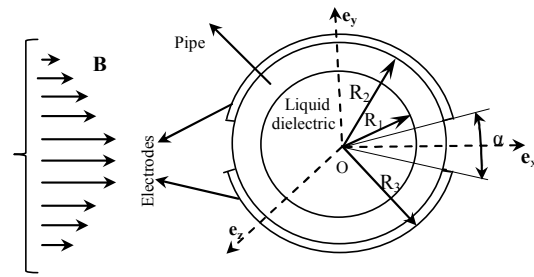

Fig. 5 The magnetic field distribution with the trapezium form

Equalizing two right sides of (7) and the transformed equation (1) the exciting source of the static field ρ is obtained. The analytical expressions of this source are presented in Table I for the relevant exciting magnetic fields.

TABLE I
EXPRESSIONS FOR THE EXCITING SOURCE

Case	Magnetic flux density	Corresponding source ρ
1	$\mathbf{B} = B_m \mathbf{e}_x$	ρ = 4.248e-8*y
2	$\mathbf{B} = B_m(1 - y/R_2)\mathbf{e}_x$	ρ = 5.312e-10*(-4800*y*y+80*y+ +1-1600*x*x)
3	$\mathbf{B} = B_m(1.6 - 48y)\mathbf{e}_x$	ρ = 26.55e-13*(-1152000*y*y+ +25600*y+240-384000*x*x)

The numerical solution is possible to be found then applying the software package Quick Field 5.6 [10].

B. The Exciting Magnetic Field Distribution Influences the Output Electrical Signal

Additional calculations for the cases 2 and 3 of the exciting magnetic field distribution and for different types of the exciting wave shape- linear (case 2, Fig. 4) and in the form of the trapezium (case 3, Fig. 5) show that these factors significantly influence the magnitude of the output electrical signal. The results are presented and discussed below.

The linear distribution is characterized with the same maximal value of the magnetic flux density $B_m = 0,5T$, but it has to be taken into account that the total amount of the exciting magnetic field energy is approximately two times smaller than in the case with homogeneous magnetic field. The induced electric field is presented in Fig. 6.
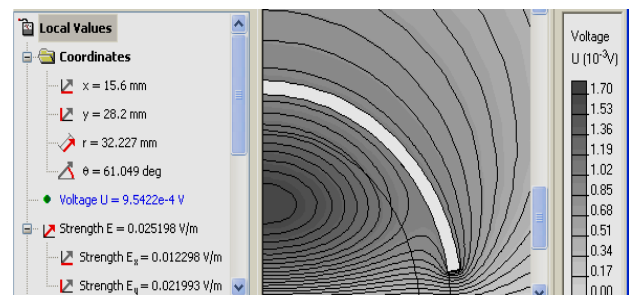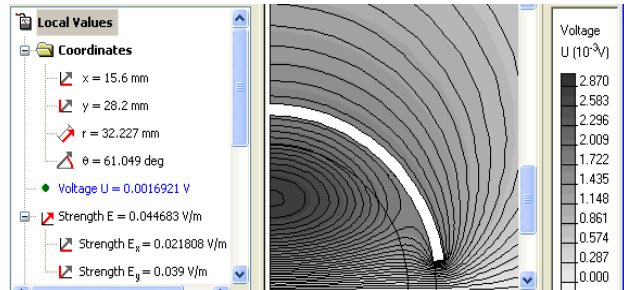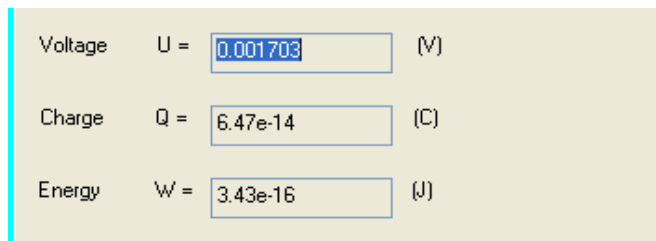

Fig. 6 Distribution of the electric field in the flowing dielectric. The exciting magnetic field is linearly changing

It ascertains that the output electrical signal decreases $\varphi = U = 0.954$ mV and $U\mathrm{es} = 2U = 1.908$ mV. The percentage decreasing is with 44%.

For checking-up the hypothesis that the shape of the excited field wave influences the output signal the next variant is examined: $\mathbf{B} = B_m(1.6 - 48y)\mathbf{e}_x$ -trapezium form. Now the exciting magnetic energy is the same as in the first studied case but the shape of the wave distribution is different. The results with respect to the induced electric field distribution and characteristics are shown in the next Fig. 7.

(a)

(b)

Fig. 7 The exciting magnetic field has the trapezium form.(a) Distribution of the electric field in the flowing dielectric; (b) the values of the voltage U, charge and the electric energy

The results show that all values characterizing excited electric field increase: the voltage between electrodes with 24%, the electric charge with 8% and the electric energy with 85%. It is clear that this action depends on the form of the magnetic flux density distribution and obviously needs of additional investigation.

C. The Influence of the Angle α between Electrodes

The influence of the angle α has been also studied. It proves (Fig. 8) that the opening angle α between electrodes considerably affects the output electrical signal. Two or three times increasing this angle leads to 26% and respectively 48% increasing of the voltage between two electrodes. But this very favorable change causes unfavorable and even dangerous effect because now the rate of the external parasite influences also increase. The preferable value of α could be found formulating and solving the problem as optimization one.
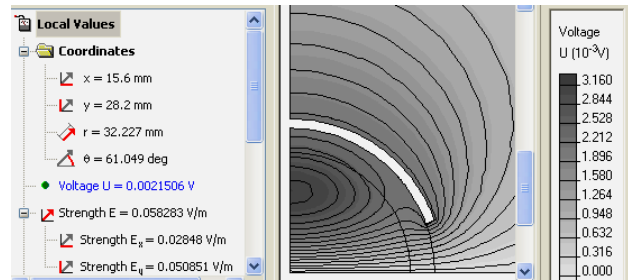
(a)
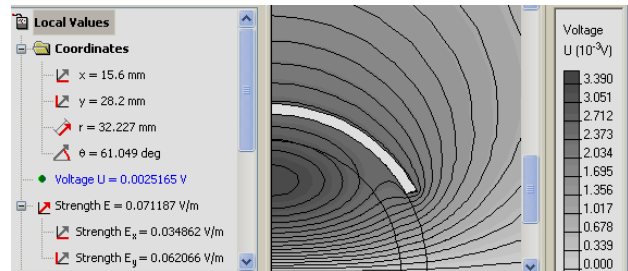
(b)

Fig. 8 Electric field in the dielectric at exciting magnetic field with trapezium form. The opening angle α is: (a)- 40deg.; (b)- 60 deg

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