Design and Simulation of Electromagnetic Flow Meter for Circular Pipe Type

M. Karamifard, M. Kazeminejad, A. Maghsoodloo

***Abstract*—**Electromagnetic flow meter by measuring the varying of magnetic flux, which is related to the velocity of conductive flow, can measure the rate of fluids very carefully and precisely. Electromagnetic flow meter operation is based on famous Faraday's second Law. In these equipments, the constant magnetostatic field is produced by electromagnet (winding around the tube) outside of pipe and inducting voltage that is due to conductive liquid flow is measured by electrodes located on two end side of the pipe wall. In this research, we consider to 2-dimensional mathematical model that can be solved by numerical finite difference (FD) solution approach to calculate induction potential between electrodes. The fundamental concept to design the electromagnetic flow meter, exciting winding and simulations are come out by using MATLAB and PDE-Tool software. In the last stage, simulations results will be shown for improvement and accuracy of technical provision.

***Keywords*—**Electromagnetic Flow Meter, Induction Voltage, Finite Difference .

I. INTRODUCTION

ELECTROMAGNETIC flow meters rely on the Faraday principle, that works with Emf which generated by changing on magnetic flux density. The magnetic field produces by exciting wire in two kinds of DC and AC excitation systems. Therefore, induced voltage between electrodes calculated by simple equation $E = B \cdot d \cdot \upsilon_m$, that illustrate the operation of an electromagnetic flow meter that based on the Faraday's law. In above equation, B is magnetic flux density, d is length of conductive which is equal to diameter of the pipe and υ_m is mean flow velocity [1]-[3], [6].

Also, by selecting constant magnetic field, the magnetic potential is directly proportional to transposed velocity of flow [1]-[4], [10]. Generally, for measuring of difficult fluid velocity such as slurry, melting material and special liquid by electrical conductivity is useful. In [1], [6] a primary design is presented by the form of a two-dimensional weight function, that shows profile the velocity-to-voltage signal ratio of flow in cross-section pipe.

Shercliff has illustrated a weighting function $W = B \times j$ for electromagnetic flow meter with circular cross-section which can be developed in a three-dimensional form by using a virtual current density vector $\vec{j}$ in which an ideal flow meter including an uncondensed fluid with $curl\,\vec{W} = 0$. The voltage signal of electrodes will be in perspective rate of the passing fluid without making allowance to velocity distribution [2]-[3], [5]. The operation of electromagnetic flow meter by circular cross-section is presented in [3], [8]-[9], in comparison with rectangular cross-section or open channel on which the induced voltage is independent from the distribution of fluid velocity [6]-[7], [11].

In this paper, we are going to address the modeling of electromagnetic flow meter with homogeneous magnetic field and effective velocity of fluids on induced voltage. For this case, the general principles used to modify the design of the circular cross-section pipe that is simulated by m-file programming in MATLAB software and PDE-Tool. Finally, the results of simulation are presented on the operation of EM flow meter, effects of fluid conductivity coefficient and effective of the fluid level in pipe on induced voltage.

II. GENERAL OPERATION PRINCIPLE OF EM FLOW METER

The operation of electromagnetic flow meter based on Faraday's law that is known from theoretical analysis which is seen for static magnetic field. The produced voltage signal is consistent of the volume rate of fluid flow in transposed velocity profile.

The dependence of induced electrical voltage ϕ, in measurement region to fluid velocity $\bar{\upsilon}$ ''$\frac{m}{s}$'' and magnetic density of flux $\vec{B}$ ''T'' is shown in Fig. 1.

Generally, prevailing EM flow meter that is consist of pipe with circular cross-section for passing a fluid, producer of magnetic field in the direction of fluid and a couple of electrodes on the cross side of pipe wall is shown in Fig. 2.

Usually, the magnetic field is produced by exciting wires with alternative current from one side to another of the pipe . Also, the material of the pipe must be made of non-magnetic ones because of the self influence.

Magnetic field interaction that is caused to generate an electrical field $\vec{E}$, inside fluid by positive (negative) ions movements of fluid that is based on Lorentz law . Therefore, this electrical field can present by gradient of electrical potential ϕ. Thus, induced voltage between electrodes in simple E.M. flow meter calculate as follow

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$$\Delta U_{EE} = B \cdot d \cdot \upsilon_m = \frac{4B}{\pi \cdot d} Q \tag{1}$$

Where we get ΔU_{EE} as induced voltage ‘‘$volt$’’, d as the distance of the electrodes ‘‘m’’, υ_m as average velocity in cross-section of tube ‘‘$\frac{m}{s}$’’ and Q as the volume rate of transposed fluid ‘‘$\frac{m^3}{s}$’’

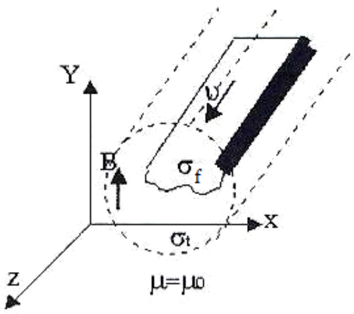


Fig. 1 Modeling of Electromagnetic flow meter

Note that ΔU_{EE} in (1) is depended on electrical conductivity coefficient, viscosity and pressure of flow meter which will satisfy when electromagnetic field is uniform and the velocity of profile is symmetrical [3], [7]-[8]. So, explanation and illustration of the operation principle for electromagnetic flow meter is necessary in identifying the electric and magnetic information of flow meter environment.

Thus, the permeability μ of transposed fluid is qualified the fluid conductivity coefficient σ_f, and the tube conductivity coefficient σ_t ‘‘$\frac{S}{m}$’’ are independent of electrical and magnetically flux density that is not correspond to Hall's effect [11]. The kind of transposed flow and field don't have self induced effects. Also, we supposed the velocity vector υ on the surface of magnetic field have horizontal component υ_z which is $\frac{\partial \upsilon_z}{\partial z} = 0$. Of course, the velocity vector is defined in the case of full pipe and the magnetic analysis being homogeneous that is because of law frequency case. ($\frac{\partial \upsilon_z}{\partial z} = 0$ in which z is measurable parameter).

III. Material and Method

In this paper, design of electromagnetic flow meter is used by simulation and m-fie programming in Matlab soft ware.

A. Structure of E.M. flow meter

Entirely, electromagnetic flow meters are made up two sections, signal detecting unit and signal processing unit. Signal detecting is included of non-conductive tube for fluid flow, electrodes and electromagnet parts.

The electrodes are considered as copular shape like. The magnetic field is usually produced by a pair of identical circular coils that spaced one radius apart and a laminated yoke. Also, they wound the current flows through both coils in the same direction.

The electromagnet can supply with two kinds of excitation, AC and DC. After all, most of measurement are done on low-conductive fluids, we can use of sinusoidal exciting system by AC power supply. This kind of power supply can be controlled by frequency convertor of the power supply that can decrease the peaks of the noise caused by AC voltage which is arisen into error signals in the detecting section of this kind of flow meter by AC excitement.

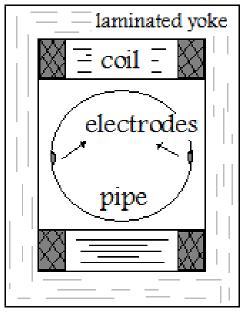


Fig. 2 Structure of Electromagnet

The second part of the electromagnetic flow meter, we have signal processing that shown on Fig. 3. In this section, detecting signals in comparison with small unwanted voltages are filtering then amplifing.

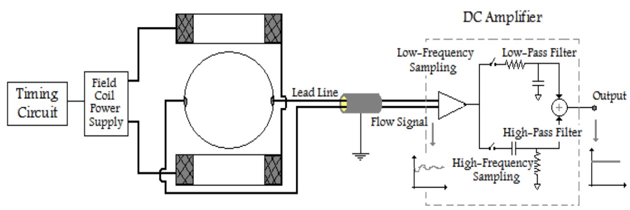


Fig. 3 Signal processing unit

B. Mathematical model and analytical relations

The basic relation in electromagnetic flow meter theory by Shercliff is:

$$div(\sigma \cdot grad\,\phi) = div[\sigma \cdot (\vec{\upsilon} \times \vec{B})] \tag{2}$$

in which σ is conductivity coefficient of fluid and pipe. Thus, by solving $div(\sigma \cdot grad\,\phi) = 0$ and assuming the Neoman and Drichle conditions, we can determine the vector potential between two electrodes (Notice on the division of tube). Consequently, induced voltage, $\vec{\upsilon}_e$, between to point of measurement volume is as follow:

$$U_e = \phi_{e1} - \phi_{e2} = \int_V \vec{\upsilon} \cdot (\vec{B} \times \vec{j}) dv \tag{3}$$

Where V is the volume of measurement region, and $\vec{j}$ is as virtual current density vector .

Bevier and Shercliff have expressed $\vec{W} = \vec{B} \times \vec{j}$ as a vector for weighting function. Now we assume electromagnet produce a field that keep the vector $\vec{W}$ constant, then we have a voltage between electrodes inside the volume that is proportional to average velocity of fluid flow in measurement region.

According to Divergence theorem:

$$U_e = \frac{2aB}{(\pi r^2)} \iint \upsilon(x, y) \cdot W(x, y) dxdy \tag{4}$$

Where a is inner radius of tube and B as the homogeneous field that produced by electromagnet .

C. Calculate of weighting function

Designing of primary transducer for flow meter tube will need to calculate the weighting function that is determined by the shape of measurement region, electrode's shape and size and the conductivity coefficient between fluid and pipe wall. Then, by using of numerical model we can solve the following Laplace equation:

$$div(\sigma \cdot grad\, \phi) = 0 \tag{5}$$

In this step, we consider the Drichle conditions, i.e. voltage $\phi = 1$ for first electrode and $\phi = 0$ on another one. So, the weighting distribution function can be calculated as:

$$\vec{j} = -\alpha \cdot \sigma \cdot grad\, \phi \tag{6}$$

$$\vec{W} = \vec{B} \times \vec{j} \tag{7}$$

Where α is a coefficient for normalizing the total density current that will pass from electrodes, which is shown as:

$$\alpha = \frac{1}{\int_{Se} \sigma \cdot \frac{\partial \phi}{\partial n} ds} \tag{8}$$

Where S_e is the surface of measurement electrode , σ is the conductivity coefficient between fluid and pipe wall.

By noting the position of tube between electromagnet poles and electrodes, the inside magnetic field is on $\hat{a}_y$ direction. The weight function is cross product $\vec{B} = B_0 \hat{a}_y$ magnetic field function by current density vector.

$$W = (B_0 \hat{a}_y) \times (-\alpha \cdot \sigma \cdot (\frac{\partial \phi}{\partial x} \hat{a}_x + \frac{\partial \phi}{\partial y} \hat{a}_y)) \tag{9}$$

That may lead to:

$$W(x, y) = \alpha \cdot \sigma \cdot B_0 \frac{\partial \phi}{\partial x} \hat{a}_z \tag{10}$$

As shown in above equation the direction of fluid flow in tube and the direction of the weight function are same.

D. Numerical method for solving problem

One of the basic approaches in solving of electrical field equations in electromagnetic flow meters are using of Finite Difference method (FDM). In this method, the mentioned equations changed to linear equations that work by dividing of the opinion region to methodical grids as shown on Fig. 4.

As considered the change of potential in electro static field is continues, then by using of Taylor's series expansion around the point with coordinate component (i,j) and linear approximation, potential of (i, j-1), (i, j+1), (i-1, j), (i+1, j) points can determine as:

$$\begin{aligned}
V(i+1, j) &= V(i, j) + h_g \cdot V_x(i, j) + \frac{1}{2} h_g^2 \cdot V_{xx}(i, j) \\
V(i, j+1) &= V(i, j) + h_g \cdot V_y(i, j) + \frac{1}{2} h_g^2 \cdot V_{yy}(i, j) \\
V(i-1, j) &= V(i, j) - h_g \cdot V_x(i, j) + \frac{1}{2} h_g^2 \cdot V_{xx}(i, j) \\
V(i, j-1) &= V(i, j) - h_g \cdot V_y(i, j) + \frac{1}{2} h_g^2 \cdot V_{yy}(i, j)
\end{aligned} \tag{11}$$

In which $h_{g1} = h_{g2} = h_{g3} = h_{g4} = h_g$. If we assume the region by electrostatic field have not any electrical charge. We will receive:

$$V(i, j) = \frac{1}{4}[V(i+1, j) + V(i, j+1) + V(i-1, j) + V(i, j-1)] \tag{12}$$

As the length of grid get smaller, the determination of equipotential lines and field lines can be more accurate.

In this method, at first we estimate the potential of all unknown point of grid and then by using (12) amend potentials of the whole point of grid. This procedure will repeat until achieving the more accurate determination of potential for whole points.

The results of simulations in this section for analyzing of electromagnetic flow meter are presented by DFM that are included calculation of the potential difference between two electrodes. The distribution weight function in different sate of fluid level, the effects of transposed fluid conductivity coefficient and the height of fluid on induced voltage that will be explained continuously .

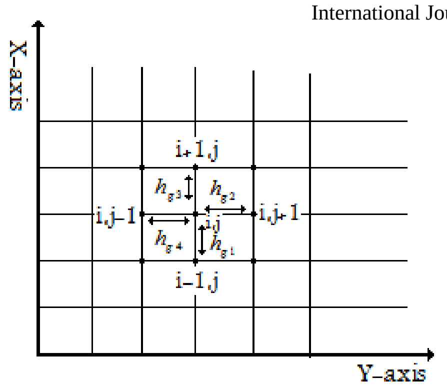


Fig. 4 Dividing of measurement region

IV. Results

The distribution of produced magnetic field and so distribution of electric field between two electrodes has been shown in Fig. 5 and 6, respectively.

Also, in the Fig. you can obviously seen the effects of produced magnetic field lines on electrodes by high conductivity coefficient, as a result the nearly homogenous magnetic field inside the tube can clearly seen.

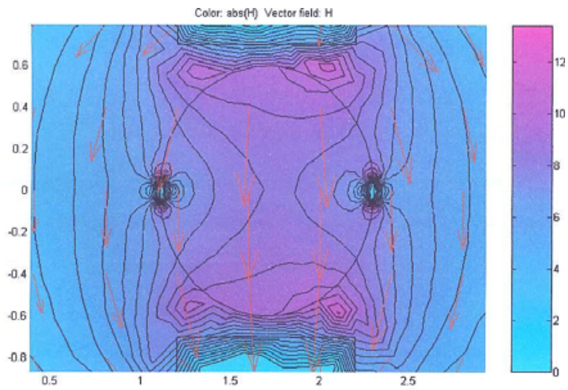


Fig. 5 Distribution of magnetic field inside tube

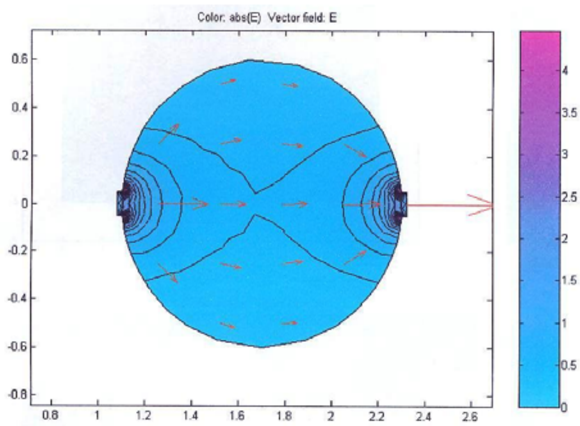
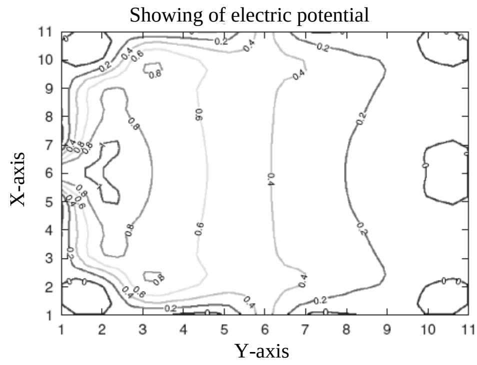


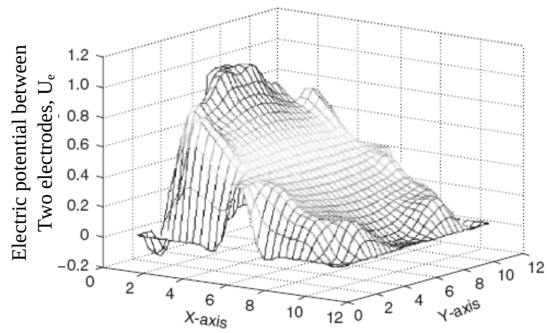
Fig. 6 Electrical field distribution around electrodes

The results of calculation for voltage variations between two electrodes for difference state of fluid level are shown in Fig. 7 and Fig. 8.

The distribution of electric potential between electrodes in cross-section measurement region can be seen in two-dimensional and three-dimensional states that are illustrated fully filled pipe and 60% filled pipe condition. As seen on Fig. 7. the position of electrodes on our coordinate system (x, y) have (6, 1) and (6, 11) points whose potential are $\phi = 1$ and $\phi = 0$, sequentially.

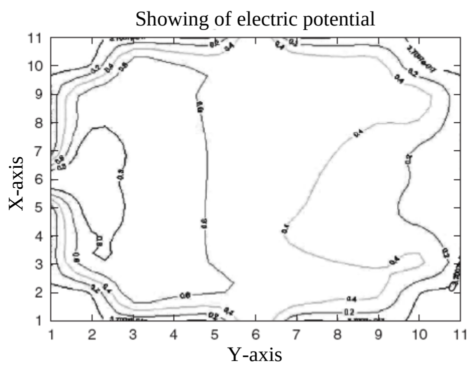


(a)

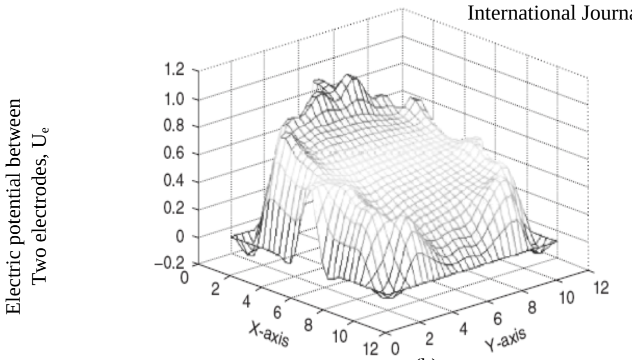


(b)

Fig. 7 Distribution of electric potential for fully filled pipe condition (a) Two-dimensional state, (b) Three-dimensional state



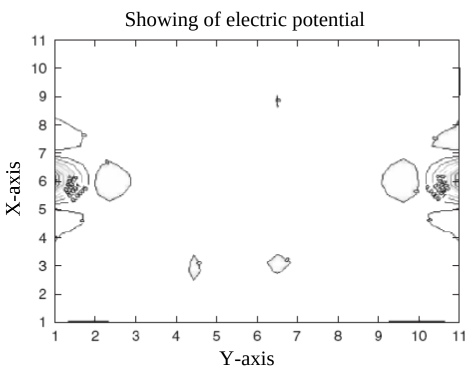
(a)



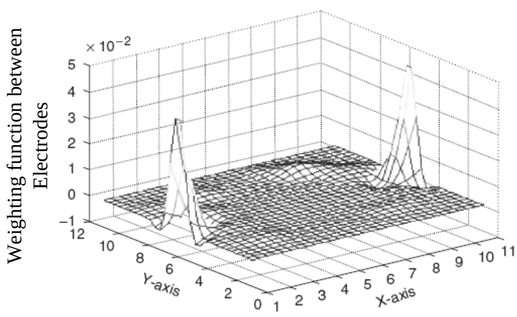
(b)

Fig. 8 Distribution of electric potential for 60% filled pipe condition
(a) Two-dimensional state, (b) Three-dimensional state

The distribution of electrostatic potential for fully filled pipe condition is symmetrical. In contrast, the state of inhomogeneous on fluid flow for 60% filled pipe condition is shown obviously where is because of the fluid-to-air conductivity coefficient ratio effect. The Shercliff weight function distribution for flow meter is shown in Fig. 9, without normalization factor (α) for fully filled condition that can demonstrate the maximum effect of fluid flow velocity on induced voltage in each point of the tube.



(a)



(b)

Fig. 9 Distribution of weight function in flow meter for fully filled pipe condition
(a) Two-dimensional state, (b) Three-dimensional state

The induced voltage between two electrodes by changing on conductivity coefficient of fluid flow for two different velocity of fluid inside the tube is shown in Fig. 10 and Fig. 11.

As defined in the Fig. 10, by increasing the fluid conductivity coefficient the induced voltage between electrodes is increased, that has a linear functional the induced voltage increased.

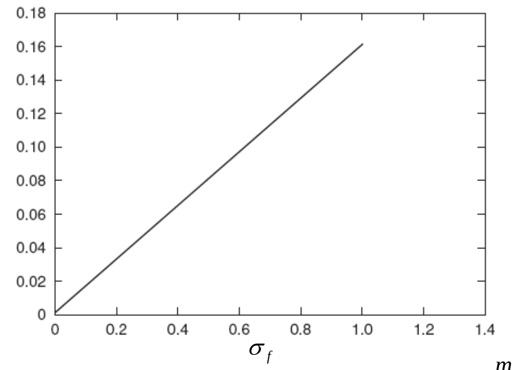


Fig. 10 Induced voltage for constant velocity $\upsilon_m = 1\frac{m}{s}$

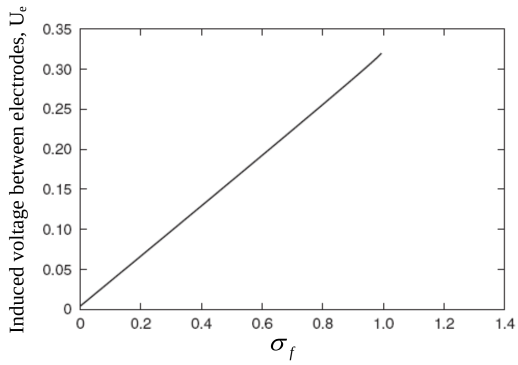


Fig. 11 Induced voltage for constant velocity $\upsilon_m = 2\frac{m}{s}$

To evaluate the effect of fluid level variation in induced voltage between electrodes and for fluid-to-tube conductivity coefficient ratio that is $\frac{\sigma_f}{\sigma_t} = 10$, we have shown the results of simulation in Fig. 12.

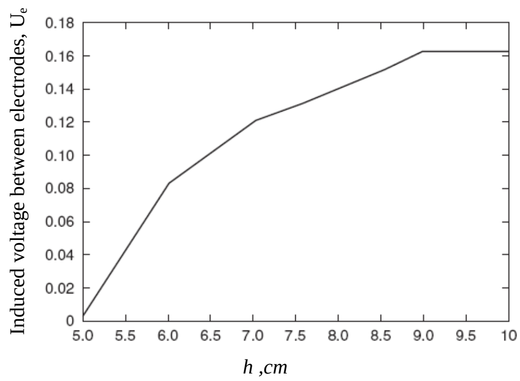


Fig. 12 Induced voltage for variable fluid level with $\frac{\sigma_f}{\sigma_t} = 10$

We can see when pipe is fully filled state; the induced voltage will remain constant. By assuming the electrodes been on a dotted form, the fluid level must not be less than half of the pipe.

V. Summary and Conclusion

We present the analysis and design of circular E.M. flow mete. This analysis is based on induced voltage as rely on the Faraday's law.

According to simulation results, we can calculate the distribution of magnetic flux density on the flow cross-section of tube that is almost uniform. Comparatively, in our design, the outcomes of induced voltage variation between electrodes in fully filled tube state by 60% filled pipe condition were surveyed.

In this manner, weight distribution function showing in fully filled state that will represent the quantity of fluid flow effect on measurement section. Furthermore, we describe the effect of increasing fluid flow velocity and fluid conductivity coefficient on electromagnetic flow meter, perfectly.

This method of measurement for fluid flow have very wide application arena, which can entirely use for any type of fluid like acids, polymer in chemical industry, and especially for their infusion.

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