An Numerical Analysis Approach for a Novel Electromagnetic Flow Meter with Multi-Electrode

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Abstract. Electromagnetic flowmeter (EMFM) plays an important role in technological processes such as the cooling of nuclear reactors. The internal EMFM must have large-size magnet to provide uniform magnetic field. In this paper present a novel electromagnetic flowmeter, which has multi-electrode and non-insulation pipe wall. We present an extended theory and compare it with experimental results. A finite element procedure for the solution of the novel EMFM is presented.

1. Introduction

Multiphase flow measurement occurs in many industrial processes. It is a very challenging task to accurately measure the flow of each phase in multiphase flow [1]. Process tomography (CT) is the current multiphase flow measurement technology [2], including electrical capacity tomography (ECT), electrical resistance tomography (ERT) and electromagnetic tomography (EMT) [3].

ECT installed electrode array on the basis of measuring the capacitance of pipeline. The phase distribution in the flow cross section can be inferred from the dielectric constant distribution. ERT is used for visualization of multiphase flow system [4]. Electromagnetic tomography is a computer tomography technology based on electromagnetic theory. [5,6].

In industrial application, it is very important to measure the volume flow of each phase of multiphase flow. In the past decade, significant progress has been made in this regard [7,8]. However, little progress has been made in the measurement of continuous phase volumetric flow.

Electromagnetic flowmeter (EMFM) based on electromagnetic induction has been one of the standard instruments to measure liquid flowrate in many fields. Commonly, the magnetic field generated by a pair of field coils. The voltage across the pipe induced by the motion of the conductive liquid through the uniform magnetic field is measured between the electrodes. A traditional EMFM has the insulated pipe wall and a pair of point electrodes in the circular insulation pipe wall[1]-[3]. And the electrodes must be in the pipe wall and touch the flow. But it brings lots of problems like dirtying of the electrodes and pipe wall. The insulation pipe wall brings some difficulty in medical measurement like measure blood velocity[4]. The EMFM with non-insulation pipe wall is important to the flow measurement to solve those problems but few papers have research about that.

Multi-Electrode EMFM measure the axial velocity profile of both the conducting continuous phase of multiphase and the single phase conducting fluids. Such as Horner[5] who described a six electrodes EMFM and Miki Sakuratani[6] described a kind of EMFM with eight electrodes. Non-uniform velocity profiles. To improve the accuracy, multi-electrodes EMFM is proposed. But sometimes, we need lower error and some medical measurement need multi-electrode EMFM with non-insulation pipe wall. Or we need research pipe of multi-electrode EMFM dirty effect the measurement result.
Weight value (W) shows velocity distribution in the flow cross section. So we need weight value uniformity ($\epsilon$) is smaller traditionally. The velocity profile can be derived by measuring potential difference within the EMFM.

2. Theory of EMFM with non-insulation Pipe Wall

2.1. Basic theory

According to the Bevir’s law, the weight vector of common EMFM can be described as\([1]\):

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

(1)

$B$ is magnetic flux density; $j$ is virtual current density

Where $B = -\nabla F$; $F$ and $G$ are solutions of Laplace’s equation.

$$W = \begin{bmatrix} B_x j_y - B_y j_x \\ B_y j_z - B_z j_y \\ B_z j_x - B_x j_z \end{bmatrix}$$

(2)

The virtual current $\vec{j}$ depends on the electrode shape and the thickness and conductivity of flowmeter pipe wall. The aim of the EMFM designer is to arrange $B$ and $j$ so that the sensitivity is independent of the flow pattern.

The induced voltage is

$$\vec{U} = \iiint W \times \vec{v} dV$$

(3)

Where $\vec{v}$ is velocity. As can be seen from the Fig.1.

$$\begin{align*}
\vec{B}_x &= B_z = 0 \\
\vec{j}_y &= j_z = 0 \\
\vec{v}_x &= v_y = 0
\end{align*}$$

(4)

So the equation (3) can be transformed to

$$\vec{U} = \iiint B_j \vec{j}_v dV$$

(5)

And we can divide the pipe into many elements. Then $\vec{U}$ can be represented as

$$\vec{U} = \sum_{i=1}^{n} B_j \vec{j}_v$$

(6)

2.2. Theory of Multi-Electrode EMFM with non-insulation pipe wall

The virtual current density $\vec{j}$ depends on the EMFM geometry and the electrode shape as mentioned above. The conventional EMFM pipe wall is insulation, so $\vec{j}$ on the edge of pipe equals 0. But the pipe wall of the mold in this paper is non-insulation, so $\vec{j}$ is not 0 at the boundary of pipe wall. It’s the problem to solve the weight vector ($\vec{W}$), but few paper or book mention the way to solve this.

Assuming the virtual current density on #1 is 1(A/ m²), and virtual current on inner wall point B (see Fig.1a) is $j$ ($0 < j < 1$), therefore its projection on non-insulation pipe wall is $j \sin \alpha$ (A/m²), as shown in Fig.1b. The conductivity of pipe wall and flow is $\sigma_1$ and $\sigma_2$ respectively. Thickness of pipe is $h$. 
According to the Ohm’s law
\[ j = \sigma \vec{E} \]  
(7)

Where \( \vec{E} \) is the current density electric field intensity on point A is:
\[ E = k \frac{Q}{h^2} \]  
(8)

And \( k = \frac{1}{4\pi} \), \( \varepsilon = 8.8542 \times 10^{-12} \text{F/m} \), \( Q \) is the electric quantity of the electrode. Put (7)(8) in (1), then we can get
\[ \vec{W} = B \times \sigma k \frac{Q}{h^2} \sin \alpha \]  
(9)

If magnetic field is uniform and the velocity of flow is fixed. The change of weight function reflected as change of induction electromotive potential between electrodes. The boundary condition between wall and flow is \( \sigma \frac{k}{h^2} \sin \alpha \).

Uniformity of the weight function is given by [3]
\[ \varepsilon = \frac{\int \int |w_i - \overline{w}| dx dy}{\int \int \overline{w} dx dy} \]  
(10)

Where \( \overline{w} \) is mean of weight value. The flow cross section is divided into N pixels, and \( w_i \) is the weight value in every pixel. So the
\[ \overline{w} = \frac{\sum \overline{w_i}}{N} \]  
(11)

3. Numerical simulation

3.1. Weight value uniformity (\( \varepsilon \))

To verify the theory, the traditional EMFM mold with insulated pipe and two point electrodes is first simulated.

The cross section of traditional EMFM mold is divided into 1001×1001 pixels. As mentioned, we can use software Comsol 3.5. The simulation result of weight value distribution is shown in Fig.2. The weight value on center is about 1. The largest value on the points and the least on the edge is about 0.5[8].

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![Schematic diagram of EMFM with Non-insulation pipe wall](image1)

**Fig.1** EMFM with non-insulation pipe wall

**a)** Schematic diagram of EMFM with Non-insulation pipe wall  
**b)** Schematic diagram of EMFM with Non-insulation pipe wall
Fig. 2 Traditional EMFM weigh value distribution

Uniform of traditional EMFM average weight value ($\bar{w}$) is 1 and the uniform of weight value is 0.66 (simulated under analyzed method mentioned above). The simulated results are the same with analytical solution of others paper mentioned[3]. So it is believed that the simulation method is correct and then we use it in the novel mold of this paper to get the average weight value and weight value uniformity.

3.2 Relationships of $\varepsilon$ with pipe wall thickness and conductivity

To understand how the thickness and conductivity of the pipe wall influence the weight value, we simulated weight value uniformity at different thicknesses and conductivities with above simulation method (Equ.(10)). The cross section of the pipe is also divided into 1001×1001 pixels so $i = 1001 \times 1001$. The outer diameter of the pipe is 0.10m. Pipe thickness is 0.012m. A block diagram of the conductivity of water is content and set as 1.5e-2 [S/m]. And wall conductivity is set as a variable, (where the value of conductivity_wall/ conductivity_water is set from 0.001 to 0.1).

For a uniform velocity profile, the weight value with the pipe conductivity is shown in Fig. 3.

![Fig. 3 weight value with the pipe conductivity](image)

Fig. 3 weight value with the pipe conductivity(conductivity_wall/ conductivity_water=0.0055–0.001)

For a uniform velocity profile, the relationship of the weight value uniform with the pipe conductivity is shown in Fig. 4.

![Fig. 4. The relationship of the weight value uniform with the pipe conductivity](image)

Fig. 4. The relationship of the weight value uniform with the pipe conductivity

From Fig. 4, it can be seen that the weight value uniform decreases with the increase of the pipe conductivity under the same pipe wall thickness. Change rate weight value uniformity is 19.6%. Conductivity_wall has no significant influence on uniformity.

The weight value with the pipe thickness is shown in Fig. 5 while the wall conductivity is unchanged and conductivity_wall/ conductivity_water=1/10000(conductivity_water=1.5e-2 [S/m]). The outer diameter of the pipe is 0.10m.
The relationship of the weight value uniform with the pipe thickness is shown in Fig. 6 while the wall conductivity is unchanged and $\text{conductivity}_{\text{wall}}/\text{conductivity}_{\text{water}}=1/10000$ ($\text{conductivity}_{\text{water}}=1.5 \times 10^{-2} \text{[S/m]}$) and the outer diameter is 0.1m. Fig. 6 represents that the uniformity increases with the pipe thickness.

Fig. 5 weight value with the pipe thickness

The result shown in Fig. 6, the pipe thickness is increased and the uniformity is increase. But the uniformity is smaller than uniformity of traditional EMFM (about 0.66 as mentioned above). Change rate of thickness is 80% while change rate weight value uniformity is 28.6%. So the thickness has a significant effect on uniformity. We can change the thickness of wall to make reduce the weight value uniformity.

3.3 Induce voltage at different thicknesses and conductivities of the pipe wall

Fig. 7 (a) shows the EMFM in a 3-D system. Sixteen electrodes are placed at the pipe wall with the angular intervals of 22.5 degrees and #5 on the top of the pipe and #13 at the bottom of the pipe, as shown in Fig. 7(b). Because the pipe is non-insulation, the electrodes are on the outer side of the pipe. It is the character of the novel EMFM, and it’s meaningful to measuring the blood and to analyzing the dirty pipe wall. Water flow direction is Z and velocity is 2m/s. Conductivities of water and air are $1.5 \times 10^{-2} \text{[S/m]}$ and 0 S/m respectively. Helmholtz coil material was assumed to be copper with a conductivity of $5.96 \times 10^7 \text{[S/m]}$, and magnetic flux density $\vec{B}$ is $4.61 \times 10^{-4} \text{T}$. The inner and outer diameters of the two coils are 0.2048m and 0.2550m.
15S/m, 1.5S/m, 0.15S/m, 0.015S/m, 0.0015S/m respectively and wall thickness is 5mm. The relationship of induced voltage at electrodes with pipe wall conductivity is shown in Fig. 8.

From the simulation results above, $U_j$ is decreased while conductivity is increased. And the rising rate is smaller than the rising rate of the conductivity of wall. So to improve $U_j$, decreased the wall conductivity is not very good way.

From simulation results, the induced voltage decreased as wall thickness increased. So to improve $U_j$, decreased the wall thickness is better.

4. Conclusion
This paper describes a novel non-insulation pipe wall EMFM with sixteen electrodes. And new analysis approaches of boundary condition and weight value uniformity are present. The boundary condition is researched and relationships between wall thicknesses and conductivity with induced voltage are analyzed. The simulation results show that the induced voltage force increases with the decreases of the thickness and the wall conductivity.

Weight value uniform that shows the weight value distribution is very important to EMFM, and we simulated the relationship of the uniform with wall conductivity under same water conductivity. The uniform increases with the decreases of wall conductivity.

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