Simulation Research on Optimal Installation Position of partially-filled pipe Electromagnetic Flowmeter sensor

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Abstract. The measurement sensor of the partially-filled pipe electromagnetic flowmeter must be installed where the fluid is fully developed. For partially-filled pipe electromagnetic flowmeters, the boundary conditions vary with the fullness of the pipe, and the distance from the pipe inlet to the fully developed is not the same as the distance of the full-filled pipe flowmeter. Therefore, in the partially-filled pipe state, the mounting position of the electrode sensor is also different from the mounting position at full-filled pipe state. Based on the measurement principle of electromagnetic flowmeter, the finite element simulation method is used to simulate the flow field development of partially-filled pipe electromagnetic flowmeter. First, according to the knowledge of hydraulics, the variable boundary constraint is established, and then the simulation model of flowmeter fluid development process is established. Second, the Comsol Multiphysics finite element simulation software is adopted to solve the fluid development process, and the required distance for the full development of the partially-filled pipe fluid is obtained. Finally, the optimal installation position of the partially-filled pipe electromagnetic flowmeter sensor was determined based on the distance. The simulation results prove the feasibility of the proposed method, which can provide powerful theoretical support for the fabrication of partially-filled pipe electromagnetic flowmeters.

1. Introduction
According to Faraday’s law of electromagnetic induction, when the fluid reaches a fully developed state, the output signal of the electromagnetic flowmeter sensor is proportional to the average flow velocity of the measured flow field [1,2]. According to the knowledge of hydraulics, the distance from the entrance to the fully developed flow state of fullness circular pipe is at least 10 times the pipe diameter of the pipe, and the length of outlet section should be at least 5 times the diameter of pipeline. Therefore, the measuring sensor of the traditional electromagnetic flowmeter is usually installed at the position of at least 10 times the diameter from the inlet of the pipeline, and the sensor electrodes are at least 5 times the diameter of the pipeline from the outlet of the pipeline[3]. However, when the fluid is in a partially-filled pipe state, the distance of fully developed fluid is far than that of fullness pipe due to the influence of pipeline degree and wall friction. The studies have shown that if the flow field is not fully developed, there is a non-stationary nonlinear relationship between the output signal of the sensor and the average flow velocity of the measured flow field [3]. Therefore, whether the flow field of the sensor measurement position has reached fully development is an important factor affecting the measurement accuracy of the partially-filled pipe electromagnetic flowmeter.

The research on the installation position of the electromagnetic flowmeter sensor mainly focuses on the pipe cross-section shape, the length of the straight pipe section, pipe bending, etc[4-8]. If the
length of straight pipe is not enough, the flow field can not meet the conditions for fully developing, which will undoubtedly directly affect the flow measurement accuracy of the flowmeter [9]. However, all the researches on the installation position of the sensor are based on the assumption that the flow field reaches full development and steady state. Since the study of the full development distance of the partially-filled pipe flow field involves complex nonlinear equation solving, which increase the difficulty of studying the flow field development of partially-filled pipe, so the research results on these kinds are relatively rare.

In recent years, the development of computer hardware technology and finite element theory has provided a powerful tool for solving complex nonlinear flow field models, making the solution of partially-filled pipe flow field feasible. Aiming at the problem of the required distance for the fully development of the partially-filled pipe flow field, the finite element simulation method is combined with the traditional flow field development theory to study the required distance for the fully development of the partially-filled pipe flow field. Based on the simulation results, the optimal mounting position of the measurement sensor is determined.

2. Measuring principle of electromagnetic flowmeter
The basic structure of the electromagnetic flowmeter is shown in Figure 1. In the figure, 1 is the measuring pipe of the flowmeter, 2 is the sensor signal converter, 3 is the excitation coil, 4 is the electrode sensor, and 5 is the fluid flowing through the pipeline.

![Figure 1. Schematic diagram of electromagnetic flowmeter](image)

When the conductive fluid flows through the pipe at an average flow rate $\bar{v}$, the fluid cuts the magnetic field $B$, then there is an induced potential $E$ output on the electrode sensor. If the exciting magnetic field is evenly distributed, the average flow velocity of the fluid and the induced potential have the following relationship

$$\bar{v} = E(BD)^{-1}$$  \hspace{1cm} (1)

where $D$ is the hydraulic diameter of the pipe. For a electromagnetic flowmeters using circular pipe, the volume flow rate is

$$Q = \pi DE(4B)^{-1}$$  \hspace{1cm} (2)

The formula (1) and (2) are the basic measurement principle of electromagnetic flowmeter. One of the basic conditions for the above formula to be established is that the fluid is fully developed at the sensor measurement position. However, when the length of the straight pipe section at the front end of the sensor is insufficient, the fluid in the pipe is not fully developed due to the distortion of the velocity distribution of the fluid in the pipe, which may cause the uncertainty of the measurement data to increased. Therefore, whether the front end of the electrode sensor has sufficient long straight pipe length is an important factor affecting the real-time measurement accuracy of the electromagnetic flowmeter. When the flowmeter is in the full filled pipe state, the length of the straight pipe section of the flowmeter front end has been given a clear standard in the literature [3]. But when the flowmeter is in a partially-filled pipe state, since the pipe fullness and the pipe friction resistance are variables, the
boundary conditions are far more complicated than that of the full pipe. Regarding the study of the length of the straight pipe section at the front end of the flowmeter, there is no clear theoretical basis in the relevant literature. Therefore, how to determine the length of the straight pipe section under the condition of partially-filled pipe state is the primary problem to be solved.

3. Establishment of simulation model for partially-filled pipe flow field

It is known from the foregoing discussion that if the installation position of the non-full-tube electromagnetic flowmeter sensor is to be determined, the length of the straight pipe section of the sensor front end must be determined first. The specific method can be summarized as follows: Separately investigate the distribution of fluid at different degrees of fullness of the pipeline, when the velocity distribution on a section of the pipeline is close to the velocity distribution of the downstream section and reaches a steady state, then the distance between the section and the inlet is considered to be the shortest inlet section length of the partially-filled pipe, and the downstream position of the section is the fully development interval of the pipeline.

In this thesis, the length of the inlet section of the circular partially-filled pipe is studied by the finite element simulation method, and then the optimal length of the inlet section is determined. A two-dimensional partially-filled pipe flow velocity development model was established by using the turbulence model in the fluid flow module of the finite element simulation software Comsol Multiphysics. The specific parameter setting are as follows:

1) The hydraulic caliber of the model is the diameter of the experimental equipment used in the experiment, and is set to \( D = 50 \text{mm} \).

2) In order to ensure the length of the pipe is long enough, in the case where the length of the inlet section is not determined, the initial length of the pipe model is set to \( 20D \).

The material in the pipe model is set to water, its density \( \rho \) is set to \( 1.0 \times 10^3 \text{kg/m}^3 \), and the kinematic viscosity \( \mu \) is set to \( 1.308 \times 10^{-3} \text{Pa.s} \).

4) Initial velocity setting of the inlet section of the pipeline: Since the pipeline is a circular partially-filled pipe, its theoretical average velocity can be derived from the Manning formula [10].

\[
\bar{v} = \frac{1}{n_r c} R_H^2 S_g \frac{1}{2}
\]

where \( n_r c \) is the surface friction coefficient of the pipe model. The material used for the measuring pipe is plexiglass in the experiment, the surface friction coefficient can be found as \( n_r c = 0.0085 \) by using the manual, \( R_H \) is the hydraulic radius, \( S_g = 0.0033 \) is the hydraulic gradient of the pipe model. The average flow rate of different fullness degree is shown in Table 1.

| Fullness(%) | 20   | 30   | 40   | 50   | 60   | 70   | 80   | 90   |
|------------|------|------|------|------|------|------|------|------|
| Average flow velocity(m/s) | 0.2239 | 0.2825 | 0.3284 | 0.3640 | 0.3904 | 0.4076 | 0.4149 | 0.4093 |

5) The boundary conditions of the pipe inlet are set to the velocity field, the turbulent length \( L_r \) and turbulence intensity \( I_r \) can be obtained by equation (4) and (5).

\[
L_r = 0.07D \]

\[
I_r = 0.16 \times \text{Re}^{1/8}
\]

6) The boundary condition of the pipe outlet is set to no pressure field, in order to simulate the influence of the wall to be measured, the bottom wall of the pipe is set to the near wall surface function, and the fluid surface is set as a sliding wall function.

Since there is only fluid and air in the partially-filled pipe, and the effect of air on fluid flow rate is very small in non-closed space. Therefore, when choosing the calculation area, only the fluid flow area
is needed for calculation. According to the above description, the finite element simulation model is shown in Figure 2.

![Figure 2. Simulation model](image)

According to the above parameter settings, the flow distribution under full-filled pipe conditions is simulated. The simulation results are shown in Figure 3.

![Figure 3. Simulation result](image)

Obviously, when the pipe is full, the fluid reach fully developed between 0.45m–0.5m (9D ~ 10D). The simulation results are consistent with the previous research results, which proves that the established model and the corresponding boundary conditions are correct.

4. Simulation analysis of Length of Straight Pipe Section

Based on the flow velocity simulation model established in the previous section, the fluid development was simulated to determine the length of the inlet straight pipe section, and then the optimal installation position of the sensor is determined. The specific method is as follows: First, the flow velocity distribution was calculated when the pipe fullness are 30%, 40%, 50%, 60%, 70%, 80% respectively. Second, the approximate distance for the fluid to reach full development was obtained according to the fluid development cloud image. Then according to a certain distance interval, the flow velocity distribution on each section in the range is laterally compared to determine the length of the inlet section of the straight section of the electromagnetic flowmeter.

4.1. Finite element simulation

According to the parameter setting in the previous section, the whole computational area is first meshed. In order to ensure a small calculation amount and computational convergence, the standard grid is selected to divide the entire calculation area. After calculation, the whole flow velocity distribution of the fluid is obtained as shown in Figure 4(a)–(f)
Figure 4. Flow field development at different water depth. (a) water depth=30%. (b) water depth=40%. (c) water depth=50%. (d) water depth=60%. (e) water depth=70%. (f) water depth=80%.

It can be seen from Figure 4(a)–(f) that the flow velocity distribution of the fluid at different heights is relatively uniform at the inlet. With the fluid flow, the flow velocity is gradually stable, and most of the pipeline fluid enters a stable and fully developed stage after 0.6 m ($D/2$). The flow velocity distribution of different cross sections in the downstream is intercepted at equal intervals, and a more precise position that is fully developed can be obtained by comparison. Taking the flow rate development at 70% fullness as an example, it can be seen from Fig. 4(e) that the fluid flow rate gradually enters a stable development state at 0.6 m ($2D$) from the inlet, so the straight pipe length of the inlet section of the pipe at 70% fullness can be preliminarily judged.
4.2. Optimal installation position at different fullness

Based on the previous simulation analysis, the flow velocity distribution on different sections is further compared horizontally to determine whether the flow field is fully developed. Taking the flow velocity distribution at a water depth of 70% as an example, the flow velocity distribution on different cross sections is as shown in Figure 5.

![Figure 5. Velocity Distribution in Different Sections of Pipeline at 70% Water Depth](image)

In Figure 5, \( D \) is the diameter of the pipe, and \( 8D, 10D, 12D \), etc. refer to the distance between the measured section and the inlet of the pipeline. Obviously, the flow velocity curve is very similar near the pipe wall and near the water surface. At the maximum velocity point, the larger the measurement distance is, the larger the velocity is, and the velocity curve is very similar between \( D_{18} \sim D_{12} \). It shows that the flow field has been fully developed.

Taking the length \( D \) as the interval, the flow velocity distributions on the subsequent different sections are taken and further compared. If the flow velocity on adjacent sections are similar, the flow rate is considered to be fully developed. Let \( v_i,j \) be the flow velocity of the measuring point, where \( i \) is the measuring cross section, and \( j \) is the measuring points on the cross section. Then the flow velocity absolute deviation on the adjacent sections can be expressed as

\[
\zeta_i = \sum_{j=1}^{m} \left| v_{i+1,j} - v_{i,j} \right|, \quad i = 1,2,3,...,n
\]

where \( j = 1,2,3,...,m \), and \( m \) is the number of longitudinal measurement points. If the flow rate deviation satisfies the following expression, the flow rate is considered to be fully developed

\[
\epsilon_i = \frac{\zeta_i}{\sum_{j=1}^{m} v_{i,j}} \leq 0.1\%
\]

The flow velocity distributions at different fullness are compared according to Equation (6) and (7), the shortest distance from the inlet to fully development is obtained at different degrees of fullness, as shown in Table 2.

| Fullness(%) | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
|-------------|----|----|----|----|----|----|----|
| Shortest inlet length(D) | 8  | 10 | 12 | 12 | 12 | 13 | 14 |

It is clear that the shortest inlet length for the fluid to reach full development during different fluid fullness is not fixed. The shortest distance is \( 8D \) and the longest distance is \( 14D \). Since the fluid flowing in the pipe is often changed between the full pipe and the partially filled pipe, and when the pipe is full filled, the distance of fluid reaches fully developed is \( 10D \), so the optimal installation position of the electrode sensor for the partially filled pipe electromagnetic flowmeter should be at the distance of \( 14D \) from the inlet end.
5. Conclusion
In this paper, the optimal installation position of the electrode sensor of the partially-filled pipe electromagnetic flowmeter is studied. Whether the fluid is fully developed is one of the key factors affecting the installation position of sensor. According to the knowledge of hydraulics, the boundary constraints of partially-filled pipe electromagnetic flowmeter measurement are given, then the simulation model for the development of partially-filled pipe turbulent flow velocity is established. The model is solved by the PDE module in the finite element simulation software Comsol Multiphysics, and the distance required for the partially-filled pipe fluid to reach full development from inlet is obtained, then the optimal installation position of the electrode sensor is determined. The simulation results show that under the given boundary conditions, the optimal installation position of the partially-filled pipe electromagnetic flowmeter is $14D$ away from the inlet.

Acknowledgments
This work was supported by the Science and Technology Project of Education Department of the Guangdong Province, China(2017GKTSCX079), and Science and Technology Project of Education Department of the Jiangxi Province, China(GJJ151069), and the Research Project of Zhongshan Polytechnic, China(2018G01)

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