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New Method of Flow Measurements Based on CFD for Partially Filled Pipe

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***Abstract*— Aiming at the problems that current methods of flow measurements for partially filled pipe are difficult to measure flow at low liquid level , install and maintain, the new measured method for partially filled pipe is proposed. The liquid level is got by using a high-precision pressure sensor that is based on the theory of communicating pipe. The measured value is processed by the liquid level-flow function model to obtain the precise flow value. Before the experiments, a U-shaped communicating pipe was externally connected at the appropriate position of the steel pipe. Based on the computer fluid dynamics (CFD) simulation technology, the flow state of the gas-liquid two-phase flow in the pipe was simulated, and the optimal installation position and diameter size of the U-shaped communicating pipe were determined. According to the simulation results, it could be concluded that the reasonable installed position of the communicating pipe was that the position distances from 1m to 2.5m from the water inlet place of the steel pipe, and the diameter of the communicating pipe should be selected as 0.02m. The experimental results showed that when the liquid level was below than 10% of the diameter of the steel pipe, the measurement error was less than 2%, and the repeatability error was about 1.6%. The experiments verified that the method was feasible and suitable for many occasions, such as agricultural irrigation and sewage discharge.**

Keywords—partially-filled; computer fluid dynamics; two-phase flow; model; simulation

I. Introduction

Partially filled pipe state is quite common in many situations such as municipal sewage, agricultural irrigation and wastewater treatment. In comparison to the case of the fully filled pipe state, the flow measurement in the partially filled pipe can be affected by several factors due to the existence of the free liquid surface, such as the diameter of the pipe, flow rate and viscosity of the liquid and so on. At present, almost of the flow measurement systems for the partially filled pipe, including the TADALFLUX of German Cologne company, the Pati-MagII of ABB, the systems developed by Toshiba of Japan and the system developed by Shanghai University, etc., are based on the calculation according to the on-line measuring flow rate and liquid level in the pipes using the pre-installed electrode set or long arc electrodes [1~4]. In this case, the electrodes must be immersed into the fluid to achieve the online measurement of the data. However, the accuracy of the measurement can be affected by the contact resistance of the liquid/electrode interface, although the influence of the resistance can be reduced in a certain degree by reducing the size of the electrodes. Therefore, these methods are not suitable for the flow measurement in the case that the liquid level is below than 0.1D due to the limitation of electrode size[5~6]. Meanwhile, since the electrodes are generally installed inside of the pipes, the maintenance of the electrodes can increase the cost.

In this paper, a new method is proposed to address the flow measurement problem when the liquid level is below than 0.1D. A U-shaped communicating pipe was welded on the side of the steel pipe, and an external pressure sensor that is put into the communicating pipe measures the liquid level, and the measured signal is processed by the liquid level-flow model to output the corresponding flow value. Experiments are conducted to demonstrate the feasibility of the method and the reliability of the results.

II. Measuring Principle

A. Principle of Liquid Level Measurement

In order to measure the liquid level in the steel pipe, the high-precision pressure sensor is placed into the U-shaped communicating pipe, and the measuring component of the sensor is fixed at the same height as the bottom of the steel pipe. The installation position is as shown in Figure I.

The measurement principle of the high-precision pressure sensitive component is that the resistive diaphragm is tightly bonded to a fixed substrate through the adhesive. When the stress of the substrate changes, the resistance of the diaphragm changes correspondingly. After the bridge amplification, the corresponding voltage value is obtained. When it is placed in water, according to the pressure formula, the water pressure is different when the liquid level is different. Then it can be obtained that the corresponding liquid level in the U-shaped communicating pipe from the varying voltage value. According to the principle of the connected pipe:

$$\rho_1 \cdot g \cdot h_1 = \rho_2 \cdot g \cdot h_2 \tag{1}$$

Since the same fluid density is equal, $\rho 1=\rho 2$, so the liquid level in the steel pipe is equal to that in the U-shaped communicating pipe when the pressures on both sides are the same. By using this principle, the liquid level in the steel pipe can be obtained by measuring the liquid height value in the U-shaped communicating pipe without disturbing the fluid flow state inside the steel pipe. At the same time, the external type of installation also makes the replacement of the pressure sensor easier and the maintenance costs lower.

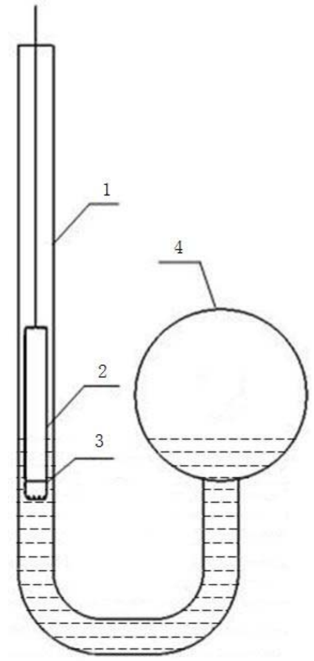

FIGURE I. PRESSURE SENSOR INSTALLATION POSITION DIAGRAM

Among them, 1--U-shaped communicating pipe; 2--pressure sensor; 3--pressure sensitive component; 4--steel pipe.

B. Liquid Level-Flow Model

According to the flow formula:

$$Q = A \cdot \upsilon \tag{2}$$

The flow value (*Q*) depends on the average flow rate (*v*)and the cross-sectional area (*A*) of the fluid in the steel pipe. The calculation formula for the cross-sectional area(*A*) of the fluid flowing through the pipe is as follows:

$$\begin{aligned} A = {} & \frac{\pi}{4}D^2 - \frac{D^2}{4} \cdot \arccos\frac{2h-D}{D} \\ & + (h-\frac{D}{2}) \cdot \sqrt{(\frac{D}{2})^2 - (h-\frac{D}{2})^2} \end{aligned} \tag{3}$$

Where: *D* -- the inner diameter of the pipeline, m;

h -- the height of the liquid level, m.

Since *D* is a constant, the size of *A* is only related to *h*. Therefore, by measuring the value of *h*, the corresponding value of *A* can be obtained. It can be known from the formula (2) that if the liquid levels of the fluid in the steel pipe are selected, and the flow values at these levels are measured by the flow meter, the function relationship between the average flow velocity (*v*) of the fluid flowing through the steel pipe and the liquid level (*h*) can be got.

$$\upsilon = f_1(h) \tag{4}$$

By consulting the relevant literature [7~13], it can be seen that measuring the flow value of the pipe within the same inclination, the liquid level (*h*) and the average flow velocity (*v*) of the fluid in the pipe will increase when the flow value (*Q*) increases, but the liquid level (*h*) increases obviously. Under the state of partially filled pipe, liquid level (*h*) can more sensitively reflect the changes of the flow value(*Q*). Therefore, the flow value (*Q*) can be obtained by accurately measuring the liquid level. Based on the above analysis, the liquid level-flow model is established as follows:

$$\begin{aligned} Q = {} & (\frac{\pi}{4}D^2 - \frac{D^2}{4} \cdot \arccos\frac{2h-D}{D} \\ & + (h-\frac{D}{2}) \cdot \sqrt{(\frac{D}{2})^2 - (h-\frac{D}{2})^2}) \cdot f_1(h) \\ = {} & f(h) \end{aligned} \tag{5}$$

III. EXPERIMENTAL MATERIALS AND PLATFORM

In order to verify the feasibility of the simulation results, an experimental platform was set up as was shown in FigureⅡ, the main experimental equipments that were used were showed as follows: 1) Homemade 0.5m*0.5m*0.5m stainless steel communicating water tank; 2) a pump with a rated power of 250W; 3) L20 elbow, relief valve; 4) QS intelligent electric control valve; 5) DN20 electromagnetic flowmeter with accuracy class of ±0.2% FS; 6) Signal processing unit; 7) High-precision pressure sensor (The range is 0~1m and the accuracy is 0.1%FS); 8) Customized a U-shaped communicating pipe; 9) Main steel pipe that is a standard galvanized steel pipe with the diameter size is 0.1m , matching flanges and the other water pipes which are standard galvanized steel pipe with the diameter size is 0.02m; 10) BOPU solenoid valve.

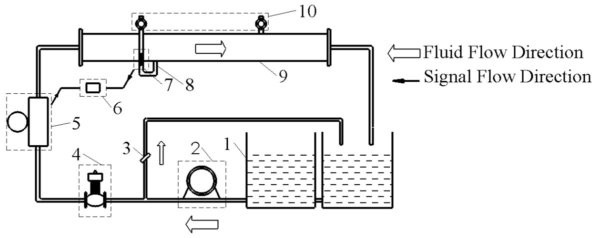

FIGURE II. SCHEMATIC DIAGRAM OF THE EXPERIMENTAL PLATFORM DESIGN

IV. SIMULATION ANALYSIS

According to hydromechanics[14], the fluid state inside the pipe can be influenced by several factors, such as viscous drag , the roughness of the inner wall, flow rate, and the inner diameter of the pipeline, giving rise to the energy loss and the fluid flow instability. Fluid flow stability is different at different locations. Therefore, selecting the position where the flow state is more stability in the steel pipe is important for the measurements. This makes the fluid in the communicating pipe can be approximately regarded as a static pressure in the axial direction of the steel pipe to improve the measurement accuracy. What's more, the diameter of the communicating pipe is also needed to be optimized to make sure that the communicating pipe can be more sensitive to reflect the changes of the liquid level in the steel pipe, so the accuracy of the measurement results can be risen.

A. Determination of the Installation Position of the Communicating Pipe

In order to determine the appropriate installation position of the communicating pipe, chosen a 3m pipe with the diameter of 0.1m (DN100). The flow state at five locations along the axial direction (*z*) of the pipe (*z*=0.25m, 0.5m, 1.0m, 2.5m and 2.75m) were selected to be simulated.

Firstly, creating a 3D geometrical model by SolidWorks. Then imported the model into ICEM for meshing generation. In order to ensure the accuracy of the calculation and the convergence of the results, the hexahedral structured grid was used to discretize the computational domain spatially. The boundary layer effect was taken into account, the boundary layer grid was divided by encrypting the near-wall surface. Then, imported the mesh into FLUENT to transient calculate. Due to the presence of both water and air two phases, the VOF model of the multiphase models was selected to calculate the two-phase flow，set the air as the basic phase. The water inlet was set as the speed inlet, the turbulence intensity was set to 4%, and the hydraulic diameter was with the diameter of the water pipe at 0.1m[15~23]. The U-shaped communicating pipe, the vent tube, and the horizontal pipe outlet were set as pressure outlets. In the transient calculation process, when the flow pattern changed was small inside the pipeline, the flow was considered to be stable, and the calculation results were analyzed as the final flow field.

Through the simulation, it was found that the pipe was in a lower filled state when the inlet flow rate was 0.5 m/s. Observed the liquid phase volume fraction cloud maps at the five locations within the pipe as were shown in FigureIII below. Compared the results of Figure III, it was shown that the stability of fluid flow in the pipe is most adequate at a distance of 1m to 2.5 m from the water inlet position. Therefore, the communicating pipe should be installed at the position where the pipe is 1~2.5m away from the water inlet place.

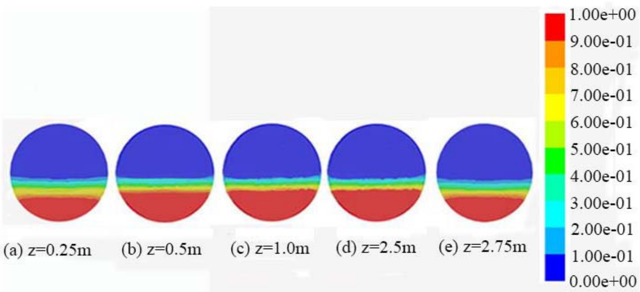

FIGURE III. VOLUME FRACTION CLOUD MAP AT FIVE LOCATIONS

B. Simulation Analysis of Inner Diameter Selection of the Communicating Pipe

According to the theory of hydraulics, the hole is opened under the steel pipe will influent the fluid flow in the pipe. If the pore diameter is too large, the eddy current phenomenon may be affected the flow state of the fluid in the steel pipe. If the pore diameter is too small, the blockage may easily occur. Moreover, the size of the opening, that is, the inner diameter of the communicating pipe, is different from the sensitivity of the flow rate changes in the steel pipe. Therefore, it is necessary to simulate and analyze the selection of the pipe diameter of the communicating pipe. The diameters (*d*) of the communicating pipe were selected to be 0.02m, 0.05m and 0.08m for simulation analysis. From the analysis results of the previous section, it is chosen to uniformly connect the communicating pipe to the position of 1.5 m away from the water inlet position of the steel pipe.

Set the initial inlet velocity to 0.5 m/s, and the transiently calculated of the flow states in the pipe were processed when the inlet flow rate was abruptly changed from 0.5 m/s to 0.3 m/s. The liquid phase volume fraction cloud diagram of the different pipe diameters were shown in Figure IV.

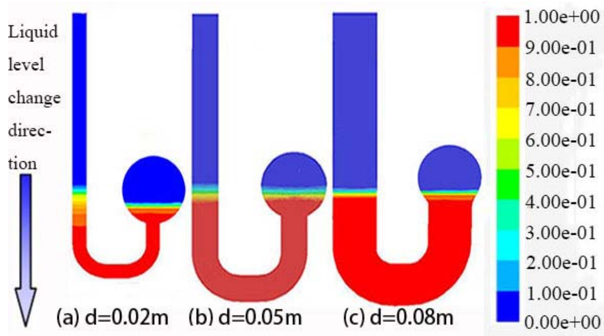

FIGURE IV. VOLUME FRACTION CLOUD DIAGRAM OF DIFFERENT PIPE DIAMETERS AT Z=1.5M

From the results of the Figure IV: The smaller of the communicating pipe's inner diameter, the more sensitive to reflect the flow rate changes. But when the size of the diameter of the communicating pipe is too small, the liquid level measuring device cannot be placed, and the clogging phenomenon is also likely to occur, so the connecting tube diameter should be chosen as 0.02 m.

V. EXPERIMENT AND ANALYSIS

A. Calibration Experiment

The liquid level-flow calibration function is determined by adjusting the electric control valve to the specified opening degree and finding the correspondence between the liquid level and the flow value. Before the start of the experiments, turned on the water pump and adjusted the electric control valve to the position of 100% of the opening degree. By adjusting the overflow valve, the water flow in the steel pipe just reached the full pipe state. The electric regulating valve was adjusted to 100%, 95%, 90%, 85%, 80%, 75%, 70%, 65%, 60%，55%，50%, 45%, 40%, 35%, 30%, 25% in order to carry out the experiment. The DN20 electromagnetic flowmeter and pressure sensor recorded data once every second, and the measurement signals were sent to the signal processing unit, then the flow value and the liquid level value were output every ten minutes after being processed by the least squares method. The measurements were lasting for 3 hours at each opening degree of the valve. The results of the liquid level-flow correspondence record were shown in Table I below.

TABLE I. LEVEL-FLOW RELATIONSHIP TABLE

Regulating Valve Opening Degree(%)	*Liquid Level h/m*	*Flow Measurement Results（m3/h）*
100	0.096	1.632
95	0.08	1.587
90	0.062	1.541
85	0.024	1.221
80	0.021	1.106
75	0.017	0.93
70	0.015	0.807
65	0.013	0.723
60	0.011	0.611
55	0.01	0.546
50	0.009	0.48
45	0.008	0.397
40	0.007	0.329
35	0.006	0.257
30	0.005	0.189
25	0.004	0.109

The obtained data was fitted to a power exponential function by MATLAB to obtain the liquid level-flow calibration function as follows:

$$Q=f(h)=39.25\exp(-15.93h) -39.48\exp(-18.13h) \quad (6)$$

B. *Verification Experiment*

After obtaining the liquid level-flow calibration function, the selected signal processing unit was programmed under the μc/osII operating system based on the Windows 64 operating platform. The electric control valve could be adjusted to different opening degrees, and the measured value of the pressure sensor was collected every 0.02 seconds. The signal processing unit removed the maximum value and the minimum value that were collected every minute and then calculated the average value. After calibration through the model (6), the flow value could be obtained. One hour of lasting the measurements, the accumulated flow value of the time period was output, and the flow value measured was obtained by the DN20 electromagnetic flowmeter through sending a command from the serial port to the according to the MODBUS standard protocol. Finally, the two results were output to the RS-485 transceiver through the serial port and sent to the PC terminal for display.

Five kinds of opening degrees of the regulating valves within the degree ranges less than 65% were randomly selected. The measurement results of the experimental platform output were compared with the experimental results of the flow values monitored by the DN20 electromagnetic flowmeter as were shown in Table IIbelow.

TABLE II. EXPERIMENTAL COMPARISON RESULTS

Regulating Valve Opening Degree (%)	*Liquid Level h/m*	*Flowmeter Measured ValueQ1/ (m3/h)*	*Platform Output Flow ValueQ0/ (m3/h)*	*Actual and Theoretical Flow Difference⊿Q (m3/h)*	*Relative Error(%)*
28	0.005	0.185	0.186	-0.001	-0.774
34	0.006	0.258	0.261	-0.003	-1.333
41	0.007	0.331	0.334	-0.003	-0.881
52	0.01	0.528	0.536	-0.008	-1.573
59	0.011	0.608	0.599	0.009	1.470

Repeated experiments were carried out on the experimental results of low liquid level (the liquid level was not more than 0.1D), it was found that the repeatability error of the experiments was the largest when the electric control valve opening degree was 45%. The experiment was repeated 5 times for 45% openness. Each experiment lasting for one hour with an interval of 10 minutes, and the results were shown in Table III below.

TABLE III. EXPERIMENTAL RESULTS AT 45% OPENNESS

Test Times	*Liquid Level h/m*	*Regulating Valve Opening Degree(%)*	*Platform Output Flow Value(m3/h)*	*Actual One Hour Flow Value(m3/h)*	*Repeatability Error(%)*
10:00	0.008	45.00	0.404	0.396	1.60
11:10	0.008	45.00	0.404	0.401	
12:20	0.008	45.00	0.404	0.411	
13:30	0.008	45.00	0.404	0.407	
14:40	0.008	45.00	0.404	0.410	

C. *Discussion*

As were seen in Table II, after processing by the liquid level-flow model, the experimental results of this platform showed that given the different inlet flow rates, the flow values that were obtained by the liquid level measurement which the liquid level were not more than 0.1D, the measurement error was less than 2%. According to the data in TableⅢ, the repeatability error of the measurements for 45% openness was about 1.6%. Based on the experiment results above, the experimental method that was proposed in this paper achieved an accurate measurement of the partially filled pipe when the liquid level of the pipe was below 0.1D. However, in the actual measurements, the flow measured method under the condition of filled pipe required the two electromagnetic valves were closed, and the measurements needed the external devices to perform, this method required further optimization and improvement.

VI. IN CONCLUSION

In this paper, a method of flow measurements for partially filled pipe was proposed by placing a high-precision pressure sensor into a U-shaped communicating pipe to get the liquid level of the steel pipe and then processing the liquid level through the liquid level-flow function model. The experiment verified the feasibility of the method. In order to improve the measurement accuracy, the flow state of the gaseous and liquid two-phase flow in the steel pipe was simulated by the CFD simulation technology. Through simulations, the U-shaped communicating pipe was installed at the position of the steel pipe 1~2.5m from the water inlet place and the diameter of the communicating pipe should be selected to be 0.02m can be determined. The experimental results showed that when the liquid level was below than 0.1D, the flow measurement error was less than 2%, and the repeatability error was about 1.6%. The measuring system is easy to install, operability and easy to repair, which greatly reduces the cost. It solves the problems that carry out the measurement of the low liquid level flow of the partially filled pipe, the installation and maintenance are difficult.

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