Application of Fluid Mechanics in Flow Meter Principle Analysis and Process Simulation

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Abstract. COMSOL is used to establish a flow field pipeline model, design and optimize flow detection, and analyze and study acoustic intensity, pressure signal and other parameters. According to the circular pipe test system used in the experiment, the flow velocity analysis model of the steady and constant flow field in the circular pipe was theoretically constructed using the finite element method. The numerical analysis results show that the flow rate in the pipeline obtained in the experiment is the average flow rate of the fluid at the section of the test location, and the test value is 0.63% different from the theoretical value.

Keywords: ultrasonic velocimetry; ultrasonic flowmeter; Velocity; Simulation experiments.

1. Introduction

Driven by the development of the global green economy, the demand for natural gas as a high-quality and efficient low-carbon energy source is increasing day by day, and it is expected that natural gas consumption will exceed 4.3 trillion cubic meters in 2024. In recent years, China has steadily promoted the reform of energy consumption and built a safe and clean modern energy system. In 2017, the state implemented a coal-to-gas policy, and in 2019, it signed a natural gas transmission agreement with Russia, importing 1.3 trillion cubic meters of natural gas per year to meet the domestic supply gap. Therefore, the natural gas pipeline network needs to have a high-precision flow meter device to provide a measurement basis for natural gas trade settlement. The flow meter is an indispensable device in the natural gas pipeline network and can provide a measurement basis for both sides of the natural gas trade. At present, due to the high pressure of domestic natural gas long-distance pipelines, the flowmeter mostly adopts imported gas ultrasonic flowmeter; The domestic urban natural gas pipeline comprehensively considers factors such as low pressure and production cost, and the roots flowmeter and turbine flowmeter are used more. However, roots and turbine flowmeters have shortcomings such as small measurement range and high maintenance costs in the later stage. Natural gas cost management runs through the entire pricing process, and reducing the cost of natural gas pipeline transportation fees can greatly reduce natural gas prices. Therefore, the development of high-precision gas ultrasonic flowmeters with state-owned independent intellectual property rights and the localization of measuring instruments are of great significance to solve the loss of state-owned assets and reduce the cost of natural gas measurement and transportation.

At present, the gas flowmeters commonly used in domestic urban pipeline networks are turbine, roots and ultrasonic flowmeters, compared with the first two flowmeters, ultrasonic gas flowmeters occupy obvious advantages in the natural gas trade measurement system due to the advantages of no built-in stopper, low pressure loss and high range ratio [2]. However, the measurement accuracy is greatly affected by the flow field distribution, and the roughness of the pipeline, the structure of the upstream choke and the degree of fluid turbulence will cause the uneven velocity distribution on the flow meter channel line, resulting in errors.

In response to the above problems, scholars at home and abroad have done a lot of work using different research methods. In terms of channel structure and algorithm, Qin et al. [4] improved the measurement accuracy of ultrasonic flowmeter by constructing an accurate gas flow field model, and designed a multi-channel experimental device to measure the flow field distribution of gas in the pipeline. Zhao et al. [5] simulated the distribution of fluid in the square pipe using CFD software to study the influence of the transducer installation position, installation direction and pipe length of the two-channel ultrasonic flowmeter on the flow measurement. Liu et al. [6] established a turbulent flow model of the flow field based on the CFD method to simulate the influence of the pipe fittings connection, obtained the flow field distribution of natural gas after passing through the pipe fittings connection, and gave the installation requirements of the ultrasonic flow meter. The optimization of channel structure and algorithm is generally applied to the pipeline structure under a specific state, which has certain limitations, and in view of the problems of flight time measurement, noise interference and complex flow measurement environment in the study of ultrasonic flow meter, this paper analyzes the time difference method detection and simulation respectively.

2. Principle of ultrasonic flow metering

The change in the propagation speed of ultrasonic waves in the medium for different flow rates is also different, which is related to the speed of movement of the medium. From this point of view, we can calculate the flow rate of the medium by changing the speed of the sound wave during the propagation process. For the distribution of the velocity field under different conditions, it is important to properly correct the flow rate before testing.

The simplified structure of the ultrasonic flowmeter is shown in Figure 1, and the angle formed by the two transducers Tx1 and Tx2 and the pipe axis is φ, and the pipe diameter is D. However, in actual use, the installation position of the transducer may not be in the diameter position.

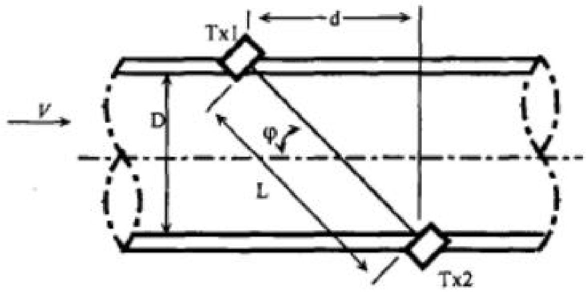

Figure.1 Schematic diagram of ultrasonic flow measurement

The actual propagation velocity c of ultrasonic waves in the propagation path is the sum of the velocity c_0 and the velocity component $v\cos\varphi$ of the flow field parallel to the pipe diameter, and the calculation formula is shown in (1).

$$c = c_0 \pm v\cos\varphi \quad (1)$$

If the transducer is installed in Figure 1, the propagation time of the acoustic signal in the medium can be calculated by formulas (2) and (3).

$$t_1 = \frac{L}{c_0 - v\cos\varphi} \quad (2)$$

$$t_2 = \frac{L}{c_0 + v\cos\varphi} \quad (3)$$

$$\frac{1}{t_2} - \frac{1}{t_1} = \frac{2v\cos\varphi}{L} \quad (4)$$

The relationship between the coefficients in equation (2, 3, 4) is as follows

$$\cos\varphi = \frac{d}{L}\# \quad (5)$$

$$\bar{v} = \frac{L^2}{2d} \times \frac{\Delta t}{t_1 t_2}\# \quad (6)$$

$$\Delta t = t_1 - t_2\# \quad (7)$$

According to Equation (6), the linear average velocity $\bar{v}$ of the fluid in the ultrasonic pulse propagation path can be obtained, and further conversion is required to obtain the volumetric flow. By calculating the velocity distribution profile in the flow meter pipe section, the flow correction coefficient K_h is obtained, and then the average axial flow velocity of the fluid on the entire pipeline cross-section can be determined, so the relationship between the average velocity of the pipe surface and the average velocity on the flow meter channel can be obtained:

$$K_h = \frac{\bar{v}_A}{\bar{v}}\# \quad (8)$$

The specific traffic can be expressed as:

$$q_v = A\bar{v}_A\# \quad (9)$$

Thereinto:

A—the cross-sectional area of the pipe;

$\bar{v}_A$—The average surface velocity of pipe flow.

3. emulation

In the propagation time method used to determine the flow rate, the ultrasonic signal propagates through the main stream of the tube to determine the flow rate. By transmitting the signal at an angle to the main stream, its speed is faster than the speed of sound when the direction of propagation of the ultrasonic signal is the same as the main stream, and its speed is slower than the speed of sound when the direction of propagation of the ultrasonic signal is opposite to the main stream. The propagation time difference in the two directions increases linearly with the flow velocity of the main stream. Therefore, the flow rate of the mainstream can be quickly inferred.

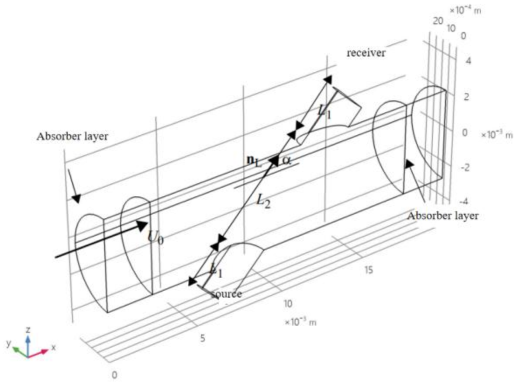

Figure.2 Schematic diagram of an ultrasonic flow meter

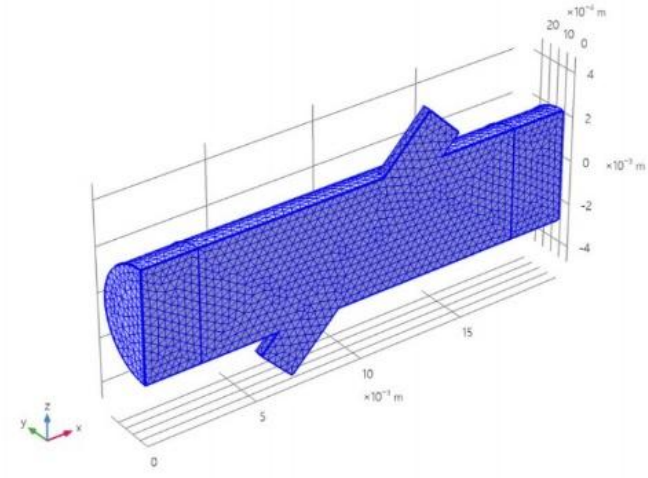

Figure.3 Free tetrahedral mesh model

A flow meter consists of a main pipe and a smaller signal tube (transducer tube) placed at an angle α relative to the main pipe. The diameter D of the main pipe is 5mm, the diameter of the signal tube is 2mm, and the angle relative to the main pipe is α=45. The length of the signal tube is $L = 2L_1 + L_2$. Under normal atmospheric conditions, the fluid is treated as water, and the average flow velocity of the background flow is U_0=10 m/s.

3.1 Background flow: CFD

Real-time background flow (p_0, u_0) is constructed, that is, the steady-state flow is obtained by CFD simulation. Under operating conditions, the background flow is expected to be a turbulence with a Reynolds number (Re) of approximately 5×10^4. Model the flow using the Turbulence, k-ω interface of the CFD Module.

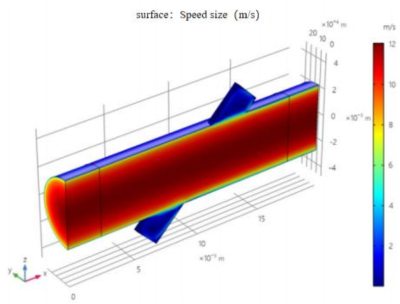

Figure.4 Background average flow amplitude in a flow meter

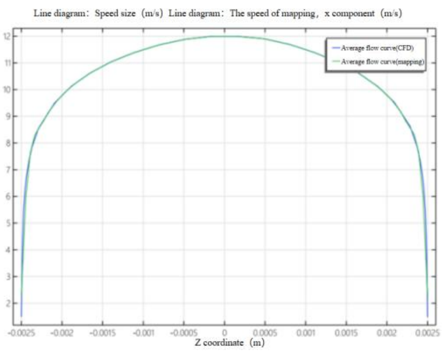

Figure.5 Background average flow curve

3.2 Acoustics: convective wave equation, time domain explicit

A sine wave modulated by Gaussian pulses is simulated by specifying a normal velocity v_n at the source boundary

$$v_n(t) = Ae^{-(f_0(t-3T_0)^2)}\# \tag{10}$$

where A=0.1mm is the signal amplitude, $\omega_0 = 2\pi f_0$, f_0=2.5MHz, $T_0 = \frac{1}{f_0}$。

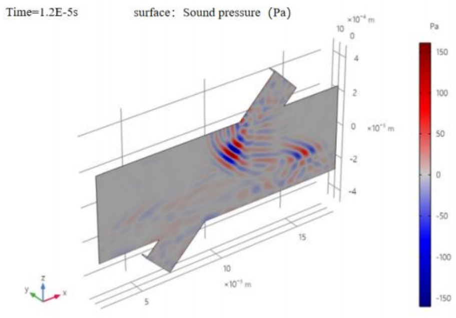

Figure.6 Acoustic pressure diagram

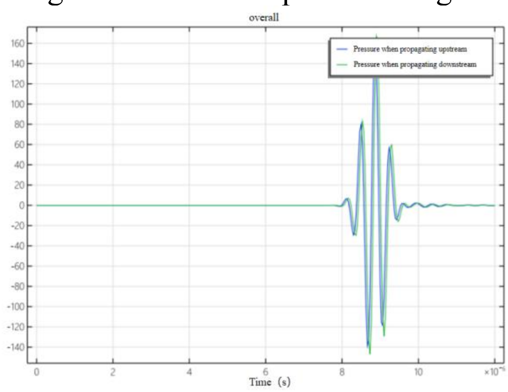

Figure.7 Pressure signal at receiver

3.3 Estimate the flow rate

We can estimate the time it will take for these two signals to reach the opposite receiver. This estimate can be used to derive an approximate expression describing the average velocity U_0 of the background stream; In fact, this is how an ultrasonic flowmeter works. That is, measuring the time difference ΔT between two transmitted signals and then using this time difference to derive the average flow velocity, possibly using the correction factors described below.

The background flow is mainly in the main pipe, the flow rate in the signal tube is very low, the distance of the signal tube through the main pipe is represented by the L_2, and the part extending on either side has an axial length of L_1 (side branch). Therefore, the total length of the signal tube satisfies $L = 2L_1 + L_2$. The direction of the signal tube is represented by the n_L, and the angle between the signal tube and the main pipe is the α described above. Assuming that the background flow in the side branch is negligible, the propagation time T_1 1 is $T_1 = L_1/c_0$, regardless of whether the ultrasonic signal propagates upstream or downstream. Now, assuming that the background flow in the supervisor is constant, the velocity field can be written as $u_0 = U_0 e_x$. The distance a signal travels L_2 the time it takes T_2 depend on whether it propagates upstream or downstream. Under the preset conditions, the expression of the time T_2 is

$$T_{2,\text{upstream}} = \frac{L_2}{c_0 + n_L \cdot U_0} = \frac{L_2}{c_{0+} + U_0 \cos\alpha}\# \tag{11}$$

$$T_{2,\text{downstream}} = \frac{L_2}{c_0 - n_L \cdot U_0} = \frac{L_2}{c_{0+} - U_0 \cos\alpha}\# \tag{12}$$

c_0 of these is the speed of sound. Therefore, the estimated time difference ΔT between the two signals is given by the following equation

$$\Delta \mathrm{T} = \mathrm{T}_{2,\text{downstream}} - \mathrm{T}_{2,\text{upstream}} = \frac{2\mathrm{L}_2 \mathrm{U}_0 \cos\alpha}{\mathrm{c}_0^2 - \mathrm{U}_0^2 (\cos\alpha)^2} \# \quad (13)$$

The above expression can be used to estimate the average flow velocity of the background average stream based on the measured time difference $\Delta\mathrm{T}$. The expression is

$$U_0 = \frac{L_2}{\Delta T \cos\alpha}\left(-1 + \sqrt{1 + \frac{\Delta T^2 c_0^2}{L_2^2}}\right) \# \quad (14)$$

A key simplification of equation (14) assumes that the background flow through the pipe is constant. In fact, most of the background flow is not constant as it passes through the main. The extreme case is laminar flow, where the flow curve will be parabolic, but typical turbulence will also exhibit a changing velocity curve.

Figure 8 depicts sound pressure in the symmetrical plane of four flow meters corresponding to different times. Under the Export node in COMSOL, selecting the animation player animates this sequence, which provides a very intuitive way to visualize propagation pulses.

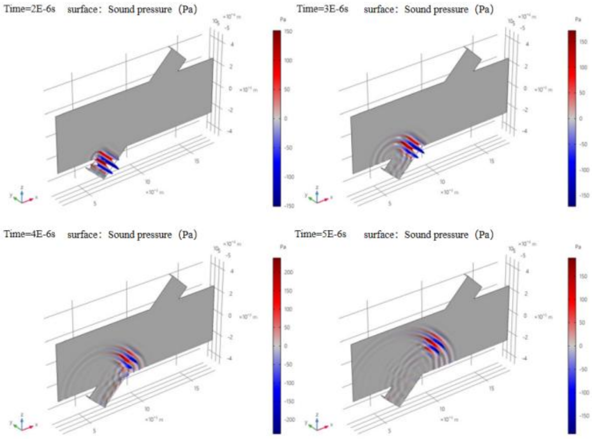

Figure.8 depicts the velocity of the sound particle as $\mathrm{t} = 8 \times 10^{-6}\mathrm{s}$ is the time before the pulse reaches the receiver.

Figure 9 depicts the instantaneous intensity amplitude and intensity vector at the same speed of sound as Figure 10. The intensity graph provides a better indication of the energy flow of the acoustic signal in the flow meter system.

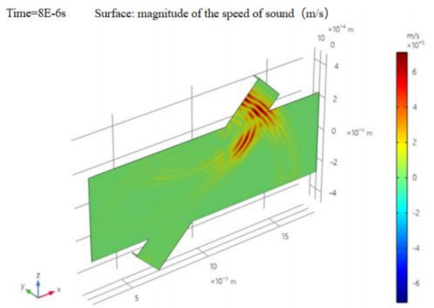

Figure.9 Velocity of sound particles in a symmetrical plane of a flow meter

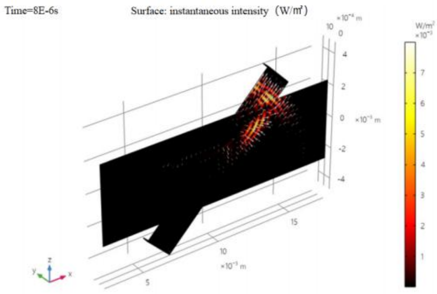

Figure.10 The amplitude and intensity vector of the acoustic instantaneous intensity before the signal reaches the receiver

Figure 11 depicts the pressure signal along the transducer tube spindle at timet $= 4 \times 10^{-6}$s (see Figure 4). Finally, one of the key results of this model is shown in Figure 12, the average pressure at which the signal recorded on the receiver propagates downstream and upstream. Based on this graph, we can measure the time difference between the two signals. Zooming in on the figure, visual inspection shows that $\Delta T_{\text{Analog value}} = 4.86 \times 10^{-8}$ s. The simulated time difference is compared to the estimated time difference calculated from the known flow curve $U_0(x)$. The calculated time ΔT_{calc} given by the following equation

$$\Delta T_{calc} = \int_0^L \left[\frac{1}{c_0 - n_L \times u_0(x)} - \frac{1}{c_0 + n_L \times u_0(x)}\right] dl \,\# \qquad (15)$$

This integral is calculated under the result node with a value of $\Delta T_{calc} = 5.01 \times 10^{-8}$s， , which is very close to the above analog value (visual reading).

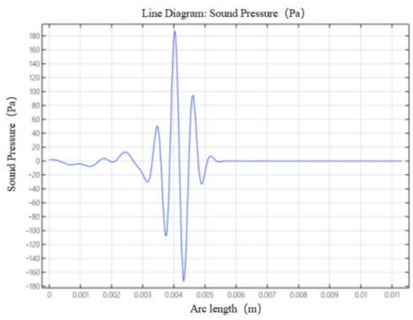

Figure.11 Sound pressure signal along the central axis of the transducer

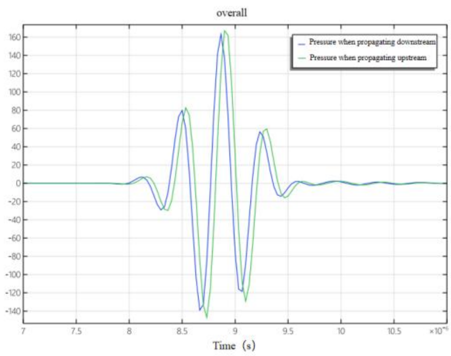

Figure.12 Average sound pressure on the receiver as the signal propagates downstream and upstream

3.4 Flow profile correction factor

According to the above simplified model, the error of estimating the U_0 is one of the core problems of ultrasonic flow meter data analysis. This is usually described by the Flow Profile Correction Factor (FPCF).

$$\mathrm{FPCF} = \frac{\text{The measured average flow velocity along the signal tube}}{\text{Actual average flow rate}} \# \quad (16)$$

The problem with determining FPCF theoretically is that the background stream is often unknown; This is especially true for turbulence. In addition, the flow profile through the signal tube may depend on the acoustic medium, flow rate, helix angle α and design parameters such as the radius of the main pipe and signal tube. In this model, we did not make any explicit assumptions about the exact velocity distribution in the signal tube, but determined by CFD simulation, thus explicitly including the contribution of all the unknowns listed above. As a result, COMSOL Multiphysics can be used to calculate flowmeter-specific FPCFs to obtain more accurate flow meter results at different flow rates and geometries. For the specific cases described above, it can be found

$$\mathrm{FPCF} = \frac{10.66\mathrm{m/s}}{10.0\mathrm{m/s}} = 1.066 \# \quad (17)$$

And the model can be extended to perform sweeps on parameters such as flow rate to obtain FPCF in each case.

4. Conclusion

In this paper, the finite element-based numerical analysis method is used to analyze the flow velocity distribution characteristics of the air flow field in the pipeline, and the ultrasonic flow field test and measurement experimental system for cylindrical pipeline is established by using the time difference method, and the average flow rate of the flow field in the pipeline can be obtained, and the flow rate is basically consistent with the numerical simulation results based on finite element.

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