Large eddy simulation study on flow characteristics of ultrasonic heat meter at low Reynolds number

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Abstract. Ultrasonic heat meter is widely used in heat metering, and its measurement accuracy depends on the flow characteristics of the reflected channel. In this paper, LES (Large Eddy Simulation) method is used to calculate the flow field of the ultrasonic heat meter at low Reynolds number. Through the analysis of the flow field, it is shown that the velocity gradient near the cylindrical reflector is larger, especially at the tail of the first cylindrical reflector; the eddy formed by the flow can scour the reflecting surface and prevent scaling; the average linear velocity over time of the reflecting channel is obtained by the calculation results. The range of velocity variation is 0.609%.

Key words. Ultrasonic heat meter; Large eddy simulation; Low Reynolds number; Cylindrical reflector

1. Introduction
Ultrasound heat meter has been widely used in heat metering because of its advantages in accuracy and structure. The testing accuracy of ultrasonic heat meter mainly depends on the flow testing accuracy. The principle of flow testing is shown in Figure 1 and 2. Because of the different ultrasonic velocity in the downstream and upstream, the time of the ultrasonic signal received by the two transducers is different, and there is a time difference $\Delta t$. The accuracy of flow testing of the ultrasonic heat meter mainly depends on the measurement of time difference $\Delta t$.

Figure 1. Flow testing principle
Figure 2. Internal Structure of U-shaped reflector
In order to obtain the flow characteristics more accurately, the large eddy simulation (LES) method is used to study the flow characteristics of the ultrasonic heat meter at low Reynolds number. For the method of LES, Zhang Zhao-shun [1] et al. carried out theoretical analysis of LES; Yao Shi-zhu [2] et al. used the LES method to study square cylinders with chamfered corners; Ning Tao [3] et al. studied the turbulence of circular tubes with LES method; Wu Yanchao [4] studied the circular cylinders with low Reynolds number via LES method; J. Boudet, Sajjad Mira and so on. N[5,6] et al. used LES method to study the effect of roughness on transition; C.W.H. van Doorne [7] et al. used PIV method to measure the flow in a circular tube; the present author [8,9] also used LES method to study the flow in pipe in the previous study, and used k-e model to study the velocity characteristics of the U-shaped reflecting channel [10]. In summary, there are few studies on the flow characteristics of low Reynolds number in the channel of ultrasonic heat meter, and few studies on the application of LES to the flow in complex small chambers.

In this study, the velocity characteristics in the reflecting channel of the ultrasonic heat meter are studied. The low Reynolds number flow in the reflecting channel is calculated by LES method in order to obtain the relevant laws.

2. Mathematical and Physical Models

2.1 LES Model

Mathematical equation [1] of LES is as follows:

\[
\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i}{\partial x_j} \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} \quad (1)
\]

Where \( \tau_{ij} = \tilde{u}_i \tilde{u}_j - \tilde{u}_i \tilde{u}_j \) is defined as Subgrid stress, and Smargorinsky model is used in this paper, which is shown in Equation 2:

\[
\tau_{ij} = 2\mu_2 \tilde{S}_{ij} + \frac{1}{3} \tau_{kk} \delta_{ij} \quad (2)
\]

Where \( \mu_2 \) is Subgrid turbulent viscous stress, \( \tilde{S}_{ij} \) is tensor rotation rate, as shown in Equation 3 and 4.

\[
\tilde{S}_{ij} = \frac{1}{2} \left( \frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) \quad (3)
\]

\[
\mu_2 = \rho L_s^2 \left| \tilde{S} \right| \quad (4)
\]

Where \( L_s \) is the mixing length of mesh, and \( \left| \tilde{S} \right| = \sqrt{2 \tilde{S}_{ij} \tilde{S}_{ij}} C_s \), \( C_s=0.1 \).

2.2 Reflecting device

U-shaped reflecting device is used in this paper. As shown in Figure 2, the reflecting device is made of stainless steel cylinder and polished by 45 degree reflector. After two reflections, the sound wave is received by the receiving transducer and a measurement is completed. The distance of the ultrasonic reflector on the central axis is 80 mm.

2.3 Grid resolution
According to literature \cite{7} and previous research experience \cite{8,9}, the minimum mesh size requirement is as follows:

$$L < 5 y_0^+$$

\hspace{1cm} (5)

Where $y_0^+$ is defined as viscosity scale and its formula is: $y_0^+ = v / u^*$, Where frictional velocity $u^* = \overline{u} \sqrt{f / 2}$, $f=0.079 \text{Re}^{-1/4}$

When the flow rate is 0.05 m$^3$/h. According the above formulas, we obtain $u^*=5.7\times10^{-3}$m/s, $y_0^+=1.7\times10^{-4}$m, and the minimum mesh scale $L<y_0^+=8.5\times10^{-4}$m=0.085mm. Therefore, according the requirement of mesh size, the mesh size is 0.8mm in the middle reflection area, as shown in Figure 3.

**Figure 3.** Mesh distribution in reflection region

**Figure 4.** Physical model

\subsection*{2.4 Time step resolution}

In unsteady calculation, from the previous time to the next time step, the calculation in each time step is equivalent to a quasi-steady state solution. In this paper, the resolution of time step is determined by trial calculation. The initial step is 0.0005s by two orders of magnitude smaller than the ratio of minimum mesh size to average velocity. The time step is gradually increased during the calculation.

\subsection*{2.5 Boundary condition}

When the flow rate is 0.05 m$^3$/h, the inlet velocity is 0.01966 m/s, the outlet is free flow, and the temperature is 20℃. The turbulence intensity $I = 0.16 \text{Re}^{-1/8} = 0.72$ is added as the inlet disturbance. The physical model of the calculation is shown in Figure 4.

\section{3. Flow Characteristics of Internal Flow Field in Ultrasonic Heat Meter}

\subsection*{3.1 Distribution characteristics of flow field}

Figure 5 and 6 are the velocity contour maps of the longitudinal and transverse sections of the flow field respectively at the time $t$ of 7.3235s. From the velocity distribution in the maps, the reflecting device has great influence on flow field turbulence. When the water flows around the first reflecting cylinder, vortices are generated on the upper reflector, which washes away on the reflecting surface. Two symmetrical vortices are formed at the tail. Because of the flow around the reflecting device, the velocity gradient of this region is larger and flow-velocity contour lines are denser. The flow tends to be stable in the middle, and the flow-velocity contour lines are sparse. Then the flow is blocked by the second reflecting cylinder, which leads the denser flow-velocity contour lines and the larger velocity gradient, and the vortex street developed at the tail.

**Figure 5.** Flow-velocity contour lines of longitudinal sections

**Figure 6.** Flow-velocity contour lines of transverse sections
According to the analysis of the flow field, there is a greater velocity gradient near the reflecting cylinders, and the flow is stability in the reflecting device middle. Because of the influence of the second reflecting cylinder, there is no shedding vortex street at the tail of the first reflecting cylinder, and the second reflecting cylinder forms shedding vortex street at the tail and develops backward. The first reflector is washed by the vortex and the second reflector is washed by the fluid in the forward, which can play a self-cleaning role and prevent the reflection surface from scaling.

3.2 The velocity characteristics in the reflecting channel

The reflecting channels of the two reflecting surfaces are shown in Figure 7.

![Figure 7. Reflecting channel of heat meter](image)

![Figure 8. Linear velocity vector of channel](image)

When measuring the flow rate with an ultrasonic heat meter, the propagation time is mainly influenced by the velocity of the fluid in the reflecting channel, so, it is very important for measuring accuracy of the linear average velocity of the channel. In this paper, the linear average velocity in the reflecting channel is analysed and Figure 9 is a vector diagram of the linear velocity in the reflecting channel. Through the analyzing of the vectors distribution, as shown in Fig.9, the velocity vector direction varies greatly behind the first reflector, and the velocity gradient is larger, then its tends to be stable until the velocity in the area before the second reflector. The flow is blocked by the second reflector, resulting in upward flow direction.

3.3 Analysis of flow velocity characteristics in reflecting channel of ultrasonic heat meter

The stability of the flow measurement of the ultrasonic heat meter is influenced by the stability of the linear average velocity in the time domain. Therefore, this paper studies the variation of the linear average velocity in the reflecting channel calculated at each time step. Fig. 10 shows the linear average velocity in the reflecting channel in the time range of 0-7.323s.

![Figure 9. Linear average velocity of 0-7.323s](image)

![Figure 10. Linear average velocity of 6.5-7.323s](image)

As shown in Figure 9, the velocity distribution increases first and then stabilizes with time. Carve of velocity tends to be straight after 2.5s. Therefore, the velocity at the time step of the last stage of calculation is obtained for analysis, as shown in Figure 10. The average linear velocity in the reflecting channel varies in time domain, ranging from 0.0861 to 0.08663 m/s, with an average value of 0.08638 m/s.
m/s. And the velocity greatest range is 0.609%. It shows that the velocity variation is relatively small with time of the U-shaped reflector device and can meet the testing requirements.

4. Conclusion
(1) Established the LES calculation method of the complex flow inside the small cavity of the ultrasonic heat meter.
(2) The flow in the middle of the reflecting device is relatively stable, the velocity gradient is small, and the velocity gradient near the reflecting device is large, especially at the tail of the first reflector.
(3) At low Reynolds number flow rate, the average linear velocity of the reflecting channel fluctuates in time domain, and the velocity range is 0.609%.

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