Experimental Thermal and Fluid Science 94 (2018) 49–58

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Applicability of hybrid ultrasonic flow meter for wide-range flow-rate under distorted velocity profile conditions

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ARTICLE INFO

Keywords:
Ultrasonic Doppler velocimetry
Transit-time ultrasonic flow meter
De-aliasing method
Flow rate measurement
Hybrid ultrasonic flow meter
On-site calibration

ABSTRACT

In transit-time ultrasonic flow meters (TOF), the flow rate is derived from the transit time of an ultrasonic pulse between two ultrasonic transducers. To convert the transit time into flow rate, a profile factor (PF) is required. Because the PF strongly depends on the velocity profile, a precise calibration of the PF is essential to the accuracy of the TOF. Hence, a field calibration, referred to as on-site calibration, is desirable. In this study, a hybrid ultrasonic flow meter that helps calibrate the TOF using ultrasonic Doppler velocimetry (UDV) is proposed for on-site calibration by integrating the velocity profiles over the cross-sectional area of a pipe. Thus, a new system of hybrid ultrasonic flow meter was developed. The maximum flow rate measured using a conventional UDV is significantly lower than that measured using the TOF. Therefore, a system was developed to measure higher velocities and flow rates. The system is novel in that the transit time and velocity profile can be simultaneously measured using a de-aliasing method. To evaluate the influence of the velocity profile on the PF, experiments were conducted under a wide range of flow-rate conditions, which otherwise cannot be implemented using the conventional UDV. To evaluate the influence of the velocity profile in the pipe, an obstacle plate was placed at 8*D* upstream the test section. Radially arranged measuring lines were employed. The experimental results show that increasing the number of measuring lines did not improve the accuracy of the TOF. On the other hand, the flow rate could be accurately obtained using the proposed UDV by measuring the velocity profile even under distorted flow conditions. Furthermore, the calibration of the PF based on the flow rate obtained using the proposed UDV was found to be feasible.

1. Introduction

In hydraulic power plants, the limitations on the flow rate of intake water flowing from a river or sea are strictly followed for environmental protection. Because of the uncertainty associated with flow meters, the intake-water flow rate is determined considering this uncertainty in actual operations, resulting in limited power generation [1]. Furthermore, water is used as a coolant and as a moderator in boiling-water reactors, wherein it is important to control the feedwater flow rate. More accurate flow-rate measurements helps in reducing the degree of uncertainty in the power level and increasing the power output by up to 2% [2].

In most flow meters, the flow rates are derived from certain physical quantities that are related to the bulk velocity in the pipe. For example, the flow rate is derived from the rotational frequency of a turbine in a turbine flow meter; from the pressure difference in an orifice flow meter; and from the electromotive force in an electromagnetic flow meter. Correction factors are required for these flow meters, and the factors are multiplied by the physical quantities to derive the flow rates. The ultrasonic transit-time flow meter (TOF) has also been widely employed in industrial plants. The TOF is known for its high repeatability and reproducibility [3]. In addition, the pressure loss in the TOF is lower than that in other flow meters, such as the differential pressure and turbine flow meters, because the TOF does not obstruct the flow. Similar to other flow meters, in the TOF, the flow rate is derived from the transit time of an ultrasonic pulse using a correction factor known as the profile factor (PF). Precise calibration of the PF is essential to ensure the accuracy of the TOF.

It is well known that the PF strongly depends on the velocity profile in a pipe. Two methods have been employed to calibrate the PF. The first one involves determining the velocity profile in a pipe by numerically simulating a flow condition of an actual situation using pipe

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https://doi.org/10.1016/j.expthermflusci.2018.01.032
Received 10 March 2017; Received in revised form 20 December 2017; Accepted 26 January 2018
Available online 31 January 2018
0894-1777/

layouts and physical properties. The second method involves experimentally calibrating the PF with reproducing the actual situation in a calibration facility. In a previous study [4], velocity profiles under different upstream conditions have been determined by numerical simulation, and the flow rate could be measured within an error of 0.1%. However, the velocity profile also depends on the surface roughness of the inner pipe wall and the physical properties of the working fluid, which change with temperature and pressure [5,6]. Jung and Seong [7] reported that the PF could vary up to 2% depending on the physical models, even when an axisymmetric velocity profile is assumed. The real situation in which the flow rate is to be measured cannot be perfectly reproduced or simulated, and therefore, measurement errors beyond the specification of the flow meter may occur when the TOF is used in actual industrial plants. Furthermore, the velocity profile may change because of the variation due to the aging of the pipes, thus increasing the error in the flow rate. Although there have been some attempts to reduce the influence of the velocity profile by optimizing the transducer configuration [8,9], it has not been established whether the optimized configuration can be applied to various velocity profiles. Therefore, an on-site calibration is required to precisely determine the PF and to maintain the accuracy of the flow meter over the course of its lifetime. To conduct the on-site calibration, a highly accurate reference flow meter is required.

The ultrasonic Doppler velocimetry (UDV) is a suitable candidate for the on-site calibration. The method has been developed since the 1960s, primarily in the medical field for measuring the blood flow in a vessel [10,11]. Since the 1980s, the method has been applied to engineering fields [12] for measuring the velocity profiles of various flows, such as in the ultrasonic pulsed Doppler method (UDM), ultrasonic velocity profiler (UVP), and UDV [13–15]. The UDV can be used to obtain the velocity profile along the ultrasonic beam path. Because the flow rate can be directly calculated by integrating the obtained velocity profile over the cross-section of the pipe, a correction factor is not required in the measurement of the flow rate. In previous studies, it has been shown that the UDV could be used to measure flow rates with high accuracy [16]. Furthermore, the method has been applied to drifted and asymmetric velocity profile conditions with several number of radially arranged measuring lines [17]. However, the application of the UDV is limited because the method requires an ultrasonic reflector in the flow. Hence, a flow meter that combines the TOF and the UDV, namely the hybrid ultrasonic flow meter, has been proposed [1,16]. This flow meter employs the TOF as usual, and the UDV is periodically used for the flow rate calibration.

However, the UDV is limited in that its maximum measurable velocity is based on the Nyquist sampling theorem. In the UDV, if the flow velocity exceeds the maximum velocity, a phenomenon referred to as velocity aliasing occurs, and the actual velocity cannot be obtained. Hence, the maximum measurable flow rate is limited for the UDV and is significantly lower than that obtained using the TOF. Consequently, the on-site calibration using the UDV is restricted to low flow rate conditions.

To avoid the velocity aliasing, the authors have developed a dealiasing method, which is referred to as the feedback method, and have applied it to measure the flow rate [18,19]. For a fully developed pipe flow, the flow rate obtained using the aforementioned method was approximately six times greater than the maximum measurable flow rate obtained using the conventional UDV, measured with an error of less than 1%. Furthermore, it was revealed that a larger measurement volume is required to measure the higher velocity, and the influence of the measurement volume size on the measurement results should be considered.

Thus, the UDV has been well-established for flow-rate measurements. Nevertheless, a hybrid ultrasonic flow meter must be developed to improve the applicability of the UDV, as mentioned above. In the next step, the authors propose a new system of hybrid ultrasonic flow meter that can be used to simultaneously obtain the transit time of an ultrasonic pulse and the velocity profile of a pipe. The developed system can be applied to conditions wherein the flow rate varies with time, by conducting simultaneous measurements. To measure higher flow rates, the feedback method is applied to the UDV. The calibration of the PF under higher flow rate conditions using a hybrid ultrasonic flow meter has been performed for the first time in this study. The velocity profiles in the pipe and the transit times of the ultrasonic pulses are simultaneously measured to validate the developed measuring system. Furthermore, the influence of the velocity profiles on the accuracy of the TOF is evaluated, and the PF is calibrated.

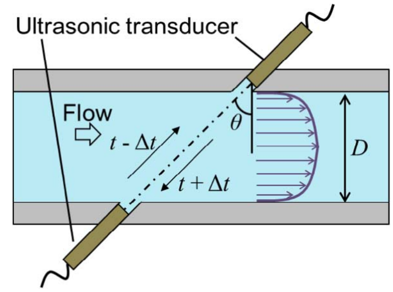

Fig. 1. Measurement principle of the TOF.

2. Hybrid ultrasonic flow meter

2.1. Measurement principle of the TOF

Fig. 1 shows the measurement principle of the TOF. A pair of ultrasonic transducers is installed with an inclination angle, θ, on the pipe wall; t represents the transit time of an ultrasound signal between transducers under the stagnant flow condition. If the ultrasonic pulse is emitted from the upstream transducer, the transit time is reduced to $t-\Delta t$ depending on the flow velocity, whereas the transit time from the downstream transducer is delayed to $t+\Delta t$. In this study, Δt was derived from the time difference between the forgoing and returning times as follows.

$$\Delta t=\frac{1}{2}[(t+\Delta t)-(t-\Delta t)] \tag{2.1}$$

Δt can be derived without calculating t using the above equation. Although t varies with the speed of sound, c, in this manner, the influence of c on t can be ignored. Δt is related to the line-averaged velocity V_L along the measuring line between the sensors, and the relationship is expressed as follows.

$$V_L=\frac{c^2}{D\tan\theta}\Delta t \tag{2.2}$$

As shown in the above equation, the TOF can be used to derive only the line-averaged velocity. Hence, the PF is required to convert V_L to the flow rate as follows.

$$Q_{TOF}=PF\cdot\frac{\pi D^2}{4}\cdot V_L \tag{2.3}$$

where Q_{TOF} is the flow rate measured using the TOF.

2.2. Measurement restrictions of the UDV

In the hybrid ultrasonic flow meter, the PF is determined using the UDV. In the UDV, ultrasonic pulses are emitted to the flow from an ultrasonic transducer. The echo signals reflected by the ultrasonic reflectors seeded in the fluid are received by the same ultrasonic transducer that emitted the original signals. A velocity profile along the ultrasonic beam can be obtained by analyzing the recorded echo signals. As shown in Fig. 2, an ultrasonic transducer is set with an inclination angle, θ, and the measured velocity is expressed as $v\sin\theta$