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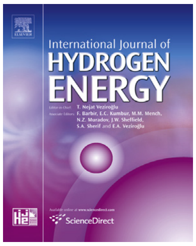

Research on the inherent error of ultrasonic flowmeter in non-ideal hydrogen flow fields

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ABSTRACT

For the widespread transmission, custody and utilization for hydrogen energy, accurate flow rate measurement is the precondition. The ultrasonic flowmeter has a prospect of wide application for the hydrogen flow measurement. To improve the measurement accuracy, this article researched the inherent error of the ultrasonic flowmeter in the non-ideal hydrogen gas flow. Computational fluid dynamics (CFD) had been used to simulate hydrogen flows downstream of the single right bend and an orifice plate at different Reynolds numbers. Based on the simulation results, this work investigated the inherent error of the ultrasonic flowmeter with different integrations and acoustic paths. The results show the errors become larger when the flowmeter position is closer to the disturbance sources. The increase in the number of acoustic paths can effectively reduce the error caused by the non-ideal flow. In the flow field downstream of the bend, the flowmeters adopting Tailored and Owics integration perform better than those with other integrations. Tchebychev and Owics integration cause less error in the front 4*D* (four times diameter) pipe downstream of the orifice plate, while Tailored and Owics cause less error in the rear 11*D* area.

1. Introduction

As a new clean energy, hydrogen is one of the most promising energy sources in the future. Accurate flow rate measurement is the precondition of widespread transmission, custody transfer and utilization for both liquid and gaseous hydrogen [1,2]. Compared with the Coriolis flowmeter and traditional mechanical flowmeters (such as turbine, orifice, or vortex meters), transit-time ultrasonic flowmeter, possesses many merits. First, it has high accuracy and reproducibility. Moreover it doesn't contain any moving parts, nor creates additional pressure drop, but allows bi-direction measurement. Finally this system can be conveniently maintained on-line without interrupting the fluid transport [3]. Thus, the ultrasonic flowmeter has been more and more widely applied in the natural gas pipeline networks in recent years [4]. Ultrasonic flowmeter can be expected to occupy an important position in the hydrogen transport and trade. But so far no relevant articles about ultrasonic flow measurement for hydrogen have been presented.

The basic principle of ultrasonic transit-time flowmeter is that line integrals of the speed along a series of chords are linearly combined to form an estimate for the mean velocity. The basic equation for a multipath flowmeter is as follows:

$$Q_v = \pi R^2 \sum_{i=1}^{N} w_i \overline{V_i(x_i)} + \sigma_{\text{inherent}} + \sigma_{\text{time}} + \sigma_{\text{other}} \tag{1.1}$$

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where Q_v is the volume flow rate, R is the internal radius of the pipe. N is the number of the channels. The set of weights $\{w_i\}$ and abscissae $\{x_i\}$ have been determined beforehand according to a certain integration and the channels. $\{\overline{V_i(x_i)}\}$ is the line velocities, which are the functions of the different flight time of the sound transiting in the flow direction and in the reverse direction. σ_{inherent} is the inherent error. σ_{time} is the timing error. σ_{other} is the error caused by other factors, including temperature, pressure, instrument geometry, etc. Ordinarily the former two errors constitute the major part of the flow error as the third one is much smaller than the others. The timing error is mostly resulted from the circuit accuracy, electron noise and acoustic interference. Profiting from the rapid development of electronic technology, the time measurement resolution can reach nanosecond level, which can satisfy the requirements of ultrasonic flowmeter [5,6]. On the other hand, noise and interference can be effectively suppressed using double threshold detection, correlation method, and other technologies [7–9]. So the proportion of inherent error in the total measurement error becomes larger. It is necessary to research on this error to improve the ultrasonic flowmeter accuracy.

The inherent error is mainly caused by truncation error of numerical integral, which is related to the integration type and the number of acoustic paths. Nowadays two to four channels are chosen by most commercial ultrasonic flowmeters. Gauss–Legendre, Tchebychev, Tailored and Owics are the four most common kinds of integrations which have theoretical and practical value. Gauss–Legendre and Tchebychev are the first two integrations adopted by early ultrasonic flowmeter [10]. In 1990 C.N.Pannell found these two kinds of numerical integration were not suitable for the velocity profile of fully-developed tube flow, because the profile was not a polynomial function. Then Pannell presented Tailored integral optimized for the velocity distribution of pipe flow, and compared the error of Tailored with the other two integrations [11]. Voser proposed a new integral function named "optimal weighted integral (Owics)", whose weight can be calculated according to the acoustic path position. Comparisons between Gauss–Jacobi and Owics were also made at different Reynolds numbers [12]. However, the inherent error comparisons of different integrations and channels in the two researches were based on the ideal straight tube flow, in which the flow velocity distribution in the pipe cross-section is constant in the axial direction.

Besides the integration type and the number of acoustic paths, the flow velocity profile can also determine the numerical size of the inherent error as the integrations are designed for the ideal flow [11]. Actually in many cases, the ultrasonic flowmeter is installed in the non-ideal three-dimensional flow field, such as the field downstream the single bend, double bend, orifice plate, vavle, etc. Fluid has not only the axial velocity, but also the radial and tangential velocity along the acoustic propagation path. And there are no corresponding researches about the inherent errors of various integrations and channels in these flow fields. It is necessary to study these non-ideal flow fields. Compared to the experimental measurements, it is convenient, flexible and economical to use computational fluid dynamics (CFD) to simulate the non-ideal flow field. And much more information can be obtained. Morrison and the others calculated the flow field downstream an orifice plate by CFD simulation in 1993 [13]. Hilgenstock team simulated the single bend and double bend flow field in 1996 [14]. Both results were corroborated by experimental measurements and confirmed the effectiveness of using CFD method to study the non-uniform flow field. However, inherent errors of ultrasonic flowmeter in these two flow fields hadn't been studied. Furthermore, their research fluids are air, rather than hydrogen. Because of large kinematic viscosity, hydrogen flow field is different from air flow.

As there are so many disturbing sources that can influence the inherent error of the hydrogen meter, and we cannot research them all in one article, so we chose two most common components and three Reynolds numbers (corresponding to slow, medium, and fast flow) to get six non-ideal hydrogen flow fields. Based on these flow fields, we analyzed the inherent error of four integrations with two to four channels. We also got the related results about how to reduce the inherent error of ultrasonic hydrogen flowmeter in these fields. And for the other fields, we can use the presented method here to research the inherent error of the ultrasonic flowmeter.

2. Method

Table 1 shows all the calculating cases carried out in this work. Through the comparison between the air flow simulation results and experimental data, we can verify the accuracy of fluid fields solved by CFD method. This work selected three conditions to simulate the hydrogen flow field. The corresponding Reynolds numbers at the pipe entrance were 928, 5661 and 11,322.

Table 1 – Analyst cases for the single bend and orifice plate.

	Fluid material	Re_{inlet}	Viscous model	Goals
Single bend	Air at 25 °C	60,000	Realizable k-ε	Verification with Sudo experiment data [15]
	Hydrogen at 25 °C	928	Laminar	Error analysis for different integration methods
		5661	Realizable k-ε	
		11,322	Realizable k-ε	
Orifice plate	Air at 43 °C	54,700	RNG k-ε	Verification with Deotte experiment data [16]
	Hydrogen at 25 °C	928	Laminar and Transition SST	Error analysis for different integration methods
		5661	RNG k-ε	
		11,322	Spalart–Allmaras	