Effect of Installation Angle of Ultrasonic Flow Meter on Water Velocity Measurement in Pipe

P. Siriparinyanan, T. Suesut, and N. Nunak

Abstract— **The aim of this paper was to study the effect of installation angle of ultrasonic flow meter on the water velocity measurement in a pipe. The path angles of 45º, 55º, 65º, 75º, and 85º were performed in this study. The velocities were estimated by CFD techniques using the realizable k-ε model and measured by a transit time ultrasonic flow meter, and then they are compared with the results obtained from weighing method (ISO 4185). It was found that velocities estimated from CFD flow simulation at various path angles and measured from ultrasonic flow meter had a similar trend. The more difference of path angle away from the recommended specification was set, the more error of velocity measurement was obtained. The velocities at the path angles of 65º and 85º were almost the same because they had an equal difference of path angle from the one that suggested in the specification. The simulated results from CFD had much error than the measured velocities of ultrasonic flow meter, especially at the long distance of path length or at a small path angle. This needed to be compensated with the correction factor.**

Index Terms—**Installation angle, velocity measurement, ultrasonic flow meter, CFD flow simulation**

I. INTRODUCTION

TRANSIT time ultrasonic flow meter is widely used to measure water velocity in many industries because it is easy installation, no moving part, nonintrusive and non-obstructive measuring and it can be applied to different sizes of pipe [1], [2], [3], [4], [5]. It consists of two transducers, which are an upstream transducer and a downstream transducer, and it measures water velocity using the difference of transit time between the sound signal traveling along and opposite to the flow direction. Transit time ultrasonic flow meter operates well, with clean and no particles in fluid, e.g., water, clear liquids and viscous liquids.

However, many factors affect velocity measurement of ultrasonic flow meter e.g., type of fluids, sound speed in fluid, flow characteristics, pipe characteristics (roughness, type of materials, coating, diameter), straight run before and after flow meter, and installation of upstream and downstream transducers (path angle) [1], [2]. Decreasing of straight run and pipe diameter lead to increasing of error of measurement [1], [6], [7], [8], [9]. Installation of transducers should conform to the recommendation of the manufacturer, which is generally reported in the form of distance between 2 transducers or path angle; otherwise, error of velocity measurement will be occurred [8]. According to diameter of pipe also affect the error, the recommended path angle from the manufacturer should be changed.

CFD flow simulation has been used in a wide range of research, for example, to examine the error of measured velocity by the ultrasonic flow meter [2], to evaluate the calibration factors of a flow meter [10], [11], and to study the flow pattern of fluid during moving through the flow meter [12]. This will be beneficial if CFD technique can simulate the velocity at each point of water flowing in the different pipe diameters. Therefore, the aim of this paper was to evaluate the velocity of water in closed conduits with different path angles by CFD techniques and to compare the measured result from a transit time ultrasonic flow meter. Measurement of water flow in closed conduits - Weighing method proposed by international standard ISO 4185 was used as reference water velocity in this paper.

II. THEORETICAL BACKGROUND

A. Transit Time Ultrasonic Flow meter

In recent years, the transit time ultrasonic flow meter has been one of the fastest growing technologies and has usually used for water velocity measurement. The ultrasonic sound signal patterns generated from upstream and downstream transducers are reciprocal, which means that the ultrasonic sound signal will be the same whether the transducer is used as a transmitter or a receiver. The transducers were designed to transmit sound wave in different types of pattern, e.g., from omnidirectional to very narrow beams.

For water velocity measurement, the ultrasonic sound signal is carried by the fluid particles, so that sound speed traveling through water is the sum or difference of its own speed and the fluid speed. This is the fundamental of the transit time ultrasonic flow meter, which uses the difference of transit time in an upstream and a downstream direction. The transit-time for the ultrasonic sound signal can be calculated using (1)

$$V_{line}=L\times(t_{AB}- t_{BA})/(t_{AB}-\times t_{BA}\times 2\cos\theta) \quad (1)$$

$$t_{AB} = L/(C+V\cos\theta) \quad (2)$$

$$t_{BA} = L/(C-V\cos\theta) \quad (3)$$

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where t_{AB} and t_{BA} is the transit time from transducer A to B (s) and transit time from transducer B to A (s), respectively. The transit time between transducer A and B is calculated using (2) and (3), which is the sum and the difference of sound speed in water (C = 1,491 m/s in water at a temperature of 23 ºC at atmospheric pressure) and water velocity (V; m/s). L is the path length (m), θ is path angle, and V_{line} is an average velocity of water across the channel in the direction of flow (m/s) [13]. If the sound transmits through the moving fluid, then the apparent speed is obtained from the hypotenuse of the triangle in Fig. 1 [1].

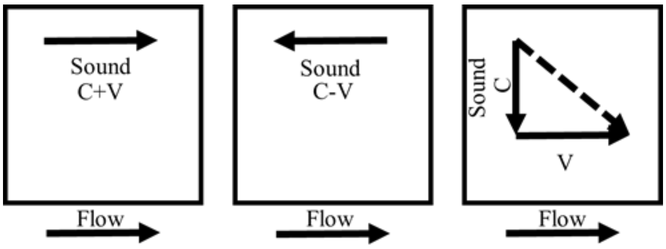

Fig. 1. Apparent sound speed as viewed by an observer outside the moving fluid (Modified from [1])

B. Computational Fluid Dynamic

Computational Fluid Dynamic (CFD) is the part of fluid dynamics, which is used for actual flow simulation by mathematical model, numerical method, and CFD software. In case of Newtonian fluid dynamic, the Navier-Stokes equations were used to simulate the real flow in the pipe. In this paper, the Transport equations of Realizable k-ε model as shown in (4), which improved predictions for the spreading rate of both planar and round jets, is used for simulation

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k+P_b+\rho\varepsilon-Y_M+S_k$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right]+\rho C_1 S\varepsilon+\rho C_2\frac{\varepsilon^2}{k+\sqrt{\upsilon\varepsilon}}$$
$$+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}P_b+S_\varepsilon \qquad (4)$$

where P_k is the generation of turbulence kinetic energy due to the mean velocity gradients and P_b is the generation of turbulence kinetic energy due to buoyancy. [14].

C. Measurement of liquid flow in closed conduits - Weighing method (ISO 4185)

This standard specifies a method of liquid velocity measurement in a pipe by measuring the mass of liquid in weighing tank with an interval time. The relation between mass and density of liquid is used for converting to liquid velocity in a pipe. Diverter, which is a moving device used to change flow direction of liquid into weighing tank, and weighing scale, which is a device for measuring the mass of liquid in weighing tank, are the most important part of this method. The motion of diverter must be quick in order to eliminate the effect of residual liquid. Also, the high resolution weighing scale is needed in order to eliminate the error. [15]

III. EXPERIMENTAL

A. Experimental Setup

Experimental unit (Fig. 2) consisted of an ultrasonic flow meter, a centrifugal pump, a testing section installed with a flow meter, a diverter, weighing tank, and a storage tank. The measuring section was located at 20D from the 45º elbow. A flow meter used in this experiment was a transit time ultrasonic flow meter (Fuji Electric System Co., Ltd. FSD220Y1), which distance between the two transducers was set at 12.9 mm (75º path angle). The water was circulated by a centrifugal pump from a storage tank to the testing section. The horizontal pipe was made of Polyvinyl chloride, of which the total length, inner diameter (D) and wall thickness were 32 inches, 1 inch and 2 mm, respectively. Weighing scale with resolution 1 g was used in this paper to measure the mass of water in weighing tank (CST: CDR-30).

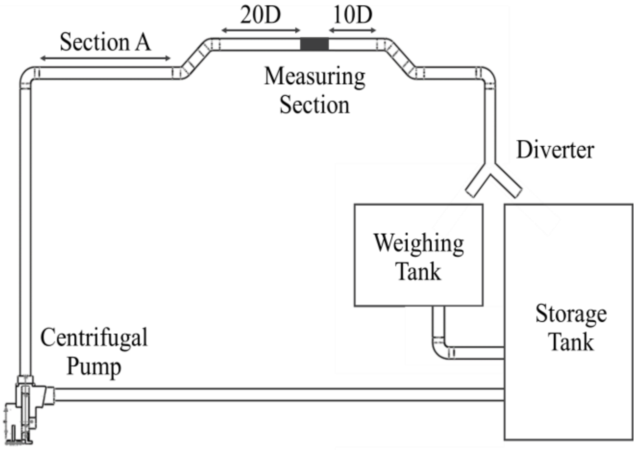

Fig. 2. Flow rate test section

B. Measurement Method

Before the experimental data were recorded, water was freely circulated at least 30 minutes for steady flow. The inlet water velocity measured at the section A using transit time ultrasonic flow meter was set at 0.28 and 0.64 m/s with the Reynolds number of 7,077 and 16,178, respectively. Flow characteristics at section A were assumed to be the same as the measuring section. Two transducers were mounted in the V method (Fig. 3) at the path angles of 45º, 55º, 65º, 75º (reference condition recommended by manufacturer), and 85º, respectively. The measured velocity of water by ultrasonic flow meter at various path angles was compared with the simulated results by CFD and that obtained from weighing method (reference velocity).

For the weighing method, the filling time was 10 s and 5s for water velocity of 0.28 m/s and 0.64 m/s, respectively. The delay time of diverter was 0.3 s, which used to compensate the loss of mass. Then, mass of water was converted to velocity by mass related corrections for the water properties at a temperature of 23 ºC.

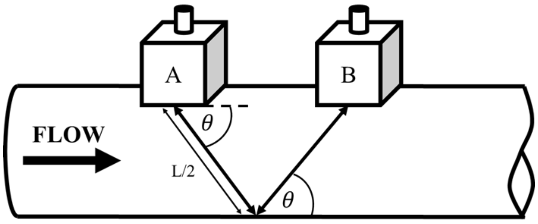

Fig. 3. Path angle condition of transit time ultrasonic flow meter (Modified from [7])

C. CFD Flow simulation

In this study, the 3-dimensional CFD flow simulation was carried out under fully developed turbulent flow. Input parameters of CFD software were boundary conditions, solution methods, and number of iterations used for prediction of velocity of fluid particles at each point of path length (see table I). Another important key for CFD flow simulation was generation of the grid as it governed the stability and accuracy of the flow predictions. In case of this experiment, three types of mesh e.g., Hexahedra, Prisms, and Tetrahedral, a simple method and a save time consumption for mesh generation, were chosen. There were 238,491 meshes in horizontal pipe. Flow simulation of the water in pipe diameter of 1 inch, mounted with two transducers of ultrasonic flow meter at different path angles was processed by CFD.

TABLE I
BOUNDARY CONDITIONS, SOLUTION METHODS AND CALCULATION USED IN WATER FLOW SIMULATIONS

Detail	Values
Boundary Conditions	
Inlet water velocity	0.28 m/s
	0.64 m/s
Outlet pressure	101.325 kPa
Density of water	998.2 kg/m^3 (23 ºC)
Viscosity of water	0.001003 Pa·s (23 ºC)
Solution Methods	
Gradient	Least Squares Cell Based
Pressure	Second Order
Momentum	Second Order Upwind
Turbulent Kinetic Energy	First Order Upwind
Turbulent Dissipation Rate	First Order Upwind
Calculation	
Number of Iterations	1000

IV. RESULTS AND DISCUSSIONS

The results (table II, III and Fig. 4 and 5) showed that the trend of calculated velocities from CFD flow simulation at different path angles and the measured velocities by ultrasonic flow meter had a similar trend. When comparing both results with reference velocities from the weighing method, it was found that the CFD velocity simulation had much error than the ultrasonic flow measurement, especially at the long distance of path length or at small path angle (Fig. 6). This might be due to the mathematical equation for velocity calculation (1). Since the difference of transit time (t_{AB} and t_{BA}) increased with increasing of the path length, this caused to the evaluated velocity was lower than the actual value.

The error of velocity obtained from CFD flow simulation could be explained with many reasons. That is, the main benefit of CFD flow simulation is to simulate the pattern of water flow in pipe in 3-dimensional flow so that generally, qualitative data are used to explain the flow characteristics of water. Since average velocities were calculated from a simulated quantitative data at each point along the path length, it was a cause of an obtained error. Another reason is the selected equation for simulation, Realizable k-ε model, is suitable for the uniform turbulent flow across the cross-section along the length of pipe, whereas the actual flow characteristic of liquid in pipe is a complex pattern (Fig. 7) [16].

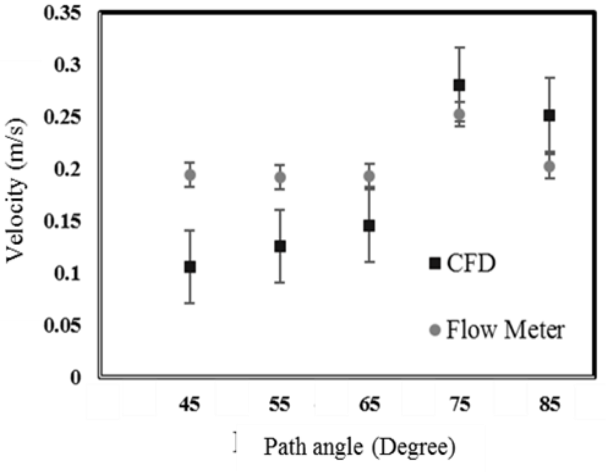

Fig. 4. Comparison of water velocity obtained from CFD flow simulation and ultrasonic flow meter at inlet water velocity of 0.28 m/s .

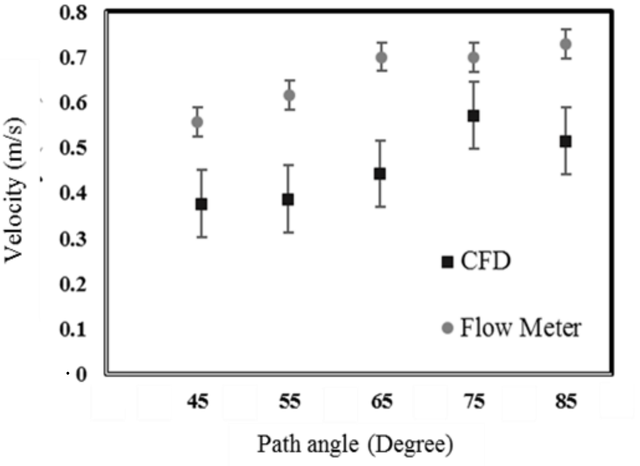

Fig. 5. Comparison of water velocity obtained from CFD flow simulation and ultrasonic flow meter at inlet water velocity of 0.64 m/s.

According to a 75º path angle was recommended by manufacturer for mounting an upstream transducer and a downstream transducer, the error of velocity measurement at this condition had the lowest. The more difference of path angle away from the recommendation was set, the more error was obtained. The velocities measurement at the path angles of 65º and 85º were almost the same because they had an equal difference of path angle from the one that suggested in the specification. It mean that the path lengths of installation angle at 65º to 85º has no a significant effect on the velocity measurement.

TABLE II
THE COMPARISON OF WEIGHING METHOD, CFD SIMULATION, AND ULTRASONIC FLOW METER

INLET VELOCITY (M/S)	WATER VELOCITY WITH DIFFERENT PATH ANGLES (M/S)														
	85°			75°			65°			55°			45°		
	Ref.	CFD	Flow meter	Ref.	CFD	Flow meter	Ref.	CFD	Flow meter	Ref.	CFD	Flow meter	Ref.	CFD	Flow meter
0.28	0.272	0.252	0.202	0.279	0.281	0.252	0.254	0.145	0.193	0.248	0.125	0.192	0.248	0.106	0.194
0.64	0.652	0.515	0.729	0.652	0.571	0.700	0.650	0.421	0.700	0.661	0.392	0.616	0.660	0.386	0.557

TABLE III
RELATIVE ERRORS BETWEEN VELOCITY FORM WEIGHING METHOD AND VELOCITY FROM CFD SIMULATION, ULTRASONIC FLOW METER

INLET VELOCITY (M/S)	RELATIVE ERROR WITH DIFFERENT PATH ANGLES (%)									
	85°		75°		65°		55°		45°	
	ε_1	ε_2	ε_1	ε_2	ε_1	ε_2	ε_1	ε_2	ε_1	ε_2
0.28	7.35	25.74	0.72	9.67	42.91	24.02	49.60	22.58	57.26	21.77
0.64	1.99	11.81	2.91	7.36	35.23	7.69	39.94	6.81	41.52	15.61

Note: ε_1, ε_2 is the relative error between velocity from weighing method and CFD flow simulation and flow meter, respectively.

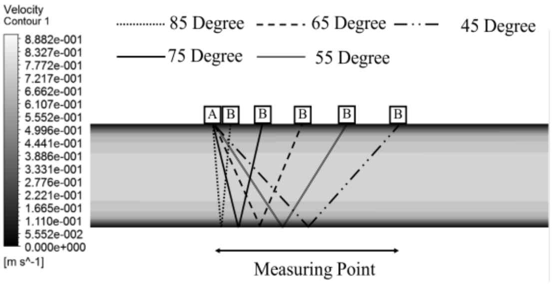

Fig. 6. Water velocity contour of 1 inch horizontal pipe with 45° elbow at inlet water velocity of 0.64 m/s

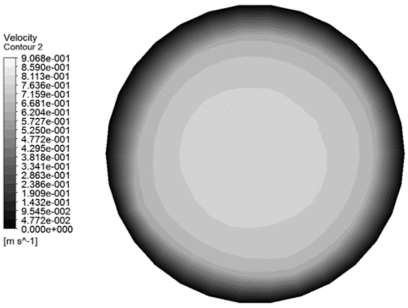

Fig. 7. Water velocity contour of cross section 1 inch horizontal pipe with 45° elbow at inlet water velocity of 0.64 m/s

V. CONCLUSION

The installation path angle is a significant factor, which affect the accurate velocity measurement with transit time ultrasonic flow meter. From this study, it can be concluded that the installation angle had an effect on the error of velocity measurement with an ultrasonic flow meter. The accuracy decreased as the increasing of the difference of path angle from the recommendation. The CFD flow simulation showed the velocity of water at each point of fluid particles and could be used to explain the effect occurred from the installation transducers. However, the estimated velocities had much lower than the actual ones, especially at the small installation angles. Also, it was observed that the wrong evaluation was in the relationship between the transit times and path angles with the exponential equation. Therefore, this will be brought to compensate in the CFD simulation in the future work.

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