Similarity Model for Estimating the Error of Clamp-On Ultrasonic Flowmeter: Flow in Water Supply Piping System

E. Sritham, R. Wachirapunyanont, P. Siriparinyanan, N. Nunak, and T. Suesut

***Abstract*— This study was aimed at presenting the similarity model for the estimation of error of a clamp-on, transit-time ultrasonic flow measurement. Dimensional analysis was based on the Buckingham Pi's theorem. The groups of independent parameters that were taken into account for the analysis included pipe characteristic, fluid characteristic, and meter installation setting. Experimental testing section was fabricated using PVC pipes with diameters of 1-in and 2-in and 45° PVC elbows. Flow velocity was fixed at 0.5 m/s. The upstream and downstream distances were in the ranges of 2D-20D and 2D-10D, respectively. It was found that the upstream and downstream distances greatly affected the accuracy of the measurement. Larger relative errors were found from the measurement on the smaller pipe. With the installation of ultrasonic transducers according to the recommended value by FCI, the error obtained with the measurements on 1-in and 2-in diameter pipes were, respectively, 7% and 0.35%. The acceptable measurement ranges of upstream distance for 1-in and 2-in diameter pipes were 16D-20D and 6D-20D, respectively. The measurements on a 2-in diameter pipe with a downstream distance in a range of 4D-10D was acceptable. For the 1-in diameter pipe, any downstream distance less than 10D resulted in unacceptable error. The accuracy of measurement was more sensitive to the change of downstream distance than the change of upstream distance. The applicable range of the prototype prediction equation was greatly affected by the flow model. The equation obtained with a 1-in diameter flow model could only be used to predict a 2-in diameter prototype within a range of 18D-20D. Increasing the size a flow model could greatly broaden the applicable range the applicable range of the prediction equation. A 2-in diameter flow model could be used to predict a prototype upto 150 in.**

***Index Terms*— Similarity model, Dimensional analysis, Ultrasonic flow meter, Error estimation**

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I. Introduction

Water supply is a closed piping system with continuous water flow. Generally, there are two types of device used to measure fluid flow rate in a closed piping; the in-line and clamp-on types. These devices require different installation techniques. The clamp-on device can be directly attached to the external surface of the pipe which makes it simple for installation and maintenance. The in-line device is installed inside the pipe, and so the maintenance work becomes more problematic. All above reasons make the clamp-on device receiving more attention than the in-line type. Among the clamp-on devices, an ultrasonic flowmeter has been widely adopted. The accuracy of an ultrasonic flow meter is dependent on several factors, e.g., upstream and downstream distances, flow velocity, pipe diameter, the change of fluid properties during the measurement [1]. Of these, the most influential factors are the upstream and downstream distances. Generally, the recommendation for installation_requires that the installation of measurement device in a disturbing environment has to have the upstream and downstream of at least 20 and 10 times of the pipe diameter, respectively [2]. In practice, however, there might be certain limit to the installation; hence the requirement by recommendation cannot be fully met and so the accuracy of measurement is lessened [3, 4].

Due to such limitation, a correction factor becomes necessary for determining an accurate fluid flow rate in a pipe. There are several techniques to determine the correction factor. A computational fluid dynamic (CFD) technique can be used to predict fluid flow rate from computer simulation. This technique takes less time and does not need any experiment; but requires a computer with the rather high specification. It has been widely adopted to predict fluid flow rate in pipe [5]. A dimensional analysis technique could also be used to scale down or scale up a system allowing the fabrication of experimental setup to be simpler. This technique is commonly employed where the real system is complex. Nevertheless, fluid flow rate obtained using the techniques without an experiment is, most of the time, not sufficiently accurate; running real experiment is still necessary to perform along with. From the studies on determining the correction factor for Venturi flowmeter and orifice plate [6, 7], it was found that when the Reynolds number (*Re*) was higher than 10^4, the error of flow measurement was within 5% and rather constant as *Re* increased.

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This study employed the dimensionless analysis together with an experiment to estimate a correction factor for the installation of the transit-time ultrasonic flowmeter at various upstream and downstream distances. The weighing technique according to ISO 4185 was used as a reference method.

II. Theoretical Background

A. Transit-Time Ultrasonic Flowmeter

Ultrasonic flow measurement based on the transit-time differential method is currently among the most widely applied flow metering processes. The flowmeter consists of two transducers - upstream and downstream transducers. Both transducers transmit similar ultrasonic wave to another. Fluid velocity can be inferred from the difference of co-current (t_{AB}) and counter-current (t_{BA}) wave travelling times as follows:

$$t_{AB} = \frac{L}{c + V\cos(\theta)} \quad (1)$$

$$t_{AB} = \frac{L}{c - V\cos(\theta)} \quad (2)$$

$$V_{line} = \frac{L(t_{AB} - t_{BA})}{t_{AB} \times t_{BA} \times 2\cos(\theta)} \quad (3)$$

where L is the wave travelling distance between the two transducers (m), c is the sound velocity in the fluid (m/s)–temperature dependent, V is the velocity of fluid (m/s), θ is the installation angle (°), and V_{line} is the reading value of fluid velocity from ultrasonic flowmeter (m/s).

B. Parameters

- Installation distances

The upstream and downstream can give rise to a substantial error of a flowmeter. When there is disturbance, the FCI recommends to install ultrasonic flowmeters [2].

- Pipe diameter

The change of pipe diameter could affect the accuracy of flow measurement. It has been reported that a reduction in pipe diameter promoted the lager error on flow measurement [3, 8, 9].

- Installation angle

From the study by Siriparinyanan et al. [10], to keep the error at a reasonably low level, it was suggested that the installation angle should not differ from the manufacturer recommended value more than 10^o [10].

- Flow velocity

Difference in fluid flow velocity could give rise to a different velocity profiles. In the event of fluid flow in pipes with the same size of the diameter, the higher fluid velocity resulted in the lower error of flow measurement [11].

Dimensional Analysis

The dimensional analysis of water supply system included a number of parameters and dimensions relating to the error of flow measurement using an ultrasonic flowmeter as given in Table I. Note that the transducers were installed with V method. In this study, the analysis was based on the Buckingham Pi's theorem which is suitable for the analysis where a large number of parameters are involved [12].

It should be noted that there are still several other parameters which could affect the error of ultrasonic flowmeter, e.g., pipe thickness, pipe material, thickness and type of scale on the pipe surface. These parameters were excluded from the analysis in this study. The reason was, in practice, the thickness and surface property of the pipe can be configured as the offset value to the flowmeter during the measurement. So, it can be considered that no other barrier to the propagation of ultrasonic wave other than the flowing fluid.

TABLE I
PARAMETERS AND DIMENSIONS RELATING TO THE ERRROR OF ULTRASONIC FLOW MEASUREMENT

Variable	Symbols	Dimension
Dependent variable:		
1) Error of ultrasonic flow meter	E	-
Independent variable:		
Pipe characterization:		
2) Internal diameter	D	L
Fluid		
3) Density of water	ρ	ML^{-3}
4) Absolute viscosity of water	μ	$ML^{-1}T\text{-}1$
5) Absolute velocity of water	v	$LT\text{-}1$
6) Disturbance effecting distance	Le	L
Meter installation:		
7) Upstream displacement	Us	L
8) Downstream displacement	Ds	L

C. Steps of dimensional analysis

Step 1: The variables relating to the error of flow measurement according to Table I can be written as Eq. 4. The total number of these variables was assigned to variable n (in this study n = 8)

$$E = f(D, \rho, \mu, v, Le, Us, Ds) \quad (4)$$

Step 2: Choosing the primary dimensions of each of n variables: *M*, *L*, and *T*.

Step 3: Assigning the repeating variables m which equal to the number of the primary dimensions (in this study m = 3) The number of dimensionless parameters or Pi terms was defined as n-m which was 5. The variables ρ, v and D were chosen as repeating variables (4) could be written in the form of relationship between Pi terms as (5).

$$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5) \quad (5)$$

Step 4: Assigning the primary dimensions into Rayleigh's theorem [12] (6) yielded (7):

$$\phi E^{C_1} D^{C_2} \rho^{C_3} \mu^{C_4} v^{C_5} Le^{C_6} Us^{C_7} Ds^{C_8} = 1 \quad (6)$$

$$\phi(1)^{C_1}(L)^{C_2}(ML^{-3})^{C_3}(ML^{-1}T^{-1})^{C_4}(LT^{-1})^{C_5}(L)^{C_6}(L)^{C_7}(L)^{C_8} = 1 \quad (7)$$

where C_1 to C_8 are constants.

Rearranging the constants according to the primary dimensions as shown in (8) to (10).

$$M: C_3 + C_4 = 0 \quad (8)$$

$$L: C_2 - 3C_3 - C_4 + C_5 + C_6 + C_7 + C_8 = 0 \quad (9)$$

$$T: -C_4 - C_5 = 0 \quad (10)$$

Cleary, there were only 3 equations, but 8 unknowns to be determined.

Step 5: Formulating Pi terms by multiplying each of the remaining variables with the repeating variables as follows:

Group 1:

$$\pi_1 = \rho^{C_3} v^{C_5} D^{C_2} E = 1(ML^{-3})^{C_3} (LT^{-1})^{C_5} (L)^{C_2} 1 = M^0 L^0 T^0 = E \quad (11)$$

Group 2:

$$\pi_2 = \rho^{C_3} v^{C_5} D^{C_2} \mu^{C_4} = (ML^{-3})^{C_3} (LT^{-1})^{C_5} (L)^{C_2} ML^{-1}T^{-1} = M^0 L^0 T^0 = \frac{\mu}{\rho v D} \quad (12)$$

Group 3:

$$\pi_3 = \rho^{C_3} v^{C_5} D^{C_2} Le = (ML^{-3})^{C_3} (LT^{-1})^{C_5} (L)^{C_2} L_e = M^0 L^0 T^0 L_e = \frac{Le}{D} \quad (13)$$

Group 4:

$$\pi_4 = \rho^{C_3} v^{C_5} D^{C_2} Us = (ML^{-3})^{C_3} (LT^{-1})^{C_5} (L)^{C_2} L = M^0 L^0 T^0 = \frac{Us}{D} \quad (14)$$

Group 5:

$$\pi_5 = \rho^{C_3} v^{C_5} D^{C_2} Ds = (ML^{-3})^{C_3} (LT^{-1})^{C_5} (L)^{C_2} L = M^0 L^0 T^0 = \frac{Ds}{D} \quad (15)$$

Substituting Pi terms into the (5):

$$E = f\left(\frac{\mu}{\rho v D}, \frac{Le}{D}, \frac{Us}{D}, \frac{Ds}{D}\right) \quad (16)$$

Rearranging the Pi terms yielded

$$E\frac{Le}{D} = f\left(\frac{\rho v D}{\mu}, \frac{Le}{D}, \frac{Us}{Le}, \frac{Ds}{Le}\right) \quad (17)$$

Step 6: Checking the independence of Pi terms by writing the dimensional matrix of the variables.

III. Experiment

A. Experimental Setup

The experimental flow model in this study can be found in Wachirapunyanont et al. [13] (Fig. 1). The model included a centrifugal pump, an inverter, a 4-in header, a flow diverter valve, a check valve, ball valves, a globe valve, weighing tank, a weighing scale, a sump, and a testing section. The testing section (Fig. 2) consisted of a clamp-on ultrasonic flowmeter, 45° elbows, and a straight pipe with a length of 30-times of diameter. The transit-time ultrasonic flowmeter (Fuji electric system Co., Ltd. FSD220Y1) having a measurement range of 0.3 to 32 m/s and fluid temperature range of -40°C to 200°C was used in this study. The error of the flowmeter when used with a pipe with a diameter of 13-50 mm and the velocity range of 0 to 20 m/s falls within ±0.03 to ±0.05 m/s, a resolution of 0.001m/s.

Since the diverter valve used in this study has a delay time of around 5 to 7 s, according to the manual; it was necessary to compensate the error of water flow. The compensation values were determined experimentally. For the pipe diameter of 1-in and 2-in, the compensation values were, respectively, 1,106±6 g and 4,770±22 g.

Prior to running the experiment, the piping system was ensured to be fully filled with water This was done by first closing the ball valve (No.4) in the air breeding section, then opening the ball valve in front of the pump (No.13) and the globe valve behind the testing section (No.7). After that the pump (No.1), which was controlled with an inverter (No.2), could be powered on. A short section the flow circuit between the header (No.5) and the test section (No.6) was made with a transparent pipe to allow the inspection of fullness of flow in pipe. Water flow rate or flow velocity was observed from the ultrasonic flowmeter installed at the testing section. Being installed with the recommended upstream and downstream distances according to FCI [25], the flowmeter should give an accurate figure of flow velocity. The flow velocity was adjusted to a desired value via the inverter. As for the main testing circuit, the pump circulated water from a sump (No.12) through a check valve (No.3), a header, a testing section, a globe valve, and finally the flow diverter valve (No.8) before returning back to the sump. Other than fully filling-up the pipe, obtaining an accurate flow measurement needs also the flow to be steady. From the experiment, a steady flow could be attained by allowing the pump to run for 30 to 45 min.

B. Test Conditions

There were two different sets of testing section. One set was fabricated with the 45° elbows and straight pipe of 1-in. (2.54 cm) in diameter, and the other was fabricated with the 45° elbows and straight pipe of 2-in. (5.08 cm) in diameter. The installation angle was fixed at 75°, according to the recommendation by the manufacturer, and the flow velocity was set to 0.5 m/s. The upstream and downstream distances were varied as shown in Table II. Due to the fact that the length of a straight pipe in the testing section was fixed at 30 times of pipe diameter (or 30D), setting the upstream to be shorter than the recommended value would always make downstream to be longer than the recommended value, or vice versa. For example, when the upstream was 18D, the downstream would be 12D, which is more than the recommended value of 10D.

The experiment was separated into two parts. The first part was done by varying the upstream distance, and the variation of downstream distance was performed in the second part. The measured velocity values were recorded using a data logger at every second for the period of 10 seconds. In the same time, the total weight of flowing water was also recorded. Before beginning the next measurement, water was allowed to flow through the model freely for 10 min to let the flow steady. Three measurements were made for each round of pumping operation. The experiment was done in triplicate.

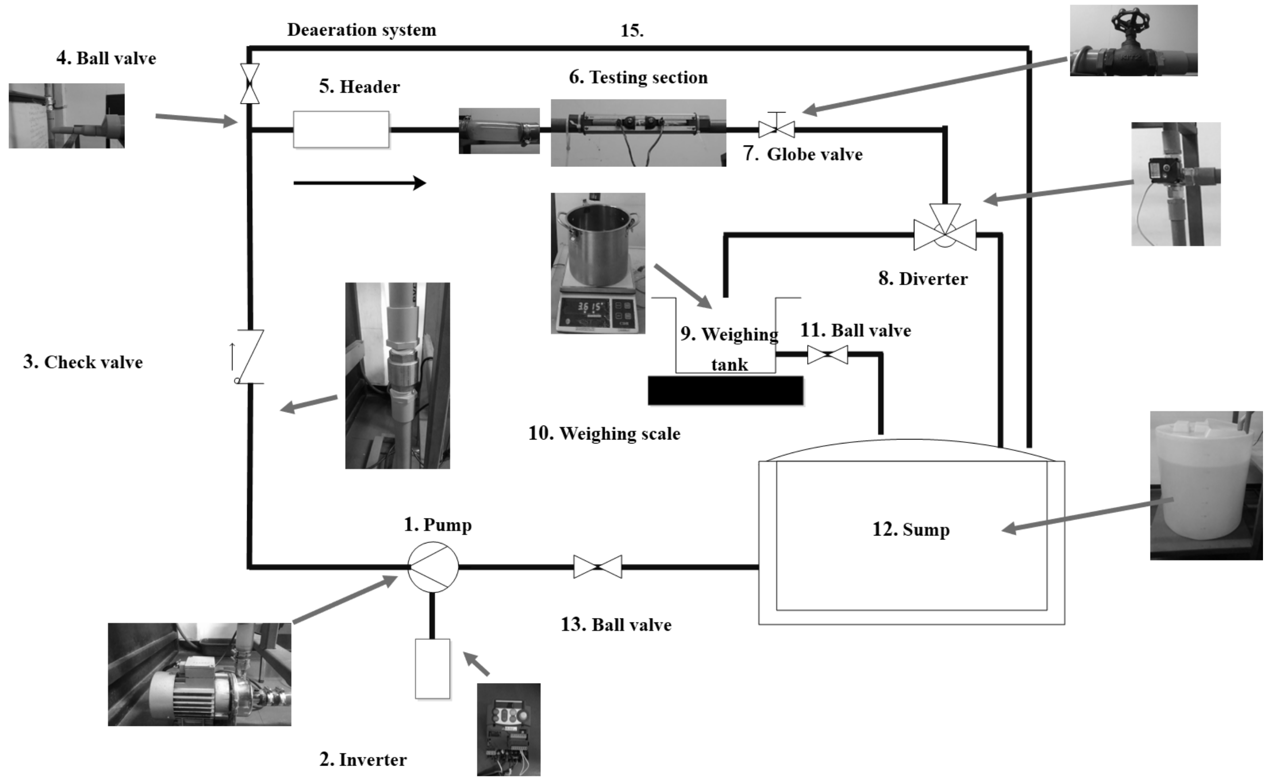


Fig. 1. Experiment setup

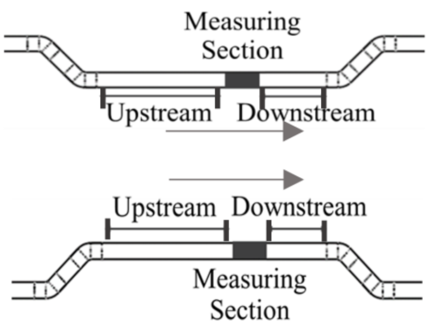


Fig. 2. Testing section

TABLE II
TEST CONDITIONS

Upstream/Downstream	Values
Upstream	20D, 18D, 16D, 14D, 12D, 10D, 8D, 6D, 4D and 2D
Downstream	10D, 8D, 6D, 4D and 2D

Remark: D is a diameter of pipe

C. Validation of the prototype prediction equation

Validation is the process to compare the errors obtained with the prototype prediction equation and those obtained from the experimental setup (or model). In this study, the 2-in. testing section was taken as a prototype while the 1-in. testing section was considered to be a model. The disturbance effecting distance (*Le*) is calculated from the entrance length for turbulent pipe flow $Le = 1.39 D \,\mathrm{Re}^{0.25}$ [14]

Therefore, the similarity model of water supply system and the validation were done as follows:

1) Specifying the setting parameters of prototype which were pipe diameter (*D*) and upstream (*Us*) or downstream (*Ds*) distance

2) Calculating upstream or downstream distance of the model using the following relationships:

$$Us_m = \left(\frac{D_m}{D_p}\right)^{1.25} \times Us_p \tag{18}$$

or

$$Ds_m = \left(\frac{D_m}{D_p}\right)^{1.25} \times (Ds_p) \tag{19}$$

3) Determining the error of model (E_m) from experimental data as shown in Table III at various calculated values of upstream or downstream distance

4) Calculating the error of prototype (E_P) using the following equation:

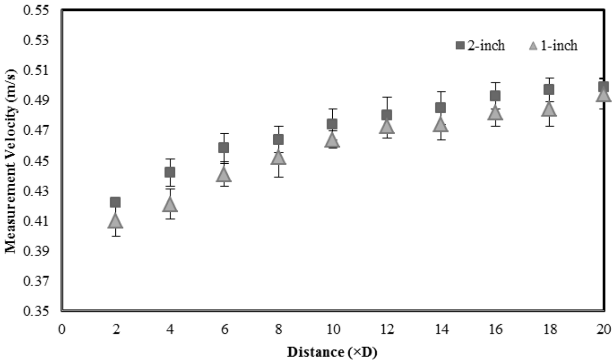
$$E_p = \left(\frac{D_m}{D_p}\right)^{0.25} \times E_m \tag{20}$$

5) Comparing the errors obtained from the prototype prediction equation (E_p) with the error from the model (E_m)

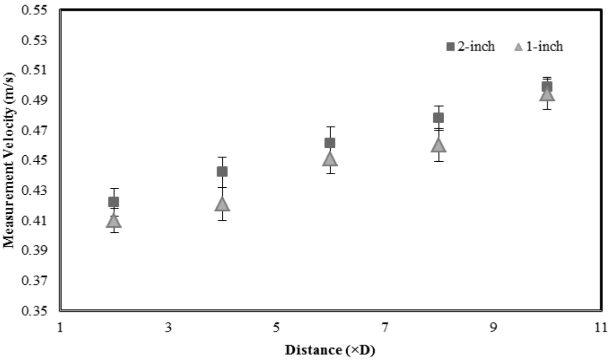
IV. Results and Discussions

A. Effect of Upstream and Downstream Distances

According to FCI [2], it is recommended that the installation of flowmeter should have an upstream and a downstream distances of at least 20D and 10D, respectively, where there should be little or no effect of disturbance on the accuracy of measurement. Following this recommendation, the measured velocity by a transit time ultrasonic flow meter was presented in Fig. 3. The error of flow measurement was found to be the smallest value in this study (see Table III).



(a)



(b)

Fig. 3. Measured velocity by ultrasonic flow meter at various installation conditions (a) upstream (b) downstream.

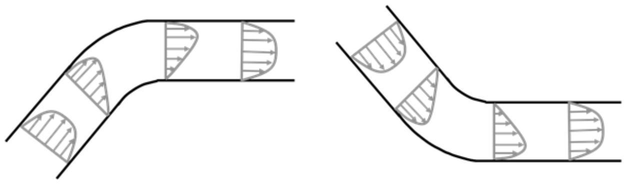
The reason would be that the velocity profiles in the region around the mounted transducers were of fully developed turbulent flow, and so velocity measurement would be reasonably accurate [4, 9]. It could be also seen from Table III that when the upstream distance was lowered, the error continually increased since the flow might might not have enough time to fully develop.

Changes of velocity profile usually occur as a fluid flows through a disturbance. The 45^o elbows were used in this study as disturbances. However, for the elbows, its orientation in the flow system could also affect a velocity profile of the flowing fluid. To represent possible situations that could significantly affect the flow, the elbows were equipped so that the flow direction were in both upward and downward directions.

When the flow is in an upward direction (Fig. 4a), the local velocity in the upper region of fluid stream should be higher than that in the lower region. In contrast, the local velocity in the lower region should be higher than that in the upper region of fluid stream flowing in a downward direction (Fig. 4b). The presence of uneven velocity profile was due to the centrifugal force and gravity comes into play. The ultrasonic velocity measurement is based on the volumetric flow metering method. The measured velocity obtained with an ultrasonic flowmeter is, in fact, an average value. Accordingly, the error of flow measurement in upward and downward directions should be similar. From this study, however, the errors found for the case of flow in upward direction were generally higher than that for the case of flow in a downward direction. As the upstream distance decreased, the difference of errors was increased. Flow in upward direction might be disturbed with higher magnitude as compared to the flow in a downward direction. The effect of this disturbance shown up obviously at a very short upstream distance since there would be not enough time for the flow to fully develop before passing by ultrasonic transducers.

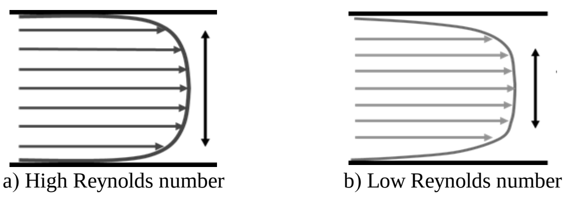
Also, it was found that the experiment with larger pipe diameter (2-in.) showed less errors than that with smaller pipe (1-in. diameter). In this study, the diameter of pipe was only a factor that caused the difference in Reynolds number, since the flow velocity was fixed at 5 m/s. The Reynolds number of the flow in the larger pipe was twice of that in the smaller pipe, 27,000 compared to 13,000. The velocity profile of a turbulent flow could be different depending on the Reynolds number.

In Fig 5 illustrates the velocity profiles of turbulent flow with different Reynolds numbers. High Reynolds number turbulent flow exhibits a rather flat velocity profile – the velocity is more even over the cross-section of flow channel (Fig. 5a). At low Reynolds number, the velocity profile of the turbulent flow may far from being flat (Fig. 5b). A flat velocity profile of high Reynolds number turbulent flow would allow the measurement to be accurate. Similar result has also been reported by Svensson [4]. He found that the error of velocity measurement tended to decrease as the Reynolds numbers increased, and when the Reynolds number was greater than 10,000, the error was nearly unchanged – staying at around 5 percent [4].



a) Flow in upward direction (+45º) b) Flow in downward direction (-45º)

Fig. 4. Velocity profile of a fluid flowing through a 45° elbow



a) High Reynolds number b) Low Reynolds number

Fig. 5. Velocity profile of turbulent flow at different Reynolds number

FCI [2] recommends that the measurement shall not be acceptable if the error is higher than 10%, even with the application of a correction factor. According to this recommendation, the acceptable ranges of upstream and downstream distances for the measurement with a 1-in diameter pipe were 16D - 20D and 10D, respectively, and for the measurement with a 2-in diameter pipe were 6D to 20D and downstream is 4D to 10D, respectively. There has also been reported in prior studies that the measurement with larger pipe tended to show a smaller error [9, 11]. It was also found that the accuracy of ultrasonic flow measurement was more sensitive to the change of downstream distance than the change of upstream distance. For example, the case of experiment with a 2-in diameter pipe where the errors were lowest. The change of upstream distance by 4D (from 20D to 16D) resulted in the increase of error only 0.4%. However, for the change of downstream distance by only 2D (from 10D to 8D) could cause the error to increase for more than 5.5%.

B. Applicable Range of the Prototype Prediction Equation

The applicable range of a prototype prediction equation was defined according to the recommendation by FCI [2] in that the relative error shall not be higher than 10%. Tables IV and V were then generated by applying the prediction equation and performing interpolation on experimental data. The following calculation sample is given To aid utilization of the proposed technique, a calculation sample is given as follows

TABLE III
RELATIVE ERRORS OF ULTRASONIC FLOW MESUREMENTS ON THE EXPERIMENTAL MODEL

Pipe Diameter [in.(cm)]	Flow direction	Average relative error[1] (%)														
		Upstream distance[2]										Downstream distance[3]				
		2D	4D	6D	8D	10D	12D	14D	16D	18D	**20D[4]**	**10D[4]**	8D	6D	4D	2D
1 (2.54)	Upward[5]	-[7]	-	16.7	16.1	15.2	12.5	10.3	9.5	7.5	**6.2**	**6.2**	10.2	11.9	17.1	-
	Downward[6]	-	-	16.0	13.6	12.6	11	10.2	9.6	8.5	**7.8**	**7.8**	10.8	12.8	15.5	-
2 (5.08)	Upward[5]	13.0	12.1	6.9	3.2	2.4	1.6	1.9	0.8	0.4	**0.4**	**0.4**	6.3	7.7	9.0	17.3
	Downward[6]	9.3	5.9	3.2	2.9	1.6	1.3	1.1	0.7	0.6	**0.3**	**0.3**	5.7	7.3	9.1	16.0

Remark [1]average value from 3 replicates [2] downstream ≥10D [3]upsteam ≥ 20D [4] recommended figure from FCI [2]
[5]45^o elbow upward [6]45^o elbow downward [7] "-" cannot measure

TABLE IV
APPLICABLE RANGE OF THE PROTOTYPE PREDICTION EQUATION BASED ON UPSTREAM DISANCE

Internal diameter of model [in.(cm)]	Internal diameter of prototype [in.(cm)]	Upstream distance of prototype[1]									
		2D	4D	6D	8D	10D	12D	14D	16D	18D	20D
		Upstream distance of model[2]									
1 (2.54)	2 (5.08)	-[3]	-	-	-	-	-	-	-	15.14D	16.82D
2 (5.08)	4 (10.16)	-	-	-	6.72D	8.41D	10.09D	11.77D	13.45D	15.14D	16.82D
	10 (25.4)	-	-	-	-	6.69D	8.02D	9.36D	10.70D	12.04D	13.37D
	50 (127)	-	-	-	-	-	-	6.26D	7.16D	8.05D	8.94D
	100 (254)	-	-	-	-	-	-	-	6.02D	6.77D	7.52D
	150 (381)	-	-	-	-	-	-	-	-	6.12D	6.80D

Remark [1 and 2]Downstream was fixed at 10D. [3] "-" Not applicable

TABLE V
APPLICABLE RANGE OF THE PROTOTYPE PREDICTION EQUATION BASED ON DOWNSTREAM DISTANCE

Internal diameter of model [in.(cm)]	Internal diameter of prototype [in.(cm)]	Downstream displacement of prototype[1]				
		2D	4D	6D	8D	10D
		Upstream displacement of model[2]				
2 (5.08)	4 (10.16)	-[3]	-	5.05D	6.73D	8.41D
	10 (25.4)	-	-	4.01D	5.34D	6.69D
	20 (50.8)	-	-	-	4.50D	5.62D

Remark [1 and 2] Upstream was fixed at 20D. [3] "-"Not applicable

Sample: A 1-in diameter pipe is used as a flow model and a 2-in diameter pipe will be considered as a prototype. The error of measurement on the prototype at 18D upstream, upward flowing, is to be predicted.

$$Us_m = \left(\frac{1}{2}\right)^{1.25} \times 18D_p = 15.1D_m \quad (21)$$

where, $D_p = 2 \times D_m$.

According to the calculated upstream value of 15.1, the corresponding E_m value, based on the experimental data given in Table IV, would be 9.9. Therefore, the error of prototype is

$$E_p = \left(\frac{1}{2}\right)^{0.25} \times 9.9 = 8.3 \quad (22)$$

The applicable range of the prediction equation based on upstream distance is given in Table IV. Table V shows the applicable range of the prediction equation based on downstream distance. It could be seen that the applicable range of the prototype prediction equation was greatly affected by the flow model. The equation obtained with a 1-in diameter flow model could only be used to predict a 2-in diameter prototype within a range of 18D-20D. By increasing a diameter of the flow model to 2-in., the applicable range of the obtained prototype prediction equation could be greatly broadened. The model could be used to a predict prototype with a diameter of 4-in. up to 150 in. The prediction on a 4-in diameter prototype could be acceptably done in the range of 8D-20D. However, the applicable prototype diameter range decreases as the prototype diameter increases. That said the closer the size of flow model and that of the prototype, the broader the applicable range of the prediction equation.

C. Validation of Prototype Prediction Equation

The process of validating the prototype prediction equation in this study used a 1-in diameter pipe setup as a flow model, and considered the setup with 2-in diameter pipe as a prototype. Accordingly, the error obtained from the model was designated as E_m. The error for the prototype (E_p) was calculated as: $E_p = E_m (D_p/D_m)^{0.25}$. It was found that the predicted values of error were rather high. This was, however, not surprising since the error obtained from the flow model was already high. Although the transducers were installed according to the recommendation by FCI [2], the relative error went up to around 7%. This is probably due to the diameter of the model was too small, allowing the friction between the pipe surface and the flowing fluid to impose a dramatic effect on the velocity profile. It is not recommended to use pipes that are too small for the modeling. While the error obtained from the pipe diameter of 5.08 cm was very low at about 0.4%. The use of prototype pipe with the higher velocity water flow and bigger pipe diameter results in a more accurate model.

V. CONCLUSION

A similarity model of water supply system and a dimensional analysis, based on the Buckingham Pi's theorem, were employed to estimate the error of flow velocity measurement using a transit-time ultrasonic flowmeter. The independent variables used for the analysis included the dimensions consisted of the pipe characteristics, fluid characteristics (*ρ, μ, v, Le*), and installation parameters (upstream and downstream distances). The upstream and downstream distances greatly affected the accuracy of the transit-time ultrasonic flow measurement using clamp-on transducers. Larger relative errors were found from the measurement on a 1-in diameter pipe than the error of measurement on a 2-in diameter pipe. With the installation of ultrasonic transducers having upstream and downstream distances in accordance with the recommended value by FCI, the error obtained with the measurements on 1-in and 2-in diameter pipes were, respectively, 7% and 0.35%. The acceptable measurement ranges of upstream distance for 1-in and 2-in diameter pipes were 16D-20D and 6D-20D, respectively. The measurements on a 2-in diameter pipe with a downstream distance in a range of 10D and 4D-10D was acceptable. For the 1-in diameter pipe, the errors of measurement with a downstream distance less than 10D, the recommend value, were unacceptable.

The accuracy of measurement was more sensitive to the change of downstream distance than the change of upstream distance. For a 2-in diameter pipe, the change of upstream distance by 4D (from 20D to 16D) resulted in the increase of error only 0.4%, while the change of downstream distance by only 2D (from 10D to 8D) could cause the error to increase for more than 5.5%.

The applicable range of the prototype prediction equation was greatly affected by the flow model. The equation obtained with a 1-in diameter flow model could only be used to predict a 2-in diameter prototype within a range of 18D-20D. By increasing a diameter of the flow model to 2 in., the applicable range could be greatly broadened. The model could be used to a predict prototype with a diameter up to 150-in. The prediction on a 4-in diameter prototype could be acceptably done 8D to 20D. However, the applicable prototype diameter range decreases as the prototype diameter increases.

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