Similarity Model of MWA Thailand Water System for Error Estimation of Ultrasonic Flow Meter

R. Wachirapunyanont, V. Kongratana, S. Gulphanich, T. Suesut, and N. Nunak

***Abstract*— This paper proposed a similarity model of MWA water system using the dimensional analysis based on the theory of Buckingham Pi for error estimation of transit-time ultrasonic flow meter with clamp-on at different installation conditions. There were three main parameters groups, i.e., pipe characteristic, meter installation, and fluid characteristic and properties and could be arranged in five Pi terms, i.e. $E\times(L_e/D)$, $\mu/\rho vD$, L_e/D, U_s/D, and U_s/D. The results showed that the relative errors of measurement increased with the decreasing of upstream and downstream of meter at the same velocity and there was a possibility to use the model to determine the correction factor to compensate the velocity measurement of ultrasonic flow meter as the installation could not comply with the requirement. However, the further experiments should be performed for validation of the model predictive equation i.e., $E_p = 0.3607 \times E_m$.**

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

I. Introduction

A large closed water piping system, containing the continuous flow of water, e.g., the water system of the Metropolitan Waterworks Authority of Thailand (MWA), is difficult to use with inline measurement. There are many types of flow measurement devices, e.g., pressure difference meter, venturi meter, and nozzle meter which is difficult to repair and install, water flow is interrupted, and flow characteristic is changed.

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There is another in-line measurement, i.e., electromagnetic flow meter, which needs to install at the beginning of piping and installation system is available only in the small size of pipe diameter [1], whereas transit-time ultrasonic flow meter with clamp-on is a nonintrusive flow meter, which can be used any time and it is available in a wide range of pipe diameters.

The ultrasonic flow meter is a clamp on flow meter, which detects flow rate by transit-time measuring and is suitable for fluid with no particles i.e., water. Also, this instrument is one of the meters used in the MWA water system for measuring of water velocity during flowing in the pipe. However, the accuracy of the measurement is affected from many factors, e.g., internal diameter of the pipe, water velocity, and the upstream and downstream distance of clamped meter [3], [4]., which is required the distance more than 20 times and 10 times of internal diameter, respectively [2]. In case of the MWA water system, there is limited installation space, which affects the error of measured velocity value. It is impossible to investigate the occurred error in the actual system; therefore, it is necessary to create a model of a large closed water piping system using the dimensional analysis under the flow characteristics and velocity profile similar to the prototype. Several researchers have studied about dimensional analysis in the point of view of flow measurement, e.g., Steven [5] studied dimensional analysis of two phase flow through a horizontally installed venturi flow meter, and Chen [6] used dimensional analysis for investigation wet gas over-reading in orifice plates under ultra-low liquid fraction conditions based on theory of Buckingham Pi (π) for flow simulation from prototype to model. Nowadays, there is no researcher studied about simulating model of the MWA water system for determination error of velocity value measured from ultrasonic flow meter with clamp on.

Therefore, this paper presents a similarity model of the MWA water system using the dimensional analysis based on the theory of Buckingham Pi for determining relative error between velocity value obtained from the transit time ultrasonic flow meter with clamp on and that from weighing method followed by ISO 4185:1980. As the upstream and downstream distance of clamped meter is one of the important problems of flow measurement in the MWA water system, this study was focused on clamped meter on pipe wall at various upstream and downstream distances.

II. Theory Background

A. *Transit-time Ultrasonic Flow Meter with Clamp-on*

The transit-time ultrasonic flow meter with clamp on (v-method) operates based on the time difference between traveling of ultrasonic wave from transmitter to receiver using pipe wall reflection and transmitting back from receiver to transmit in the same direction. The measured transit time is calculated to be the volume flow rate of fluid and fluid velocity as in Fig. 1. The advantages of this meter are noninvasive meter, nonblocking flow of fluid, no pressure loss by instrument, available in wide temperature range, and installed area less than other flow meters [7].

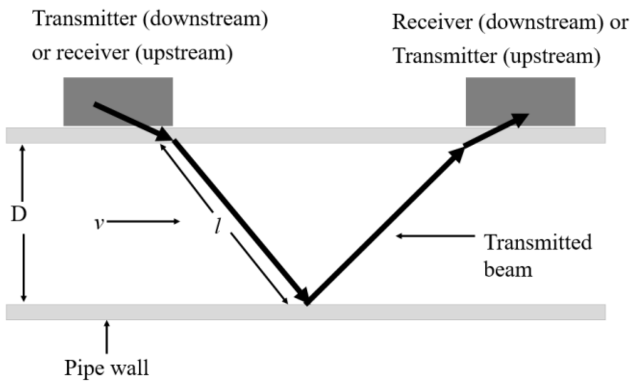

Fig. 1. Transit-time ultrasonic flow meter with clamp-on (V method) (Modified from [7])

B. *ISO 4185:1980*

ISO 4185 is an international standard used for flow meter calibration in case of liquid flow in closed system. This method was used for calculation of mass flow rate, volume flow rate, velocity, and uncertainties of measurement. Although, this method has many advantages, it is inappropriate with high vapor pressure and corrosive and toxic liquids. These might be affect with the accuracy of this method or danger with the operator during the measurement process. The volume flow rate of the liquid has to use in the range of 0-1.5 m^3/s. During the operation, air should be checked to ensure that there is no air in the system [8].

C. *Dimensional Analysis Procedure*

In this paper, the dimensional analysis based on the Buckingham Pi theorem for simulation of the MWA water system to determine the error in case of inappropriate installation of transit time ultrasonic flow meter. The parameters, which affect errors of ultrasonic flow meter, consist of 3 main parameters groups, i.e., pipe characteristic, meter installation, and fluid characteristic and properties as shown in Table I. Moreover, there are other parameters affecting with measured velocity value, e.g., pipe thickness, fouling thickness, sound speed in the pipe wall, and transit time in pipe wall [7]. Therefore, the meter had to set offset before the testing process was run. In this work, the Buckingham Pi theorem was used because it is suited for the applications having many parameters.

This experiment was operated under assumptions as follows, constant room temperature, steady flow, and fully developed and turbulent region. Prototype (MWA of Thailand water system) conditions are carbon steel pipe with an internal diameter of 1.5 m containing the water flow rate in the range of 1-3 m/s. The prototype was resized to a tested pipe with a diameter of 2.54 cm.

Eight parameters (m) "m = 8" and three primary parameters (n) "n = 3" i.e. length (L), mass (M), and time (T) are listed in table I. The independent parameters are listed in the term of

$$E = f\left(D, \rho, \mu, v, L_e, U_{s,} D_s\right)$$

and they can group in Pi term as

$$\pi_1 = \; f\left(\pi_{2,} \pi_{3,} \pi_{4,} \pi_5\right).$$

TABLE I
DIMENSION AND BASIC UNIT WHICH ASSOCIATED WITH ERROR OF ULTRASONIC METER

Variable	**Symbol**	**Basic dimensional**
Dependent variable:		
1. Error of ultrasonic flow meter	*E*	-
Independent variable:		
Pipe characterizes:		
2. Internal diameter	*D*	L
Fluid properties and characteristics:		
3. Water density	ρ	ML^{-3}
4. Water viscosity	μ	ML-1T-1
5. Velocity	*v*	LT-1
6.Entrance region	*Le*	L
Flow meter installation:		
7. Upstream	*Us*	L
8. Downstream	*Ds*	L

Considering each group of Pi term,

Group 1 is $\pi_1 = \; \{\rho^a v^b D^c\}\left(E\right)$

$$= \left\{\left(ML^{-3}\right)^a \left(LT^{-1}\right)^b \left(L\right)^c\right\} \times 1 \; = \; M^0 L^0 T^0$$

since M: a = 0, L: -3a+b+c = 0 and T: -b = 0, then a, b, and c = 0; therefore,

$$\pi_1 = E,$$

Group 2 is $\pi_2 = \{\rho^{-1} v^{-1} D^{-1}\}\left(\mu\right) \; = \dfrac{\mu}{\rho v D},$

Group 3 is $\pi_3 = \; \{D^{-1}\}\left(L_e\right) \; = \dfrac{L_e}{D}$

Group 4 is $\pi_4 = \{D^{-1}\}(U_s) = \dfrac{U_s}{D},$

and group 5 is $\pi_5 = \{D^{-1}\}(\; U_s) \; = \dfrac{D_s}{D}.$

The grouping of all Pi term was shown in (1)

$$E = f\left(\frac{\mu}{\rho v D}, \frac{L_e}{D}, \frac{U_s}{D}, \frac{D_s}{D}\right) \quad (1)$$

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and they can be regrouped by $\pi_1 \times \pi_3$, then replacing to π_1 with the new Pi term as π_3 is the most parameter affecting to the error, as presented in (2).

$$E \times \frac{L_e}{D} = f(\frac{\mu}{\rho v D}, \frac{L_e}{D}, \frac{U_s}{D}, \frac{D_s}{D}) \quad (2)$$

All Pi terms are already checked the ranking of variable to ensure that all groups are free from each other. The conclusion of dimensional group is not guaranteed, which parameter does in fact; therefore, this work has to perform by experimental data.

III. Experiment

A. Similarity of MWA Thailand water system

The parameters were used for dimensional analysis: an error of ultrasonic flow meter, an internal diameter, a water density, a water viscosity, a velocity, an entrance region, and the upstream and downstream of the meter. The pipe with an internal diameter of 1.5 m is the most using in the MWA water system at Reynolds number in the range of 1,857,635-5,614,906. From the dimensional analysis as explained in the previous section, there are 5 groups of Pi terms, i.e., $E \times (L_e/D)$, $\mu/\rho v D$, L_e/D, U_s/D, and U_s/D and the model equation can be expressed in (3) to (7)

$$E_p = 0.3607 \times E_m, \quad (3)$$

$$(\frac{\mu}{\rho v D})_m = (\frac{\mu}{\rho v D})_p \; or \; Re_m = Re_p, \quad (4)$$

$$L_{em} = 0.0169 \times L_{ep}, \quad (5)$$

$$U_{sm} = 0.0169 \times U_{sp}, \quad (6)$$

$$D_{sm} = 0.0169 \times D_{sp} \quad (7)$$

where the subscript with "*p*" is referred to prototype and "*s*" is referred to the model. The error of ultrasonic flow meter obtained from model equals to 0.3607 times of prototype error, as expressed in (3). It is called the model predictive equation. Considering in (4), the Reynolds number of models should equal to that of the prototype; however, flow characteristic of water in the model system is impossible to form the same pattern as that of in the prototype system. In this study, velocity profile of water flowing in the pipe with the Reynolds number in the range of 31,692 to 95,078 was used to simulate flow in prototype system to model system. This idea concept was supported from Carlander and Delsing [9], which has reported that a little error of velocity measurement with ultrasonic flow meter was found in the turbulent flow region. They have studied the installation effect on an ultrasonic flow with implications for self-diagnosis and were found that only ±5 percentage of actual flow rate obtained at the Reynolds number more than 10,000. In (5) to (7), the entrance region, upstream and downstream of meter equal to 0.0169 times of prototype, respectively.

B. Experimental setup

The experiment setup (Fig. 2) consists of a pump, a check valve, a header, a testing section with an ultrasonic flow meter, a globe valve, a diverter, a weighing tank, a sump and a ball valve. The transit time ultrasonic flow meter with clamp on (Fuji Electric system Co., Ltd. FSD220Y1) having a velocity range of 0.3 to 32 m/s, fluid temperature at -40 to 200 °C, the accuracy of ± 0.05 m/s, and the velocity sensitivity of 0.001 m/s, and the internal diameter in the range of 25-50 mm.

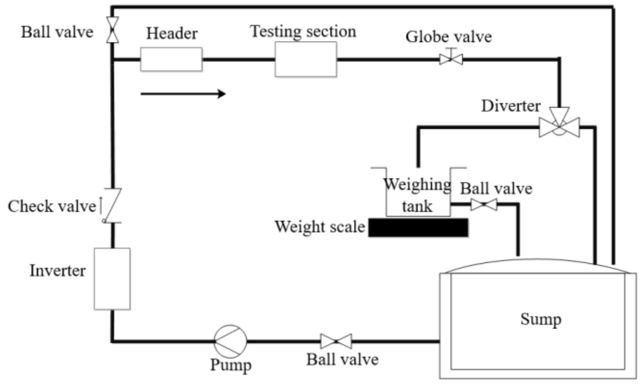

Fig. 2. Diagram of the experimental setup (Modified from [8])

The PVC pipe with an internal diameter of 2.54 cm and the length of 5.3 m, and the header pipe with an internal diameter of 10.16 cm and the length of 1.1 m were constructed to be the model. The main objective of header and globe valve mounted in the experimental unit was to adjust the pattern of water flow and to ensure that the flow characteristic of water was in the fully developed region in a short pipe. Water containing in a sump was pumped through a check valve to assure that the water flows only one direction in the system. The testing section equipped with ultrasonic flow meter was used for flow detection. Diverter was an important device used for changing of water direction from sump to weighing tank installed with the weight scale. At the beginning of the process, air bubbles in water were released from the system for 2 hours through pipe being above the header and testing section. Before running the experiment, air bubbles and flow characteristics were checked by observing via a clear plastic tube constructed as a part of the model.

C. Measurement Method

The ultrasonic flow meter with V method was clamped on the PVC pipe with a diameter of 34 mm. The sound velocity transmitted through 2 mm thickness of pipe wall was set at 2,307 m/s, while it passed through the water at 1,440 m/s. The transition voltage was set at 80 Vp-p. The operating temperature was maintained at room temperature of 23°C having the viscosity of 1.0038×10^{-6} m^2/s for all experiments.

The ultrasonic flow meter was set follows to the recommendation of the manufacturer and installed on the tested pipe having the total length of 30 cm at the upstream distance of 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 times of internal diameter (2.54 cm) and at the downstream distance of 2, 4, 6, 8, and 10 times of internal diameter (Fig. 4, table II). The velocity of water was adjusted from pump speed to

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obtain 0.2 and 0.5 m/s. During the measurement process by ultrasonic flow meter, the direction of water was changed from flowing to the sump to the weighting tank for time interval of 5 or 10 seconds depended on the mass flow rate. The experiments were run 3 replications for each condition.

The measurement results were compared between the data obtained from ultrasonic flow meter and that from weighing method and determined the relative error occurred at various positions of clamped meter on the tested pipe.

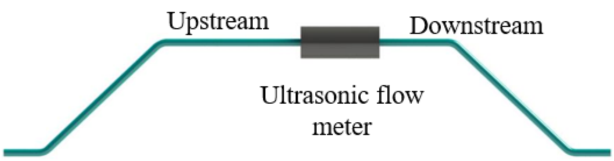

Fig. 3. Ultrasonic flow meter in experimental unit

IV. Results and discussions

The relative error is used to describe the effect of installation of ultrasonic flow meter in limited space. From table II, relative errors increased with the decreasing of upstream and downstream of meter at the same velocity. Since the installed meter was close to the 45º elbow (upstream < 20D and downstream < 10D), the flow pattern of water in pipe did not completely fully developed region. This can affect to the flow characteristic of water as explained in Ruppel [4]. In this study, the length of entrance region was about 12D and 14D at 0.2 m/s and 0.5 m/s, respectively. This was a cause of the almost constant relative error of velocity measurement beyond 12 D and 14 D of upstream distance at the suitable downstream being more than 10D.

TABLE II
RELATIVE ERRORS WITH DIFFERENT UPSTREAM AND DOWNSTREAM DISPLACEMENT, RESPECTIVELY

Upstream	Downstream	Relative error of 0.2 m/s (%)	Relative error of 0.5 m/s (%)
28D	2D	40.39	23.49
26D	4D	35.56	21.31
24D	6D	30.66	20.08
22D	8D	25.50	19.81
20D	10D	21.69	19.0
18D	12D	21.78	19.84
16D	14D	22.99	21.82
14D	16D	23.21	22.52
12D	18D	27.76	23.53
10D	20D	26.64	24.06
8D	22D	30.58	28.79
6D	24D	27.79	30.88
4D	26D	33.01	35.85
2D	28D	50.20	48.86

At the same position of installation, the more velocity it was, the less relative error was obtained. This was supported by the finding of Carlander and Delsing [3]. The relative error in velocity of 0.2 m/s was quite a lot because this velocity was below the range of recommendation from the manufacturer.

Also, in this study the observed relative errors were quite high, although the meter was installed based on the theory of fluid mechanics. This is probably due to the velocities of water tested in this paper were rather low, which affects the velocity profile of incompletely steady flow [3].

V. Conclusion

The model of the MWA Thailand water system was constructed based on the dimensional analysis and theory of Buckingham Pi, $E\times(L_e/D)$, $\mu/\rho vD$, L_e/D, U_s/D, and U_s/D, to consider the error of velocity measured from ultrasonic flow meter with clamp on at various upstream and downstream distances. It was found that the relative errors of velocity measurement increased with the decreasing of upstream and downstream of meter at the same velocity, and increasing of velocity could reduce the error. However, as the velocities of water tested in this paper were quite low, the obtained errors in this study were high, though the meter was installed followed to the recommendation. The results showed that there was a possibility to determine the correction factor to compensate the velocity measurement of ultrasonic flow meter as the installation could not comply with the requirement. Nevertheless, the further experiments should be performed under the other conditions i.e., increasing of velocity to 3 m/s and diameter of testing pipe for validation of the model predictive equation. That was $E_p = 0.3607 \times E_m$.

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