A non-intrusive method to compute water discharge in pipes with a low depth-to-diameter ratio using ultrasonic Doppler velocimetry

Authors: I. Fraga[1], L. Cea[2], J. Puertas[3], J. Anta[4]

[1] GEAMA (Environmental and Water Engineering Group), E.T.S Caminos, Universidade de A Coruña, Campus Elviña s/n, 15071 A Coruña, Spain. Corresponding autor. email: ignacio.fraga@udc.es

[2] GEAMA (Environmental and Water Engineering Group), E.T.S Caminos, Universidade de A Coruña, Campus Elviña s/n, 15071 A Coruña, Spain.email: luis.cea@udc.es

[3] GEAMA (Environmental and Water Engineering Group), E.T.S Caminos, Universidade de A Coruña, Campus Elviña s/n, 15071 A Coruña, Spain.email: jpuertas@udc.es

[4] GEAMA (Environmental and Water Engineering Group), E.T.S Caminos, Universidade de A Coruña, Campus Elviña s/n, 15071 A Coruña, Spain. email: janta@udc.es

Abstract

A non-intrusive method to calculate the water depth and discharge in partially full pipes using data from a single ultrasonic Doppler velocimeter (UDV) profiler is presented. The position of the free surface is identified from the velocity profiles measured with the UDV. The flow discharge is computed from an approximated parameterization of the velocity field in the cross section, using a single measured velocity profile. The proposed methodology was applied to steady and unsteady flow conditions in two different pipes with diameters of 90 and 200 mm, and depth-to-diameter ratios up to 0.35. Under these conditions, the water depth and discharge were measured with mean absolute errors of the order of 1mm and 0.1 l/s in the 90 mm pipe, and 0.5 mm and 0.05 l/s in the 200 mm pipe. These errors are almost independent of the discharge.

Keywords: ultrasonic Doppler velocimetry; flow discharge measurement; non-intrusive measurement; partially full pipes; urban drainage

Introduction

An accurate determination of the flow rate in partially full pipes is as a major necessity but also a difficult task. Conventional flow metering methods (such as area-velocity or turbine flow meters) present important limitations as they usually require strict conditions to obtain accurate results, such as long straight pipes and high water depths, among others (Mori et al. 2001). Because of these restrictions, the use of ultrasonic Doppler velocimetry has become increasingly popular in measuring velocity profiles and water discharges in pipes. In this context, the main advantage of an ultrasonic Doppler velocimeter (UDV) profiler is its capacity to measure in a non-intrusive way velocity profiles, with the data rate being virtually independent of the seeding concentration of particles in the water. A detailed description of ultrasonic Doppler velocimetry techniques can be found in Takeda (1990, 1995, 1999 and 2012) and Lemmin and Rolland (1997).

The capabilities of the UDV have resulted in many advances and studies in recent years, most of which have focused on pressurized flows. Mori et al. (2001) and Wada et al. (2004) developed methods to compute the flow rate in pressurized pipes integrating the instantaneous velocity profiles measured with the UDV, with relative errors in the computed discharge below 1%. In free surface flows, most of the research concerns on the interaction between air bubbles and water (Suzuki et al. 2002; Murai et al. 2006) and its effects on the UDV velocity measurements (Longo 2006)

In this technical note, we propose a methodology to compute the water discharge in partially full pipes with low depth-to-diameter ratios using a single UDV profiler, which measures the velocity of the fluid at several sampling volumes in an axial profile. The aim is to evaluate the possibility of using a single UDV profiler as a non-intrusive discharge-measuring device in partially full pipes, and to quantify the accuracy of the discharge measures. The position of the free surface is identified using the velocity profiles measured with the UDV, and the discharge is computed from a simplified parameterization of the velocity field in the cross section. The methodology was calibrated and validated using experimental data obtained in the laboratory in two pipes of diameters 90 and 200 mm.

Experimental setup

The experimental setup consists of the pipeline shown in Fig. 1. Water is pumped from a tank (1), flows through a valve (2), and it is discharged into a manhole (3). From the manhole, water flows into pipes 1 and 2 and discharges into a cylindrical basin (6) with a pressure sensor (7). The characteristics of the pipes are detailed in Table 1.

Table 1. Characteristics of the pipes used in the experimental setup.

The water discharge at the line outlet is evaluated from the time variation of the water volume in the cylindrical basin where the pipe spills. The water depth at the basin is measured with a pressure sensor at a frequency of 1 Hz.

Four meters downstream of the manhole in pipe 1, and at the central point of pipe 2, small orifices are opened on the top of the pipe to install ultrasonic distance sensors with a clamp-on system, pointing toward the bottom of the pipes to measure the water depth. The recording frequency of these sensors is 2 Hz. At the same position where the distance sensors are located, two DOP2000 (Signal

Processing S.A.) UDVs are secured with brackets to the bottom of the pipes pointing at the center of each pipe. The angle between the probes and the pipe longitudinal axis (α in Fig. 2) is 65°. As pointed in Yokoyama et al. (2004), small inaccuracies in the angle of the UDV transducer can be the main cause of error when computing discharges from measured velocities. In the results presented in this work, a deviation of only 1º implies an error of approximately 5% on the computed discharge. An accurate setup of the probe angle is therefore of great importance.

The transducers are in contact with the pipe wall, and the gap between the probe and the wall is filled with a gel (AquaGel 100, Parker Laboratories, S.A.) that works as a coupling medium to allow the propagation of the ultrasonic waves. The angles between the ultrasonic beam and the pipe longitudinal axis in both the pipe wall and the liquid (θ and β in Fig. 2) are computed from the refraction law taking into account the sound celerity of the pipe wall, the ultrasonic gel and the liquid.

Methodology

Data treatment

Despiking

Raw data from the UDV contains corrupt information that needs to be filtered, mainly because of the Doppler noise and the aliasing of the signal. Several studies have been published in which different despiking techniques are proposed and compared (Cea et al. 2007; Jesson et al. 2013). In the present study, the filter proposed by Goring and Nikora (2002) was used to detect and remove spikes from the raw velocity data registered with the UDV transducers.

Velocity projection

The UDV gives the velocity component in the beam axis direction. Measured velocities are projected in the pipe longitudinal direction, assuming that the water flows parallel to the pipe axis.

Distance correction

The following correction proposed in Wang et al. (2003) is applied to the raw distances measured with the UDV to take into account the different sound celerity in the pipe wall, the ultrasonic gel and the liquid. The correction introduces an offset in the position of the sampling volumes due to the different celerity of the ultrasonic waves in the ultrasonic gel and the pipe wall. The real distance traveled by the ultrasonic beam is computed as:

$$d = d_g + d_w + \left(\frac{d^*}{c_L \sin\alpha} - \frac{d_g}{c_g \sin\alpha} - \frac{d_w}{c_w \sin\beta} \right) c_L \sin\theta \tag{1}$$

where c_w, c_g, and c_L are the sound celerities in the pipe wall, the ultrasonic gel, and the liquid respectively, d is the real distance traveled by the ultrasonic beam, d^* is the raw distance measured by the UDV and d_g and d_w are the distances traveled by the ultrasonic waves along the ultrasonic gel and the pipe wall (Fig. 2).

Measurement volume correction

The correction proposed in Nowak (2002) is used at the sampling volumes in contact with the pipe wall and with the free surface. This correction takes into account that at the interface between medias (liquid – air and liquid – pipe wall) only part of the sampling volume is located inside the fluid. The correction consists in assigning the measured velocity to the centroid of only the volume located inside the fluid instead of the mass center of the whole sampling volume.

Position of the free surface

The position of the free surface is determined from the velocity profiles measured with the UDV. To calibrate the methodology, the water depth was additionally measured with the ultrasonic distance sensors.

The velocity profile measured with the UDV has a local minimum just above the maximum velocity in the profile (Fig. 3). The position of this minimum, referred to as d_{UDV} in Table 2, is in close agreement with the position of the free surface measured with the distance sensor (d_M in Table 2). Therefore, a simple criterion to evaluate the water depth from the UDV measurements is to locate the free surface at the position of this minimum. The ratio between the water depth corresponding to the maximum velocity and d_{UDV} is similar in all the profiles registered, with values of approximately 0.85 and 0.9 in pipes 1 and 2, respectively.

Table 2. Water depths measured with the ultrasonic distance sensor (d_M), obtained from the UDV profiles(d_{UDV}), and computed with the Sobel filter (d_s). Φ_{int} is the interior diameter of the pipe.

The water depths obtained with this criterion are compared in Table 2 with those computed with the method described in Murai et al. (2006), in which the free surface is identified using the Sobel filter on the velocity profiles. The Sobel filter overestimates in all cases the water depth, the mean absolute error (MAE) being 2.65 and 1.09 mm in pipes 1 and 2, respectively. With the proposed criterion, the MAE is reduced to 0.94 and 0.47 mm in pipes 1 and 2, respectively.

Parameterization of the velocity field

To compute the discharge in a pipe cross section, it is necessary to integrate the velocity field in the wet section. Since in partially full pipes the flow is not axisymmetric, a parameterization of the velocity field is needed to estimate the velocity distribution from a single profile. Most of the existing methods to estimate the velocity distribution in pipes and open channels are based on probabilistic and entropy-maximization approaches, such as the ones described in Marini et al. (2011), Chiu (1988) and Chiu and Hsu (2006). These methods assume that the discharge and the mean velocity in the cross section are known and therefore, they cannot be applied to evaluate the discharge from a single velocity profile.

In this study, we propose a parameterization of the velocity distribution given by a series of isovelocity curves defined from each sampling volume of the UDV in the following way. If the velocity in a sampling volume is lower than the velocity at the free surface, the corresponding isovelocity curve is defined as an arc with the same center as the pipe cross section and a radius defined by Eq. (2). This is the case of the isovelocity curve 1 in Fig. 4. In the sampling volumes in which the velocity is higher than the velocity at the free surface, the isovelocity curve is defined by an arc concentric to the pipe cross section and a chord parallel to the free surface. This is the case of the isovelocity curve 2 in Fig. 4, which is defined by Eq. (2) and (3). It should be remarked that this parameterization is just an approximation of the real velocity distribution in partially full pipes with a low depth-to-diameter ratio, the aim being to evaluate the discharge and not to reproduce the exact velocity field. The advantages of the proposed parameterization are its simplicity, that it does not rely on any calibration parameter and that it gives quite accurate discharge estimations, as will be shown in the following sections.

$$R_1 = R_{pipe} - d_1 \qquad \varphi = 2 \cdot acos\left(\frac{R_{pipe} - d_{UDV}}{R_{pipe} - d_1}\right) \tag{2}$$

$$R_2 = R_{pipe} - d_{2A} \qquad \varphi = 2 \cdot acos\left(\frac{R_{pipe} - d_{2B}}{R_{pipe} - d_{2A}}\right) \tag{3}$$

From the velocity parameterization given by Eq. (2) and (3), the discharge is computed as

$$Q = \sum_{1}^{n-1} \left(A_{i+1} - A_i\right)\left(\frac{V_{i+1} + V_i}{2}\right) \tag{4}$$

where A_i is the area inside the i^{th} isovelocity curve, V_i is the velocity of the i^{th} isovelocity curve, and n is the number of isovelocity curves, which is equal to the number of sampling points of the central UDV.

Results under steady-state conditions

The previous methodology was calibrated under steady conditions for the discharges shown in Table 3. In all cases, the velocity profiles were measured for 20 s with a measuring frequency of 10 Hz, resulting in 200 profiles per discharge. In both pipes, the mean absolute relative error (MARE) on the computed discharges is below 5%, with a slightly better performance in pipe 1.

Table 3. Discharges computed with the proposed parameterization. Relative errors are shown in parentheses.

In the results presented in Table 3, if the correction proposed by Wang et al. (2003) is not applied the computed discharge decreases. For the lowest discharge this decrease is almost 2% and 7% in pipes 1 and 2 respectively, while the effect of the correction nearly halves for the highest discharge. On the contrary, if the correction proposed by Nowak (2002) is ignored, the computed discharges increase approximately 8% in both pipes for the lowest discharge. The increase is reduced to 1.8 % and 0.4 % in pipes 1 and 2 respectively for the highest discharges. It is interesting to notice that when both of the corrections are considered the impact on the computed discharge is reduced since they have the opposite effect.

Validation under unsteady conditions

The proposed methodology was validated under unsteady conditions with a discharge increasing from zero to 2 l/s in 130 s and then decreasing again to zero (Fig. 5). The maximum depth-to-diameter ratios achieved during the validation were 0.35 and 0.14 in pipes 1 and 2, respectively. Velocity profiles were measured with a sampling frequency of 10 Hz and averaged over 1 s in order to evaluate the outlet hydrograph with a frequency of 1 Hz.

The outlet hydrograph computed from the UDV data is compared against the discharges measured at the pipe line outlet in Fig. 5. The global agreement is very satisfactory, especially in pipe 2. Differences between computed and measured discharges alternate positive and negative values in both pipes with no noticeable bias (the mean errors on the discharge are 0.0180 and 0.0002 l/s in pipes 1 and 2, respectively). It is also interesting to notice that there is no significant trend in the absolute error as the discharge increases, which implies that the relative error diminishes as the discharge increases. The mean errors in the computed discharge during the whole experiment are shown in Table 4.

Table 4. Mean errors and standard deviation of the error in the computed discharge.

Conclusions

A methodology to compute the water depth and flow rate in partially full pipes with a low depth-to-diameter ratio using data from a single ultrasonic Doppler velocimeter profiler was presented. The methodology was tested under steady and unsteady conditions in two pipes of 90 and 200 mm diameters. Discharge and water depth ranged up to 2.5 l/s and 31 mm, with depth-to-diameter ratios up to 0.35. Absolute errors on the water depth are below 1 and 0.5 mm in the 90 and 200 mm pipes respectively. Regarding the water discharge, errors are higher in the 90 mm pipe, where they reach values of the order of 0.1 l/s, while in pipe 2 errors nearly halve. No clear trend was observed between the accuracy of the methodology and the flow rate.

Although the proposed methodology has only been tested in 90 and 200 mm diameter pipes, it might be applicable to larger pipes. However, its application to hydraulic conditions different from the ones presented in this paper, especially in terms of the water depth-to-diameter ratio, may need a different parameterization of the velocity field in the cross section to ensure that the discharge is properly computed.

References

Cea, L., Puertas, J., and Pena, L. (2007). "Velocity measurements on highly turbulent free surface flow using ADV." *Exp. Fluids*. 42, 333-348.

Chiu, C.L. (1988). "Entropy and 2-D velocity distribution in open channels." *J. Hydraul. Eng.*114, 738-756.

Chiu, C.L., and Hsu, S.M. (2006). "Probabilistic approach to modeling of velocity distributions in fluid flows."*J. Hydrol*. 316, 28-42.

Goring, D.G., and Nikora, V.I. (2002). "Despiking acoustic Doppler velocimeter data." *J. Hydraul. Eng.* 128, 117-126

Jesson, M., Sterling, M., and Bridgeman J. (2013). "Despiking velocity time-series—Optimisation through the combination of spike detection and replacement methods." *Flow Meas. Instrum.*30, 45-51.

Lemmin, U., and Rolland, T. (1997). "Acoustic velocity profiler for laboratory and field studies." *J. Hydraul. Eng.* 123, 1089-1097

Longo, S. (2006). "The effects of air bubbles on ultrasound velocity measurements." *Exp. Fluids* 41, 593-602

Marini, G., De Martino, G., Fontana, N., Fiorentino, M., and Singh, V.P. (2011). "Entropy approach for 2D velocity distribution in open-channel flow." *J. Hydraul. Res.* 49, 784-790

Mori, M., Takeda, Y., Taishi, T., Furuichi, N., Aritomi, M., and Kikura, H. (2002). "Development of a novel flow metering system using ultrasonic velocity profile measurement." *Exp. Fluids* 32, 153-160

Murai, Y., Fujii, H., Tasaka, Y.,and Takeda, Y. (2006). "Turbulent bubbly channel flow investigated by ultrasound velocity profiler." *J. Fluid. Sci. Tech.*1, 12-23.

Nowak, M. (2002). "Wall shear stress measurement in a turbulent pipe flow using ultrasound Doppler velocimetry." *Exp. Fluids* 33, 249-255

Suzuki, Y., Nakagawa, M., Aritomi, M., Murakawa, H., Kikura, H., and Mori, M. (2002) "Microstructure of the flow field around a bubble in counter-current bubbly flow." *Exp. Therm.Fluid Sci.* 26, 221-227.

Takeda, Y. (1990). "Development of ultrasound velocity profile monitor." *Nucl. Eng. Design* 126, 277-285

Takeda, Y. (1995). "Velocity profile measurement by ultrasonic Doppler method." *Exp. Therm. Fluid Sci.* 10, 444-453.

Takeda, Y. (1999). "Ultrasonic Doppler method or velocity profile measurement in fluid dynamics and fluid engineering." *Exp. Fluids* 26, 177-178

Takeda, Y. (2012). "Ultrasonic Doppler velocity profiler for fluid flow." Springer, Japan.doi: 10.1007/978-4-431-54026-7

Wada, S., Kikura, H., Aritomi, M., Mori, M., and Takeda, Y. (2004). "Development of pulse ultrasonic Doppler method for flow rate measurement in power plant multilines flow rate measurement on metal pipe." *J. Nucl. Sci. Technol.*41(3), 339-346

Wang, T., Wang, J., Ren, F., and Jin, Y. (2003). "Application of Doppler ultrasound velocimetry in multiphase flow." *Chem. Eng. J.* 92(1), 111-122

Yokoyama, K., Kashiwaguma, N., Okubo, T., and Takeda, Y. (2004). "Flow measurement in an open channel by UVP". *Proc ISUD*4, 204-210

Figure Captions

Fig. 1. Schematic representation of the experimental setup.

Fig. 2. Scheme of the UDV transducers setup

Fig. 3. Velocity profiles in pipes 1 (left) and 2 (right), for water discharges Q_1, Q_3, and Q_5 (**Table 2**). Dashed lines correspond to d_{UDV}.

Fig. 4. Parameterization of the isovelocity curves (left) from the measured velocity profile with the UDV (right). The dots in the velocity profile represent sampling volumes.

Fig. 5. Hydrographs in pipes 1 (left) and 2 (right) directly measured and computed from UDV measurements.

Tables and table captions

Table 5. Characteristics of the pipes used in the experimental setup.

Pipe	Exterior diameter (mm)	Pipe wall thickness (mm)	Material	Slope (%)	Length (m)
1	90	2.5	Polypropylene	1.75	5
2	200	4.9	PVC	0.87	6

Table 6. Water depths measured with the ultrasonic distance sensor (d_M), obtained from the UDV profiles(d_{UDV}), and computed with the Sobel filter (d_s). Φ_{int} is the interior diameter of the pipe.

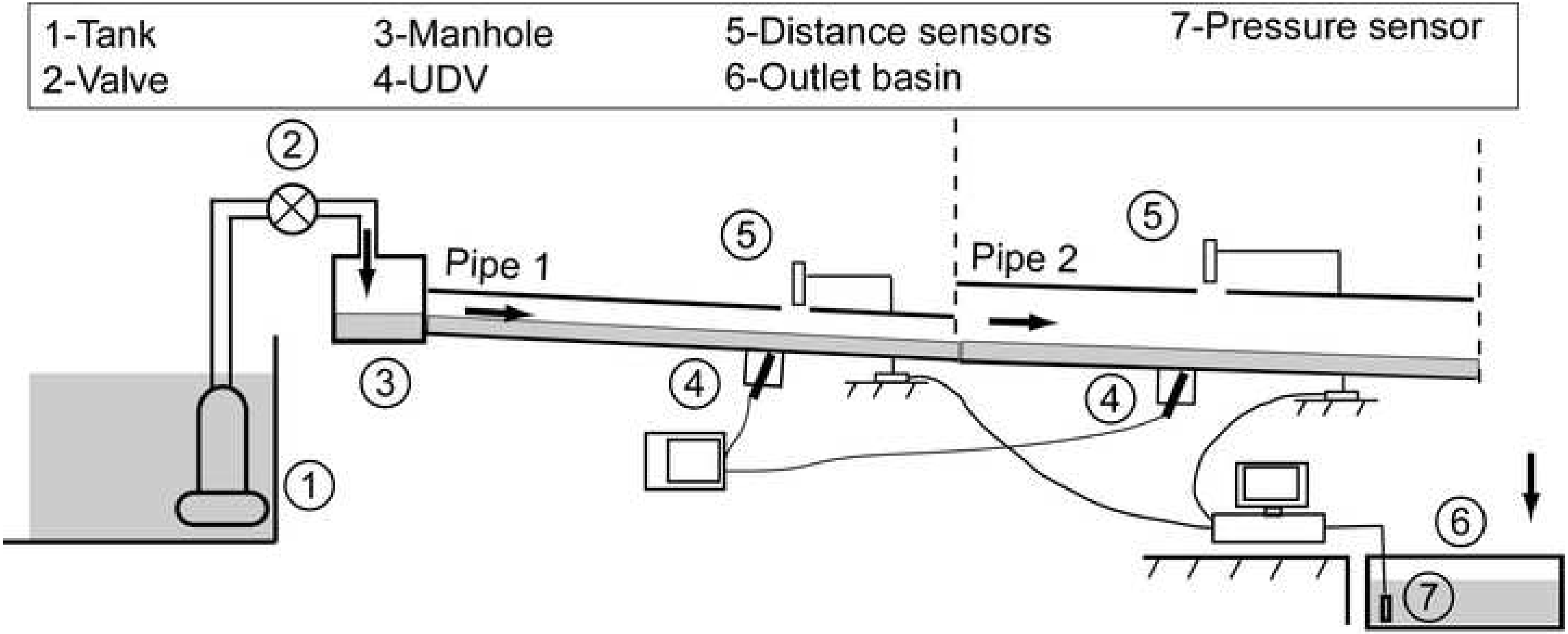
Q (l/s)	Water depths in pipe 1				Water depths in pipe 2			
	d_M (mm)	d_M/Φ_{int} (%)	d_{UDV} (mm)	d_S (mm)	d_M (mm)	d_M/Φ_{int} (%)	d_{UDV} (mm)	d_S (mm)
2.55	28.27	33.3	28.77	29.99	31.33	14.9	30.51	31.39
2.08	23.94	28.2	25.10	27.55	28.52	12.6	28.77	29.64
1.63	21.18	24.9	22.66	25.10	24.67	11.1	24.40	26.15
0.99	18.41	21.7	19.66	20.88	19.30	9.7	20.03	20.91
0.54	15.00	17.6	15.32	16.54	13.64	7.9	13.92	14.80

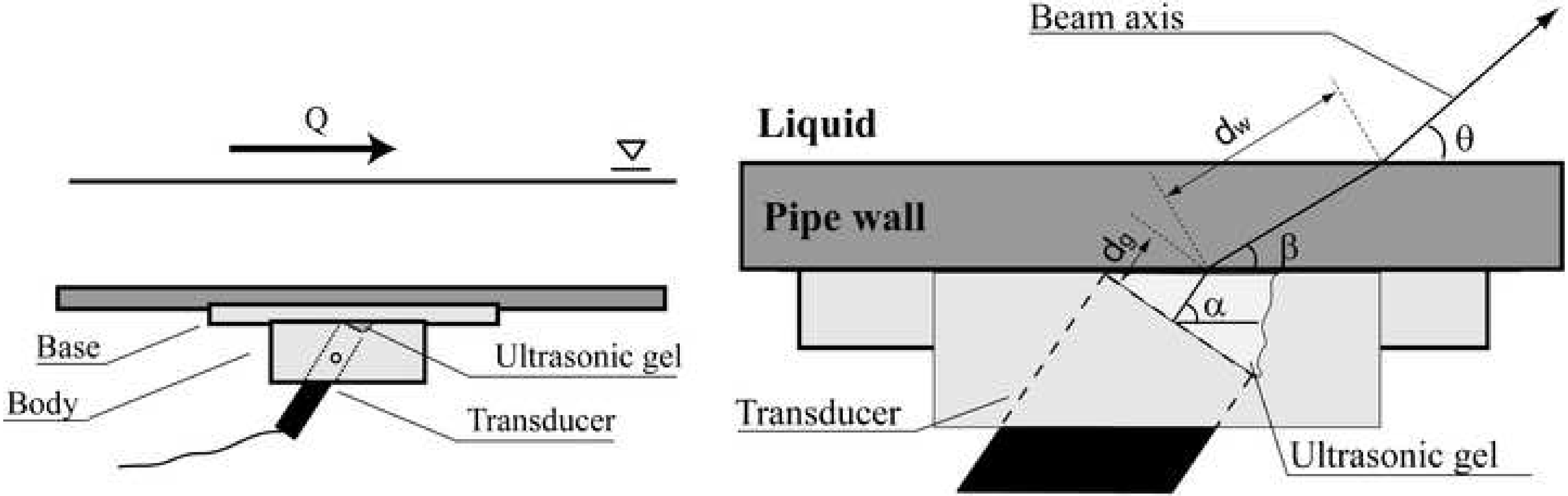
Table 7. Discharges computed with the proposed parameterization. Relative errors are shown in parentheses.

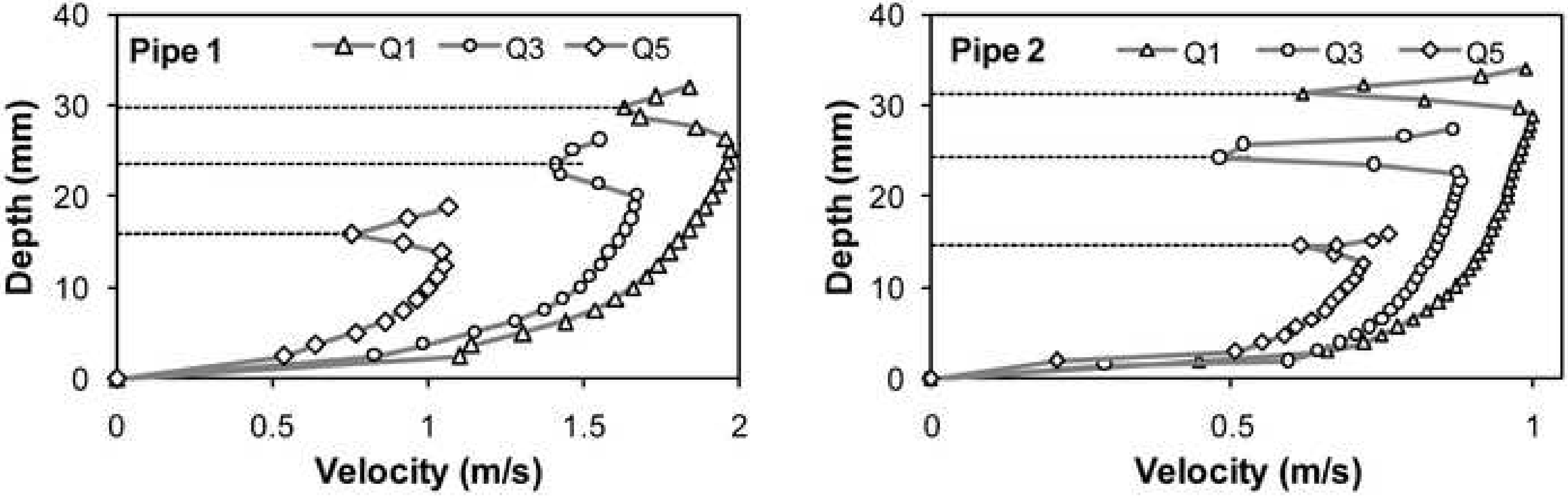
Q (l/s)	Computed discharges	
	pipe 1 (l/s)	Pipe 2 (l/s)
2.55	2.59 (1.7%)	2.44 (-4.2%)
2.08	2.04 (-2.1%)	2.14 (2.8%)
1.63	1.52 (-6.8%)	1.48 (-9.1%)
0.99	0.97(-2.2%)	0.98 (-1.2%)
0.54	0.56 (3.0%)	0.57 (4.3%)
MARE	3.1%	4.3%

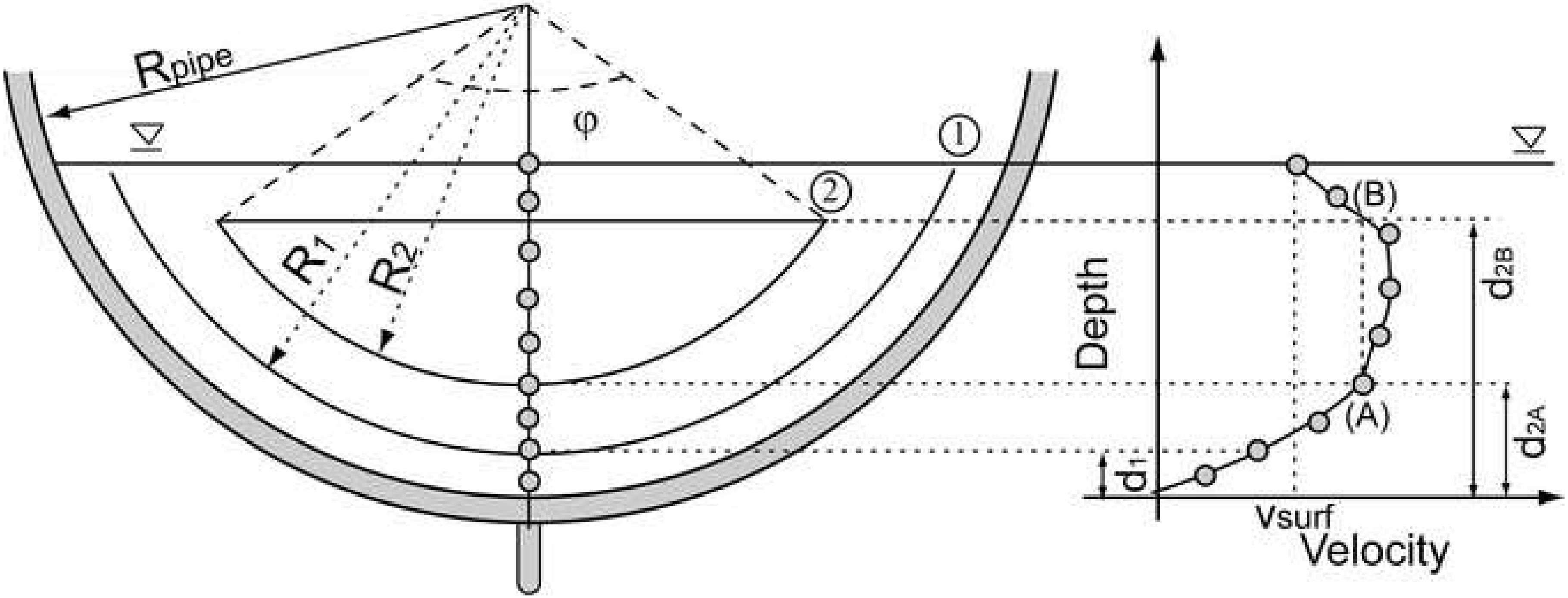
Table 8. Mean errors and standard deviation of the error in the computed discharge.

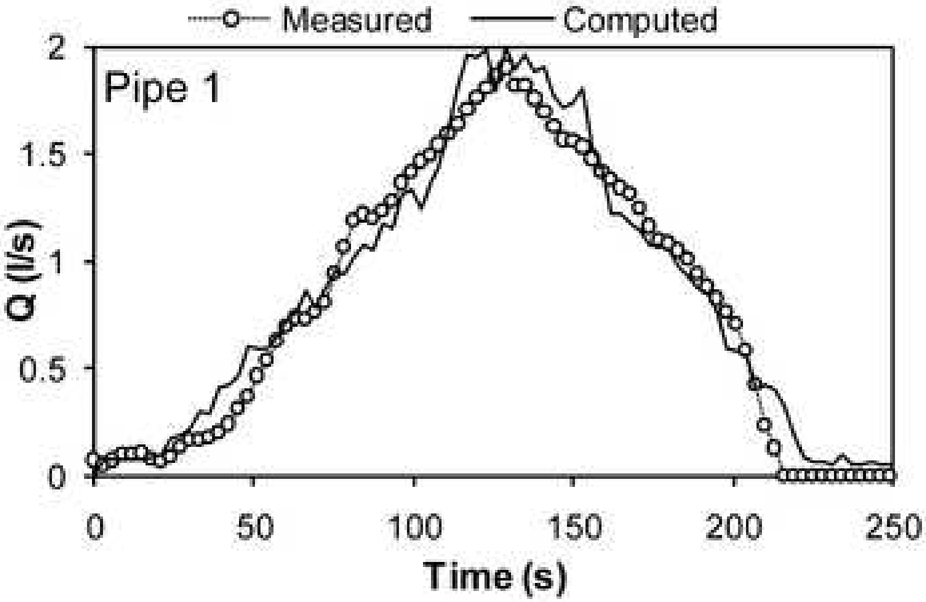
Pipe	MAE (l/s)	ME (l/s)	Error Standard Deviation (l/s)
1	0.1050	-0.0180	0.1192
2	0.0520	-0.0002	0.0712

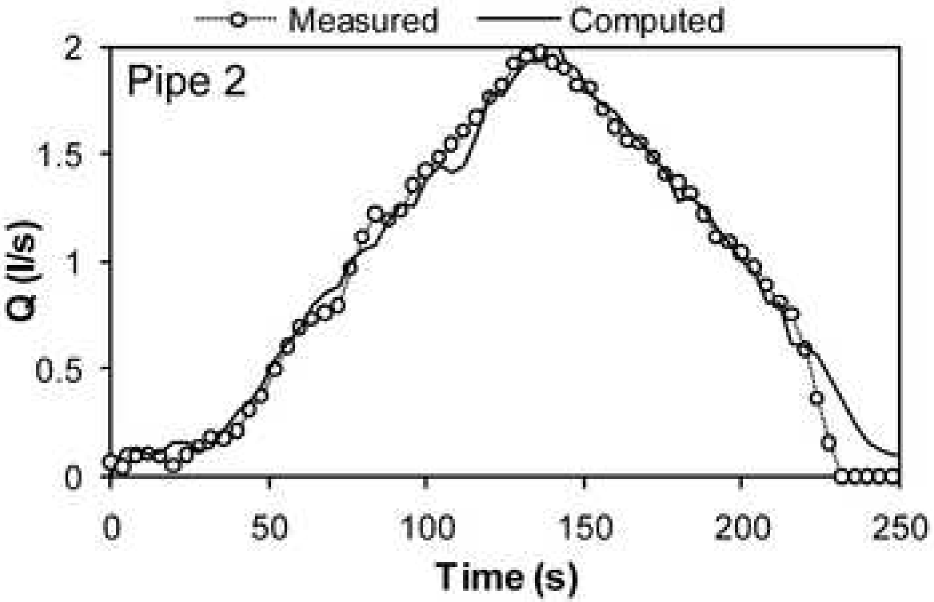

1-Tank
2-Valve
3-Manhole
4-UDV
5-Distance sensors
6-Outlet basin
7-Pressure sensor
②
Pipe 1
⑤
Pipe 2
⑤
③
④
④
①
⑥
⑦


Q
Base
Body
Ultrasonic gel
Transducer
Beam axis
Liquid
Pipe wall
d_w
d_g
θ
β
α
Transducer
Ultrasonic gel


Pipe 1
Q1
Q3
Q5
Depth (mm)
40
30
20
10
0
0
0.5
1
1.5
2
Velocity (m/s)
Pipe 2
Q1
Q3
Q5
Depth (mm)
40
30
20
10
0
0
0.5
1
Velocity (m/s)


Rpipe
φ
①
②
R1
R2
(B)
(A)
Depth
d2B
d2A
d1
vsurf
Velocity


Measured
Computed
Pipe 1
Q (l/s)
0
0.5
1
1.5
2
0
50
100
150
200
250
Time (s)


Measured
Computed
Pipe 2
Q (l/s)
0
0.5
1
1.5
2
0
50
100
150
200
250
Time (s)