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Performance of models to determine flow rate using orifice plates[1]

Desempenho de modelos para determinação de vazão utilizando placas de orifício

Nicolas D. Cano[2*], Antonio P. de Camargo[2], Gustavo L. Muniz[2], Jonesmar de Oliveira[2],
José G. Dalfré Filho[3] & José A. Frizzone[4]

[1] Research developed at Universidade Estadual de Campinas, Faculdade de Engenharia Agrícola, Campinas, SP, Brasil and Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, SP, Brasil
[2] Universidade Estadual de Campinas/Faculdade de Engenharia Agrícola/Laboratório de Hidráulica e Irrigação, Campinas, SP, Brasil
[3] Universidade Estadual de Campinas/Faculdade de Engenharia Civil, Arquitetura e Urbanismo/Laboratório de Hidráulica, Campinas, SP, Brasil
[4] Universidade de São Paulo/Escola superior de Agricultura "Luiz de Queiroz"/Faculdade de Engenharia Agrícola, Piracicaba, SP, Brasil

HIGHLIGHTS:

Three methodologies for orifice-plate water-flow estimation were evaluated.
Empirical equations demonstrated better accuracy and greater rangeability.
The Reader-Harris/Gallagher equation is useful when other calibration methods are unavailable.

ABSTRACT: This study aimed to evaluate three methodologies for orifice-plate water-flow estimation by quantifying errors in the flow determinations to propose an appropriate measurement range for each evaluated condition. Two orifice-plate models (nominal diameters of 100 and 150 mm) with 50% restriction in the flow section were evaluated. In the theoretical equations, the discharge coefficient was obtained using the Reader-Harris/Gallagher equation (Method 1) and approximated from experimental data using the angular coefficient of a zero-intercept straight line (Method 2). The recommended measurement ranges for errors that were lower than 5% for the 100 and 150 mm plates were 30 to 65 $m^3 h^{-1}$ and 70 to 130 $m^3 h^{-1}$ using the theoretical equation and 20 to 65 $m^3 h^{-1}$ and 40 to 130 $m^3 h^{-1}$ using the empirical equation, respectively. The Reader-Harris/Gallagher equation (Method 1) adequately estimated the discharge coefficient of the orifice plates; however, the use of empirical equations (Method 3) demonstrated smaller measurement errors and greater rangeability of the evaluated flow meters.

Key words: hydrometry, diaphragm, hydraulics

RESUMO: Objetivou-se neste estudo avaliar três metodologias para a estimativa da vazão de água em placas de orifício, quantificando erros nas determinações de vazão a fim de sugerir a faixa de medição apropriada para cada condição avaliada. Foram avaliados dois modelos de placa de orifício (diâmetros nominais 100 e 150 mm) com restrição de 50% em relação ao diâmetro nominal. Nas equações teóricas, o coeficiente de descarga foi obtido pela equação de Reader-Harris/Gallagher (Método 1) e aproximado a partir de dados experimentais pelo coeficiente angular de uma reta com intercepto igual a zero (Método 2). A faixa de medição recomendada para manter os erros inferiores a 5% para a placa de 100 e 150 mm foi de 30 a 65 $m^3 h^{-1}$ e de 70 a 130 $m^3 h^{-1}$ utilizando a equação teórica e de 20 a 65 $m^3 h^{-1}$ e de 40 a 130 $m^3 h^{-1}$ utilizando a equação empírica, respectivamente. A equação de Reader-Harris/Gallagher (Método 1) estimou adequadamente o coeficiente de descarga dos modelos de placas de orifício, entretanto o uso de equações empíricas (Método 3) proporcionou menores erros de medição e maior rangeabilidade dos medidores de vazão avaliados.

Palavras-chave: hidrometria, diafragma, hidráulica

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* Corresponding author - E-mail: nicduarte_91@hotmail.com
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Introduction

Differential-pressure flow meters use the differential-pressure principle to determine fluid flow (Delmée, 2003). An orifice plate or diaphragm is a differential-pressure flow meter that basically consists of a perforated circular plate that provides restriction to the flow section, causing a differential pressure that is proportional to the flow into the pipe. Orifice plates are the most common differential-pressure flow meters for determining the flow rate in pipes (Shah et al., 2012) and stand out owing to their simple construction, contain no moving parts, ease in installation, lower cost among other differential-pressure flow meters, and suitability for various fluids and in multiphase flows (Campos et al., 2014). The discharge coefficient (C_d) of an orifice plate is given by the ratio between the current and theoretical flows. C_d can be estimated from experimental data collected by calibration procedures or from equations. In the latter, the Reader-Harris/Gallagher (R-H/G) equation stands out (ISO 5167-2, 2003; Reader-Harris, 2015).

The present study aimed to compare three methodologies to estimate the water flow in orifice plates by quantifying errors in the flow determinations to propose an appropriate measurement range under each evaluated condition.

Material and Methods

The tests were carried out at the Hydraulics and Fluid Mechanics Laboratory of the Faculty of Civil Engineering, Architecture and Urbanism (FEC/UNICAMP), Brazil, in partnership with the Hydraulics and Irrigation Laboratory (FEAGRI/UNICAMP), Brazil. The water used in the tests was obtained from a local supply network at room temperature (23.8 ± 0.5 °C). Two orifice plates with concentric holes and pressure corner taps (ISO 5167-2, 2003) were evaluated. The pressure taps were annular slots located on the flanges, which provided pressure measurement close to the faces upstream and downstream of the orifice plate (Delmée, 2003) (Figure 1). The 100-mm orifice-plate model had an internal diameter of 100 mm and a 50-mm hole, whereas the 150-mm model had an internal diameter of 150 mm and a 75-mm hole. Both plates were made of 4-mm-thick stainless steel with a 45° beveled hole downstream.

The test bench was a hydraulically closed circuit where the flow was manually adjusted by a gate valve installed downstream of the flow measurement instruments in an inverted siphon arrangement to avoid air accumulation in the flow section. Straight lengths longer than 22 times and 10 times the diameter of the pipe (22D and 10D) were used upstream and downstream, respectively, of the orifice plate, as recommended in the standard for conditions where a 90° bend exists upstream in a straight length (ISO 5167-2, 2003).

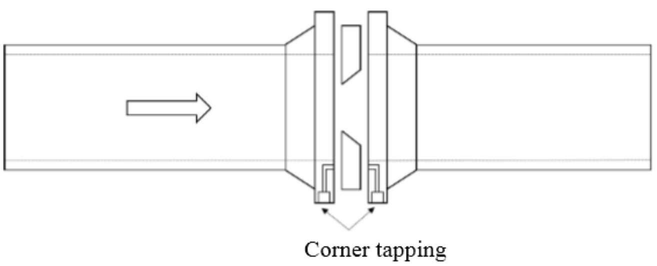

Figure 1. Orifice plate with corner tapping

The reference flow rate was determined using an electromagnetic flow meter with nominal diameter of 150 mm and measurement range from 5 to 150 $m^3 h^{-1}$ that featured 30:1 rangeability, which is typical for this type of flow meter (AWWA, 2006). The test pressure and water temperature were monitored using a pressure transducer and PT100 thermoresistance, respectively. The differential pressure through the orifice plate was monitored using a differential-pressure transducer. The specifications of the measuring instruments are listed in Table 1. All sensors provided an analog output signal that ranged from 4 to 20 mA, which linearly varied with the measured quantity. The data acquisition of all measurement instruments was performed using an electronic system equipped with a 16-bit analog-to-digital converter to acquire analog signals within the range from 4 to 20 mA and resolution of 625 nA. For each test condition, 100 records of the sensor readings were sampled at a 1-s acquisition interval.

The flow-rate range through the orifice plate corresponded to differential pressure from 10 to 100 kPa in which the 100-kPa pressure corresponded to the full scale of the differential-pressure transducer. The tests were carried out under conditions of increasing and decreasing flows to account for the hysteresis effects of the measurement instruments. The pressure upstream of the orifice plate was maintained at approximately 200 kPa during the tests.

For the orifice plate with a nominal diameter of 100 mm, data were collected at flow rates from 15 to 65 $m^3 h^{-1}$ for a total of 1200 records in this set of tests. For the 150 mm model, data were collected from 40 to 130 $m^3 h^{-1}$ for a total of 1000 records. The flow velocities in the pipeline varied from 0.5 to 2.3 $m s^{-1}$, and they belong to the typical range for design and operation of pressurized conduits (Azevedo Netto & Fernandez, 2015).

The discharge coefficient of orifice plates with corner tappings for pipes with a diameter of more than 71.12 mm and used for water-flow measurement can be estimated using the R-H/G equation (ISO 5167-2, 2003; Reader Haris & Sattary, 1990) according to Eqs. 1 to 4. The ISO 5167-2 (2003) standard also recommends that the value of β (Eq. 2) should always be between 0.10 and 0.75, with the values within this range being selected according to the application and taking into account the requirements for head-loss tolerance and required measurement sensitivity. The R-H/G equation presented in

Table 1. Specifications of the measurement instruments used in the tests

Measurement instrument	Manufacturer/ Model	Measurement range	Resolution
Pressure transducer	Velki/ VKP-011	0-400 kPa	0.1 kPa
Differential-pressure transducer	Pressgage/ TR.DIF.03.1	0-100 kPa	0.1 kPa
Thermoresistance PT100	Velki/ VKT-111	0-50 °C	0.1 °C
Electromagnetic flow meter	Khrone/ Optiflux 2000	5-150 $m^3 h^{-1}$	0.1 $m^3 h^{-1}$

ISO 5167-2 (2003) contains additional terms applicable to other pressure tap configurations (e.g., D and D/2 and flange tappings) as well as for pipes with diameters smaller than 71.12 mm. Eq. 1 is presented in a simplified manner in relation to the ISO 5167-2 (2003) standard, eliminating the null terms in the evaluated configuration. Therefore, it is applicable only under the conditions previously described.

$$\begin{aligned} C_d &= 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521\left(\frac{10^6\beta}{R_{e_D}}\right)^{0.7} + \\ &+ \left(0.0188 + 0.0063A\right)\beta^{3.5}\left(\frac{10^6}{R_{e_D}}\right)^{0.3} \end{aligned} \tag{1}$$

$$\beta = \frac{d}{D} \tag{2}$$

$$R_{e_D} = \frac{VD}{\upsilon} \tag{3}$$

$$A = \left(\frac{19000\beta}{R_{e_D}}\right) \tag{4}$$

where:

C_d - discharge coefficient of the orifice plate;
D - internal pipe diameter, m;
d - inner diameter of the plate hole, m;
β - ratio between the orifice-plate diameters;
υ - water kinematic viscosity coefficient, $m^2\ s^{-1}$;
V - average flow velocity in the pipeline, $m\ s^{-1}$;
R_{eD} - Reynolds number; and,
A - coefficient that is dependent on the Reynolds number.

Using the Bernoulli's theorem and continuity equation, the flow rate through an orifice plate is obtained by Eq. 5.

$$Q = C_d \frac{\pi d^2}{4}\sqrt{\frac{2\ g\ \Delta h}{1-\beta^4}} \tag{5}$$

where:

Q - flow rate through an orifice plate, $m^3\ s^{-1}$; and,
Δh - differential-pressure head on the orifice plate, m.

Three orifice-plate flow calculation methods were evaluated. In Method 1, the C_d value corresponding to each record was calculated using Eq. 1 (i.e., R-H/G), and an average C_d value was used. In Method 2, the C_d value corresponded to the angular coefficient of a zero-intercept straight line, which was obtained by plotting the reference flow rate as a function of the theoretical flow determined from Bernoulli's theorem (Eq. 5). In contrast to the C_d value obtained by Eq. 1, when C_d in Eq. 5 was isolated and the values corresponding to each test record were calculated, a wide variation in the C_d values existed, and thus, the use of an average value obtained by Eq. 5 could be questionable. This result justified the use of an approximation using the angular coefficient of a zero-intercept straight line. In Method 3, a power-law equation was fitted to the experimentally obtained data set, which related the flow rate to the differential-pressure head.

For the result analyses, the flow measurement errors were expressed relative to the measured values (Eq. 6) and to the full scale (Eq. 7).

$$E_{MV} = 100\frac{\left|Q_{ref} - Q\right|}{Q_{ref}} \tag{6}$$

$$E_{FS} = 100\frac{\left|Q_{ref} - Q\right|}{Q_{FS}} \tag{7}$$

where:

E_{MV} - error relative to the measured value, %;
E_{FS} - error relative to the full scale, %;
Q_{ref} - reference flow provided by the electromagnetic meter, $m^3\ h^{-1}$; and,
Q_{FS} - flow corresponding to the full scale of the orifice plate, $m^3\ h^{-1}$.

The repeatability standard uncertainty (Type-A uncertainty) was calculated to quantify the dispersion of the values over the flow-measurement range. The standard uncertainty was estimated using the standard deviation of the sample mean according to Eq. 8.

$$S_{\bar{x}} = \frac{S_x}{\sqrt{n}} \tag{8}$$

where:

$S_{\bar{x}}$ - standard deviation of the sample mean or repeatability standard uncertainty of the flow in a given test condition, $m^3\ h^{-1}$;
S_x - sample standard deviation of the flow rate, $m^3\ h^{-1}$; and,
n - sample size in a given test condition.

RESULTS AND DISCUSSION

Figure 2 shows the reference flow values as a function of the differential-pressure head under increasing and decreasing flow conditions for the two orifice-plate models (i.e., 100 and 150 mm)

For each test record, the C_d values were calculated using Eqs. 1 and 5 (Figure 3A). For both orifice plates, the C_d values estimated using Eq. 1 (i.e., R-H/G equation) showed a small variation in the values over the entire test-flow range (Figure 3A). For the 100-mm orifice plate, C_d varied between 0.605 and 0.609 with an average of 0.606. For the 150-mm plate, C_d varied between 0.605 and 0.607, and it exhibited an average of 0.606. Prediction of C_d using the R-H/G equation is recommended by ISO 5167-2 (2003), and the parameters vary according to the dimensions of the orifice plate, position

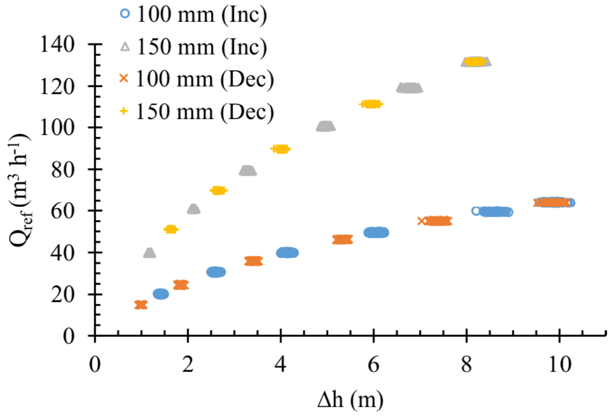

Figure 2. Reference flow (Q_{ref}) as a function of the differential-pressure head (Δh) obtained under increasing (Inc) and decreasing (Dec) flow conditions for the evaluated two orifice-plate models (100 and 150 mm)

of the pressure taps, and fluid. The use of the R-H/G equation is especially useful to provide an approximation of C_d in situations where no facilities and/or reference instruments are available for calibrating a given orifice-plate model. Because C_d practically does not vary as a function of R_{e_D} no difficulty is encountered in defining the value of the discharge coefficient. In addition, the insecurity during the selection of the value of C_d would not impair the flow-rate predictions using the R-H/G equation (Method 1).

Obtaining C_d values using Eq. 5 (i.e., comparing the theoretical and reference flow rates) is typical in orifice-plate measurement routines. However, Figure 3A shows that the C_d values obtained by Eq. 5 exhibited wide variations depending on the flow rate, which made defining a single value for the entire measurement range difficult. This difficulty led to insecurity on how to define C_d using this method, and employing an average value could be inappropriate (Rhinehart et al., 2011). The angular coefficient of a zero-intercept straight line approximates C_d. Here, it was obtained by plotting the reference flow rates as a function of the theoretical flow rates (Method 2). The same principle is often used to approximate the minor loss coefficient (K_L) in fittings and accessories used in irrigation systems (Bombardelli et al., 2019; Sobenko et al., 2020; Vilaça et al., 2017). Normally, K_L exhibits a wide variation as a function of the Reynolds number, and a suitable approximation is obtained by assuming K_L to be equal to the angular coefficient of a zero-intercept straight line, which plots the local head losses as a function of the kinetic head.

As the third method for calculating the flow in orifice plates, empirical power-law functions were fitted to the experimentally obtained data. The following empirical equations were obtained: $Q = 16.337\ \Delta h^{0.611}$ for D = 100 mm and $Q = 37.903\ \Delta h^{0.606}$ for D = 150 mm. Figure 4 shows E_{MV} (Eq. 7), and it served the following two purposes: (a) to assist in defining the appropriate flow-measurement range in each orifice-plate model and (b) to support the choice of the flow-calculation method that provided a lower measurement error.

The two theoretical options (Methods 1 and 2) for both orifice plates demonstrated similar results in terms of E_{MV}, and the flow calculation using C_d obtained by Eq. 1 (Method 1) provided slightly lower errors in lower flow rates with a gradual increase in the error at the highest flow rates. By assigning an arbitrary E_{MV} tolerance criterion of 5%, it was verified that the recommended measurement ranges varied from 30 to 65 m³ h⁻¹ and from 70 to 130 m³ h⁻¹ for the 100 and 150 mm orifice plates, respectively. When the errors were analyzed using the empirical equation (Method 3), lower E_{MV} values and an increase in the measurement range that provided $E_{MV} < 5\%$ were observed. By using the empirical equation (Method 3), the recommended measurement ranges varied from 20 to 65 m³ h⁻¹ and from 40 to 130 m³ h⁻¹ for the 100 and 150 mm orifice plates, respectively.

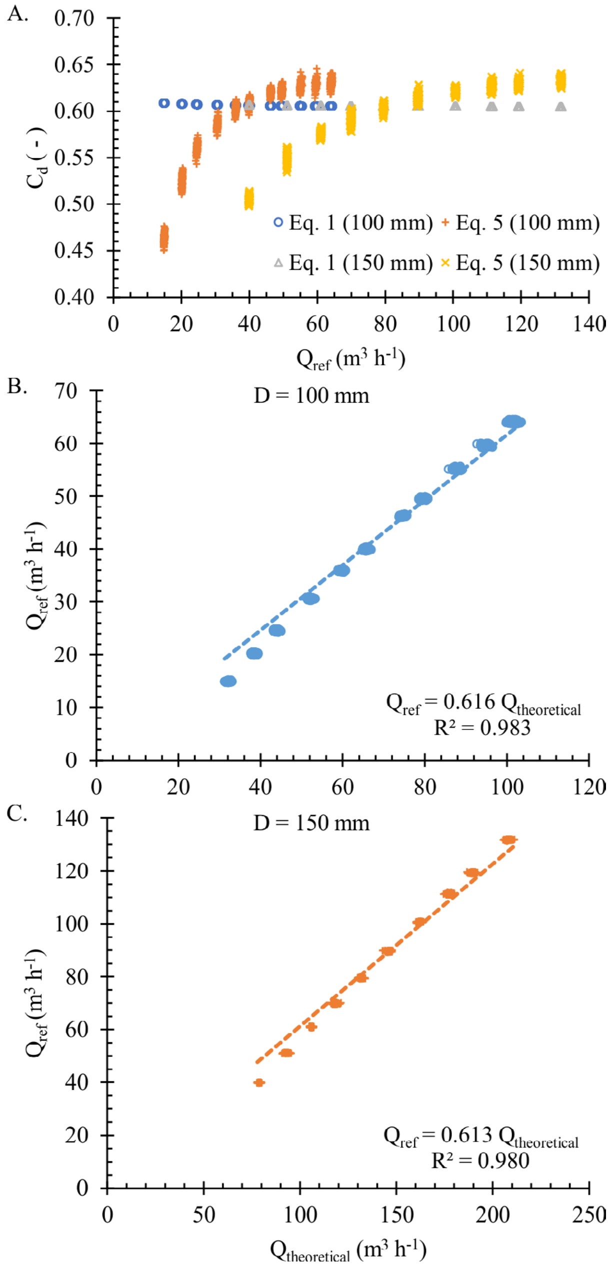

Figure 3. Variation in the discharge coefficient as a function of the flow rate for values obtained using Eqs. 1 and 5 (A); Approximation of the discharge coefficient using the angular coefficient of a zero-intercept straight line of the (B) 100 and (C) 150 mm models

From the recommended measurement ranges, the discharge coefficients were recalculated, and the coefficients of the empirical equations were readjusted for both orifice-plate models. The results are listed in Table 2.

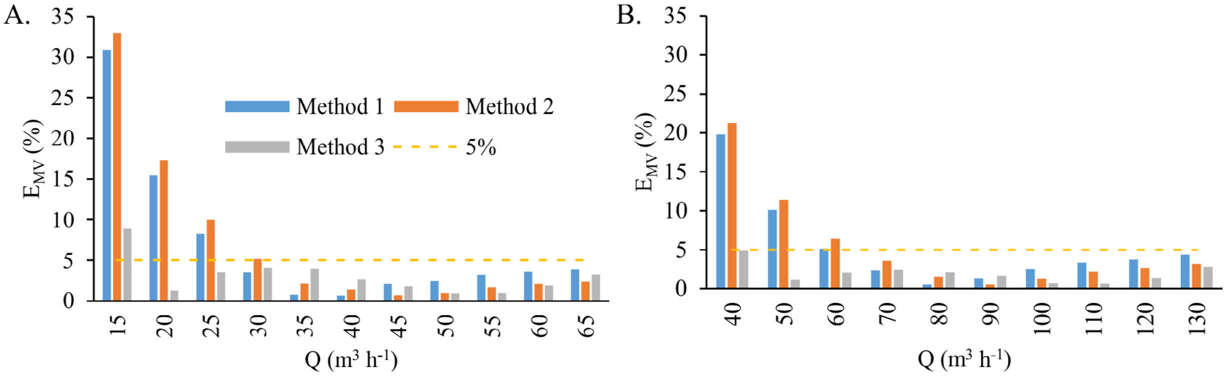

Figure 4. Errors relative to the measured flow values (E_{MV}) obtained from the three flow-determination methods: (A) 100 mm orifice plate; (B) 150 mm orifice plate

Table 2. Recommended measurement range, operational characteristics, and measurement-error estimates under two orifice plate and three method for estimation

Orifice plate	Method	Range/Rangeability	Δh_{min} (m)	C_d	Reduced equation	Maximum E_{MV}	Maximum E_{FS}	RMSE
						(%)		
100 mm	1	30-65 m^3 h^{-1} / 2.17:1	2.6	0.606	$Q = 19.591\Delta h^{0.5}$	4.0	3.9	1.711
	2	30-65 m^3 h^{-1} / 2.17:1	2.6	0.623	$Q = 20.146\Delta h^{0.5}$	6.3	3.0	1.016
	3	20-65 m^3 h^{-1} / 3.25:1	1.4	---	$Q = 17.206\Delta h^{0.582}$	4.2	1.7	0.812
150 mm	1	70-130 m^3 h^{-1} / 1.86:1	2.6	0.605	$Q = 44.044\Delta h^{0.5}$	4.4	4.5	3.434
	2	70-130 m^3 h^{-1} / 1.86:1	2.6	0.622	$Q = 45.255\Delta h^{0.5}$	5.1	2.8	2.099
	3	40-130 m^3 h^{-1} / 3.25:1	1.2	---	$Q = 37.903\Delta h^{0.606}$	4.9	2.8	1.858

Δh - Differential pressure head (m); C_d - Discharge coefficient; E_{MV} - Error relative to the measured value; E_{FS} - Error relative to the full-scale; RMSE - Root mean square error; Q - Flow rate (m^3 h^{-1})

The estimated C_d by the R-H/G equation (Method 1) led to errors that were lower than those estimated by Method 2. For both orifice-plate models, the empirical equation (Method 3) demonstrated the smallest measurement errors and increased measurement range, i.e., greater rangeability. Thus, when the use of a reference instrument for calibrating the orifice plate is possible using experimental methods, the power-law empirical equation (Method 3) is recommended because it has demonstrated better results.

According to the literature, orifice plates have E_{FS} values of up to 2% and rangeability of up to 4:1 (AWWA, 2006). For the evaluated measurement ranges, the measurement errors were found to be higher than those reported in the literature. Smaller errors could be obtained in a narrower measurement range; however, too much reduction in rangeability would limit the application of orifice plates. The errors in the flow determination could possibly remain within the suggested acceptance criteria for flow values higher than those evaluated, which would increase the rangeability of the orifice plates. However, this would be of little use because the flow velocities would exceed the recommended practical limits for the design and operation of pressurized conduits. In a study on the development and evaluation of an electronic drag force flow meter that operated in the range from 7 to 28 m^3 h^{-1}, Camargo et al. (2011) reported E_{FS} of up to 5.7% and rangeability of 4:1. As additional examples, Venturi flow meters have demonstrated E_{FS} between 0.5 and 1.5% and 3:1 rangeability. Doppler-effect ultrasonic flow meters have demonstrated E_{FS} between 2.0 and 5.0% and 10:1 rangeability (Camargo et al., 2011).

The RMSE values (Table 2) of the empirical model (Method 3) were lower than those obtained by the theoretical models (Methods 1 and 2), which contributed to the conclusion that the empirical model performs better. By comparing the RMSE values and maximum values of E_{FS} in the theoretical models, convergence in the criteria occurred, and the models that used C_d approximated by Method 2 demonstrated better performance than the models that used C_d obtained by the R-H/G equation (Method 1).

Analysis of the theoretical models (Methods 1 and 2) revealed that a contradiction existed when the RMSE and maximum values of E_{MV} were compared, which was expected because the RMSE was applied to the entire range of operation and smooth the maximum and minimum values. When the RMSE was adopted as the criterion for choosing the best model, the models that used C_d approximated using the angular coefficient of a zero-intercept straight line (Method 2) would be selected because they provided lower RMSE values. However, when E_{MV} was adopted as the selection criterion, the models that used C_d approximated by the R-H/G equation (Method 1) should be selected. When a measuring instrument is selected for a given application, care must be taken so that the maximum error in the measuring range satisfies the application requirements (Beckert & Paim, 2017; Büker et al., 2013). Thus, the selection of models that adopt E_{MV} as a performance indicator appears to be the most appropriate. RMSE measures the quality of fit of a model using the sum of the square of errors, but the point of minimum value for the sum of the square of errors does not necessary lead to the condition that provides the lowest values of E_{MV}.

Figure 5 shows the values of E_{FS} and E_{MV} in the measurement ranges listed in Table 2. Analysis of the results shown in Figures 5C and D revealed that the conditions that minimized the sum of the square of errors over the entire measurement range (i.e., Method 2) could result in E_{MV} values that are higher than the approximation of C_d using Method

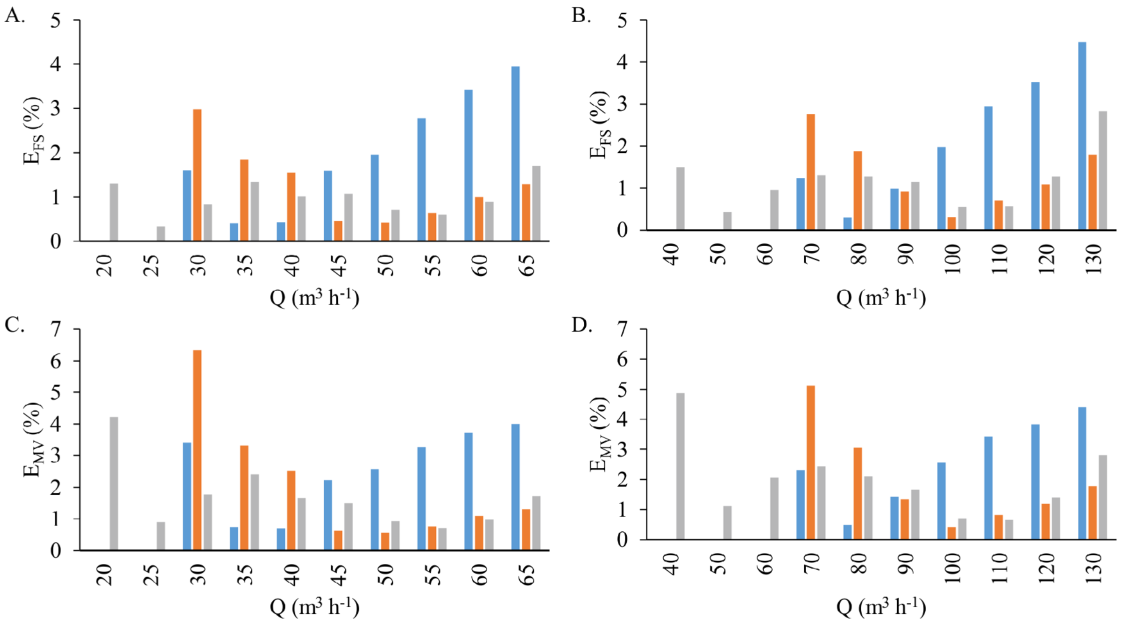

Figure 5. Errors relative to the full scale (E_{FS}) and measured value (E_{MV}) of the flow (Q) in the measurement ranges listed in Table 2: (A) and (C) 100-mm orifice plate; (B) and (D) 150-mm orifice plate

1. C_d approximated by Method 2 demonstrated $E_{VM} > 5\%$ in both orifice plates, although the RMSE values were lower.

According to the theoretical equations (Methods 1 and 2), satisfactory measurement errors were observed in the range of differential-pressure head values between 2.6 and 10 m, which provided flow velocities in the pipeline between 1.0 and 2.3 m s^{-1}. The use of empirical equation (Method 3) could possibly obtain acceptable measurement errors under differential-pressure heads of more than 1.2 m and flow velocities in the pipeline of more than 0.6 m s^{-1}. Although both orifice plates may contain measurement errors appropriate for $\Delta h > 10$ m, in practical applications, the use of flow velocities of up to 2 m s^{-1} is recommended to reduce the risk of damage associated with hydraulic transients and economic aspects related to the head loss and energy consumption. Knowledge of the minimum differential pressure that provides an acceptable flow-measurement error is of practical interest because it allows quick characterization of whether a given orifice plate may or may not provide accurate indications in each application.

Finally, the repeatability standard uncertainty of the flow rate was quantified by evaluating the reference flow rates and the flow rates obtained by the orifice plates (Figure 6). The repeatability standard uncertainty was a type-A uncertainty (Koech et al., 2015; Saretta et al., 2018) and was estimated using the standard deviation of the sample mean (Eq. 8). Figure 6 shows the superior quality of the reference instrument (i.e., electromagnetic flow meter) over the entire studied flow range, which maintained a repeatability standard uncertainty (S_x) between 0.010 and 0.021 m^3 h^{-1}. Considering the results of the three evaluated methods, the 100-mm orifice plate exhibited S_x values between 0.023 and 0.048 m^3 h^{-1}, whereas the 150-mm plate exhibited values between 0.032 and 0.090 m^3 h^{-1}. For both plates, by considering the maximum values of S_x (0.048 and 0.090 m^3 h^{-1}), a repeatability ratio of 0.07% relative to the full scale was obtained, which demonstrated adequate repeatability of the indications provided by the plate orifices.

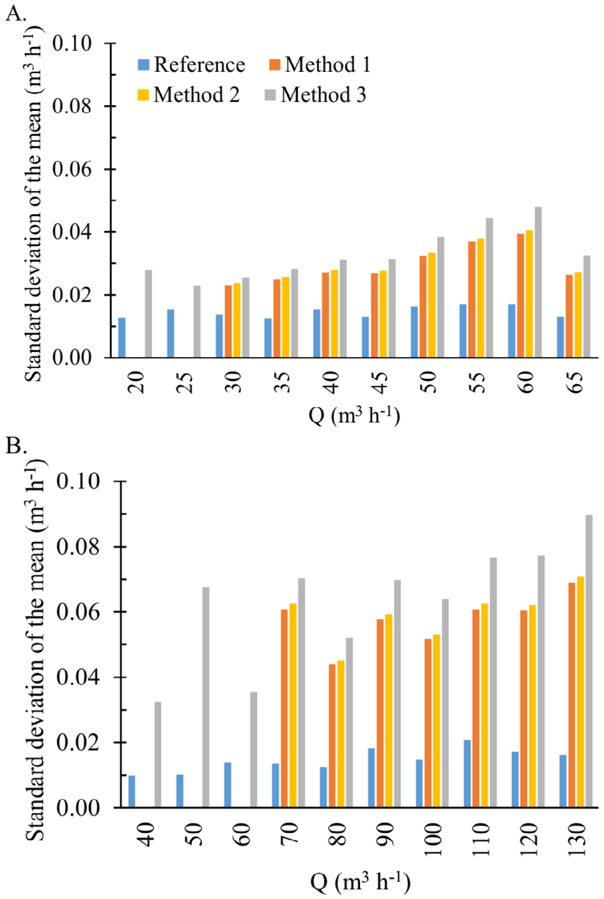

Figure 6. Repeatability standard uncertainty of the flow obtained by the reference instrument and orifice plates: (A) 100-mm orifice plate; (B) 150-mm orifice plate

Conclusions

1. The use of empirical equation (Method 3) demonstrated the smallest measurement errors and highest rangeability of the evaluated orifice plates.

2. Although the approximation of the discharge coefficient using the angular coefficient of a zero-intercept straight

line (Method 2) provided lower RMSE, it exhibited a larger maximum error relative to the measured flow values than the predictions that used the R-H/G equation (Method 1).

3. Both orifice-plate models did not demonstrate satisfactory measurement quality in low flow velocities. Flow velocities of more than 0.6 m s^{-1} are recommended to obtain measurement errors of up to 5% relative to the measured flow values.

4. For the 100-mm orifice plate, the recommended measurement range to obtain errors of less than 5% was from 30 to 65 m^3 h^{-1} using the theoretical equation (Method 1) and from 20 to 65 m^3 h^{-1} using the empirical equation (Method 3).

5. For the 150-mm orifice plate, the recommended measurement range to obtain errors of less than 5% was from 70 to 130 m^3 h^{-1} using the theoretical equation (Method 1) and from 40 to 130 m^3 h^{-1} using the empirical equation (Method 3).

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