Theoretical and Practical Integrated: Engaging Engineering Students in Fluid Mechanics Class

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Abstract

To accurately determine the flow coefficient in a didactic laboratory is a difficult task. This quantity is strongly affected by the dimensions of the devices and the results can depart from the standard values expected for the meter concerned. In order to optimize the data acquisition, increase the student's involvement in experiments and get results in agreement with the engineer professional life, the Physics Education Research Group (GruPEFE) has a research field dedicated to develop cheaper and faster technologies for practical class optimization. In the present work, results concerning flow coefficient and the calibration curves for a Venturi tube and an orifice plate are presented. The quoted results were obtained by means of measurements performed with a digital manometer, specially developed for this purpose. A good agreement between the standard values and the experimental flow coefficients was found for both meters. Furthermore, some important issues that could be addressed during this practical class are also discussed.

Keywords

Engineering Education, Venturi Tube, Standard Concentric Orifice Plate, Flow Coefficient, Calibration Curve

1. Introduction

Students are able to integrate theories with practical reality manipulating equipment and observing the experiment (Buch and Wolff 2000; Phelps et al. 2008). Practical classes help students to understand better the theory and achieve good learning outcomes and became engaged in their classes. According to Jong *et al.* (2013) by using physical equipment, students are able to develop practical laboratory skills, including troubleshooting of machinery, and they can experience the challenges many scientists face when planning experiments that require careful setup of equipment and observations over long time spans. A related affordance of physical laboratories is that students can take advantage of tactile information that, according to theories of embodied cognition, fosters development of conceptual knowledge. In physical investigations students learn about the complexities of science by dealing with unanticipated events, such as measurement errors (Toth et al 2009).

In this context, the Physics Education Research Group (GruPEFE) was created at engineering undergraduate course at Universidade Paulista (UNIP), located in Brazil, which teaches engineering since 1977. In order to get results in agreement with professional engineer life, the group has a research field dedicated to develop cheaper and faster technologies for practical class optimization. Considering the current objectives of engineering teaching, the

GruPEFE is developing didactic materials (Ferreira and Cavalheri (2014) and Santos and Ferreira (2015)) and technologies at fluid mechanics laboratories, which are used by approximately ten thousand students in several engineering fields (Civil, Mechanical, Automation, Production, Aeronautical and Petroleum), per semester.

Flow rate meters such as Venturi Tube and standard concentric orifice plate are mainly used at higher Reynolds Numbers, because they are relatively inexpensive and produce reliable results (Hollingshead et al 2011). These meters can be used in Brazilian engineering courses that seek to provide quality education with Affordable Cost. It is not easy to obtain accurate results in practical classes. Thus, the GruPEFE has performed measurements with a Venturi tube system and a standard concentric orifice plate, using cold water and obtained the characteristic curve and calibration curve of these instruments to Reynolds numbers larger than 40000. According to Miller (1996), small Reynolds numbers are defined as Re < 10,000, while large Reynolds numbers are Re > 1,000,000.

2. Materials and Methods

The setup developed for practical classes of fluid mechanics consists of a stainless steel pipeline (see Figure 1-a) with different branches, allowing multi parametrical measurements. Details on the experimental setup, concerning the didactic issues of each part of the system, are presented by Ferreira (2015). Only relevant information for what follows will be recalled. The fluid analyzed is water and this system allows studying different fluid meters, valve flow characteristics, singular and distributed head losses and pump association (series or parallel). Moreover, the system has rotameters (0.5 m³/h resolution) connected to the pumps and a graduated container which enable measuring the flow rate of water.
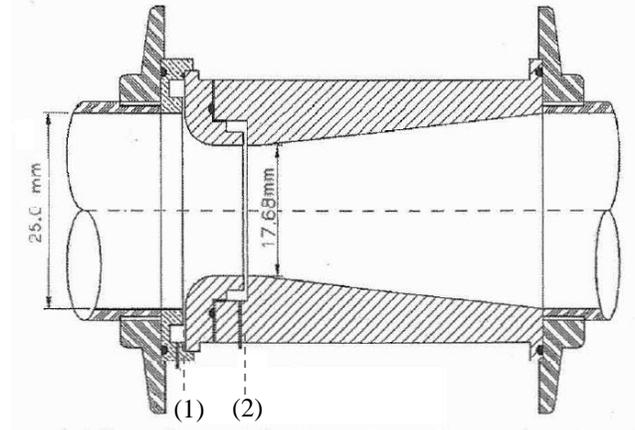

(a)   (b)

Figure 1: (a) System used for fluid mechanics practical classes and (b) digital manometer specially developed for fluid mechanics practical classes.

For flow rate measurements, there is a Venturi tube (Figure 2) and a standard concentric orifice plate (Figure 3) inserted in the pipeline. These devices were built based on the DIN (German Institute for Standardization) standards and their dimensions are depicted in Figures 2 and 3. Digital manometers were specially developed for pressure drop measurements across these meters (Figure 1-b).
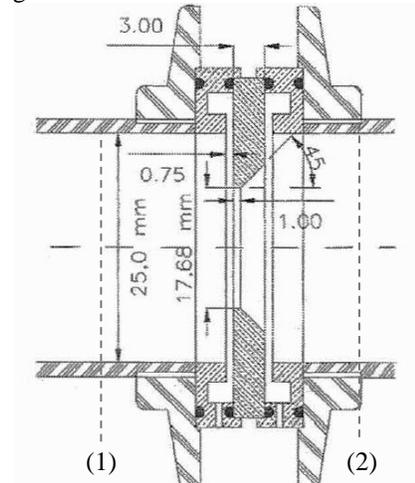
Figure 2: (a) Venturi tube (b) schematic drawing of the tube.

Figure 3: (a) Orifice plate (b) schematic drawing of the orifice plate.

According to the fluid mechanics theory (Roma (2006), Brunetti (2008) and White (2010)) the pressure drop across these obstruction devices can be determined considering the Bernoulli and continuity equations for incompressible steady frictionless flow at point (1) and (2) from Figure 2-b and Figure 3-b:

$$z_1 + \frac{p_1}{\gamma} + \frac{1}{2g} \cdot v_1^2 = z_2 + \frac{p_2}{\gamma} + \frac{1}{2g} \cdot v_2^2 \tag{1}$$

where:
v_1 and v_2 are the fluid flow velocity at point (1) and (2) on a streamline;
g is the value of acceleration due to gravity;
z_1 and z_2 are the elevation of the points above a reference plane;
p_1 and p_2 are the pressure at the chosen points, and
γ is the specific weight of the water at all points in the fluid.

Since in our system $z_1 = z_2$ Equation (1) can be rewritten as:

$$\frac{v_2^2 - v_1^2}{2g} = \frac{p_1 - p_2}{\gamma} \tag{2}$$

From the continuity equation the fluid velocity at point (1) is:

$$\frac{\pi}{4} D_1^2 \cdot v_1 = \frac{\pi}{4} D_2^2 \cdot v_2$$

$$v_1 = \left(\frac{D_2}{D_1}\right)^2 \cdot v_2 \tag{3}$$

where D_1 is the diameter at point (1) and D_2 is the diameter at point (2). It is worth noting that, for the orifice plate this latter diameter corresponds to the vena contracta diameter and it is lower than the obstruction diameter D. For the Venturi tube $D_2 = D$. The velocity v_2 can be computed by substituting Equation (3) into Equation (2). Thus, in terms of the flow rate Q_2 at this point:

$$Q_2 = \frac{\pi D_2^2}{4} \cdot v_2 = \frac{\pi D_2^2}{4} \cdot \sqrt{\frac{2.\Delta P}{\rho \cdot \left[1 - \left(\frac{D_2}{D_1}\right)^4\right]}} \tag{4}$$

ρ is the water density and the value considered in the following analyses was 1000 kg/m³. The flow rate calculated by the latter equation is referred as theoretical since the friction in a duct flow was neglected. The contraction at diameter D_2 can be written in terms of the obstruction diameter D considering the coefficient of contraction C_c:

$$C_c = \frac{D_2^2}{D^2} \tag{5}$$

Furthermore, the difference between the theoretical Q_2 and the real flow rate Q is accounted by means of the velocity coefficient C_v. Thus, the Equation (4) can be rewritten in term of the real flow rate Q and the obstruction diameter D as:

$$Q = \frac{C_v \cdot C_c \pi D^2}{4} \cdot \sqrt{\frac{2.\Delta P}{\rho \cdot \left[1 - C_c^2 \left(\frac{D}{D_1}\right)^4\right]}} \tag{6}$$

The flow coefficient C_Q is defined as:

$$C_Q = \frac{C_v \cdot C_c}{\sqrt{\left[1 - C_c^2 \left(\frac{D}{D_1}\right)^4\right]}} \tag{7}$$

Therefore, the real flow rate at the obstruction device can be expressed as:

$$Q = C_Q \frac{\pi D^2}{4} \cdot \sqrt{\frac{2.\Delta P}{\rho}} \tag{8}$$

Thus, the flow coefficient C_Q can be determined, experimentally, by measuring the pressure drop (ΔP) across the meter and the flow rate at the pipeline (Q). This coefficient is function of the ratio D/D_1 and of the approach Reynolds number (R_e), which can be computed by:

$$R_e = \frac{v_1 \cdot D_1}{\nu} \tag{9}$$

ν is the water cinematic viscosity and the value considered in the following analyses was 1 x 10⁻⁶ m²/s.

These devices obstruct the flow and cause a pressure drop which is a measure of flux. For Venturi tubes the net head losses are small and the flow coefficient is near unity. On the other hand, in orifice plates the head losses are larger, so flow coefficient is less than unity, and their costs are lower, compared to Venturi tubes. Therefore, in this practical class, students are encouraged to analyze the differences between these two flow rate meters, not only by means of their results, but also considering their construction issues and initial costs. Moreover, students have to realize the connection between the mathematical descriptions, concerning the Bernoulli's obstruction theory, and the physics observed at the laboratory, analyzing the uncertainties that could influence the measurements.

To accurately determine the flow coefficient in a didactic laboratory is a difficult task. This quantity is strongly affected by the dimensions of the devices and, considering few data sets, the results can depart from the standard values, expected for the meter concerned. In order to optimize the data acquisition and increase the student's involvement in the experiment, u-tube manometers filled with mercury were replaced by digital manometers, specially developed at UNIP. In the present work, results concerning the flow coefficient and the calibration curves for a Venturi tube and an orifice plate are presented.

3. Results and Discussion

By measuring the pressure drop with the developed digital manometer at points (1) and (2) (see Figure 2 and 3), the flow coefficient C_Q can be computed by means of Equation (8). The results for the Venturi tube and the orifice place are shown in Figures 4 and 5, respectively. The error bars represented, consist with instrumental uncertainties and correspond to $\pm$ 10% of C_Q values. The agreement among the C_Q values in three independent data sets, named Data_1, 2 and 3 in Figure 4 and 5, evidenced the repeatability of the results.
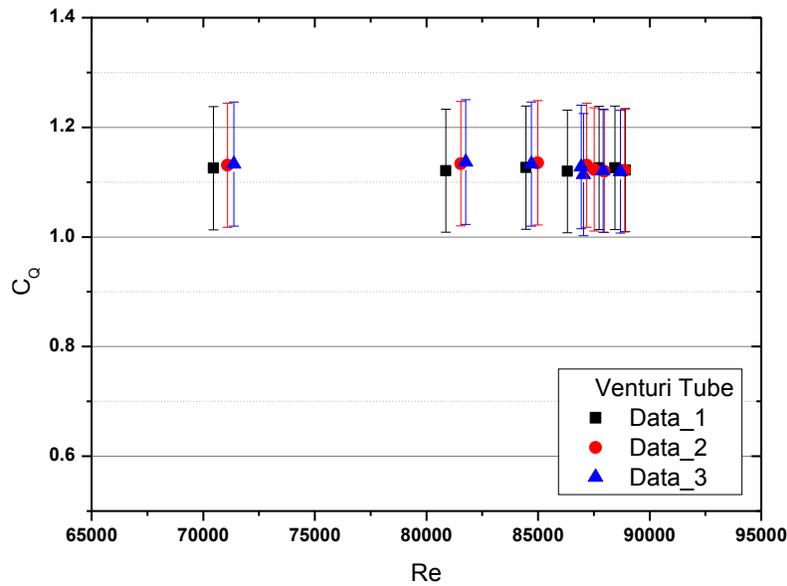

Figure 4: Venturi tube flow coefficients performance for water in a fluid mechanical practical class using a digital manometer.
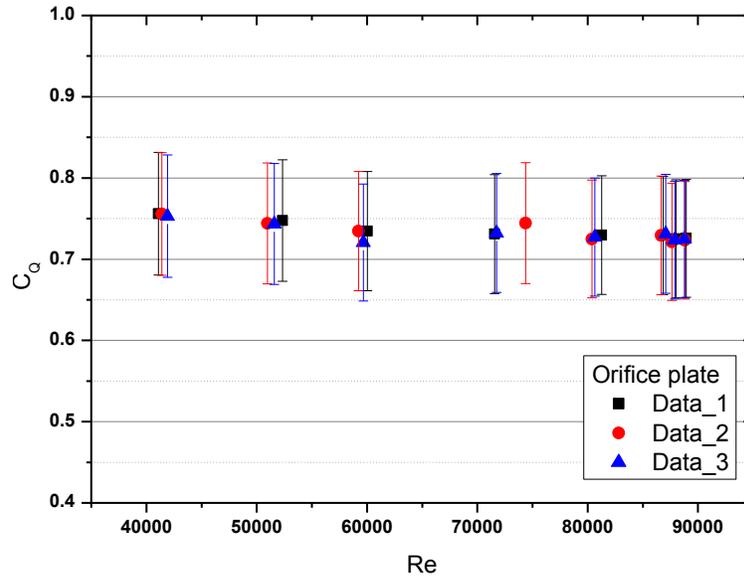
Figure 5: Orifice plate flow coefficients performance for water in a fluid mechanical practical class using a digital manometer.

During this class, it should be emphasized that over the range analyzed the flow coefficient is approximately constant for both meters. Furthermore, for Venturi tube head losses are small, which results in higher C_Q and makes this meter suitable where only small pressure heads are available. While for orifice plate, the head losses and the pressure drop across the meter are larger and its relative cost is lower than for Venturi tube. Since these meters used at UNIP were built based on the DIN standards, in Table 1 the average values of C_Q, for each data set, with the corresponding percent errors from the standard values are presented. Considering the area ratio of each device, the standard value for flow coefficient in Venturi tube is 1.10 (DIN EN ISO 5167-4: 2003) and in orifice plate is 0.71 (DIN EN ISO 5167-2: 2003). From Table 1, it can be seen that the agreement of the results obtained in a didactic laboratory is very good, with percent errors less than 5%.

Table 1: Percent errors from the standard DIN values for flow coefficient in the Venturi tube and the orifice plate used at fluid mechanics laboratory.

Data Set	Venturi Tube	Orifice Plate
1	2%	4%
2	3%	4%
3	3%	3%

The calibration curves, for each data set, for the Venturi tube and the orifice place are shown in Figure 6 and 7, respectively. It was considered only the differential pressure uncertainties. Since the real flow rate is proportional to the square root of the differential pressure, a data fit was performed for each case and the results are presented in Table 2.Considering the curve fitting is possible to use these meters as reliable flow measuring devices. The results obtained for each data set agreed within the experimental uncertainties.
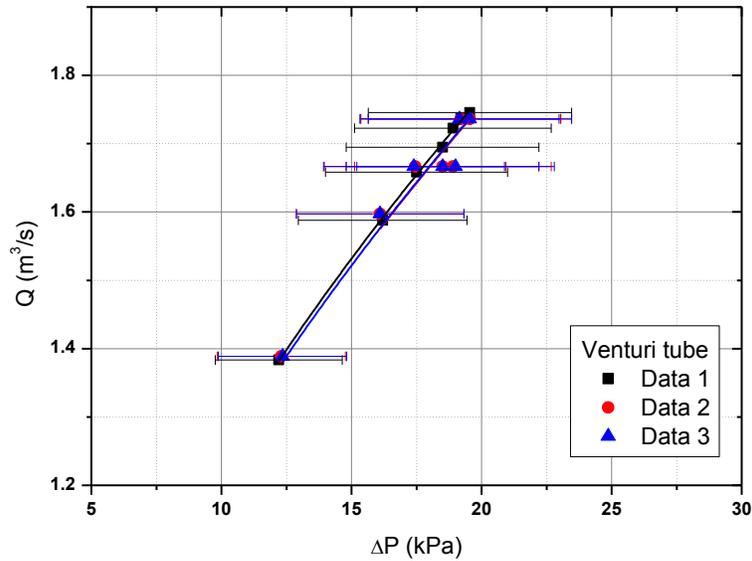
Figure 6: Real flow rate as function of pressure drop across the Venturi meter for three data sets.
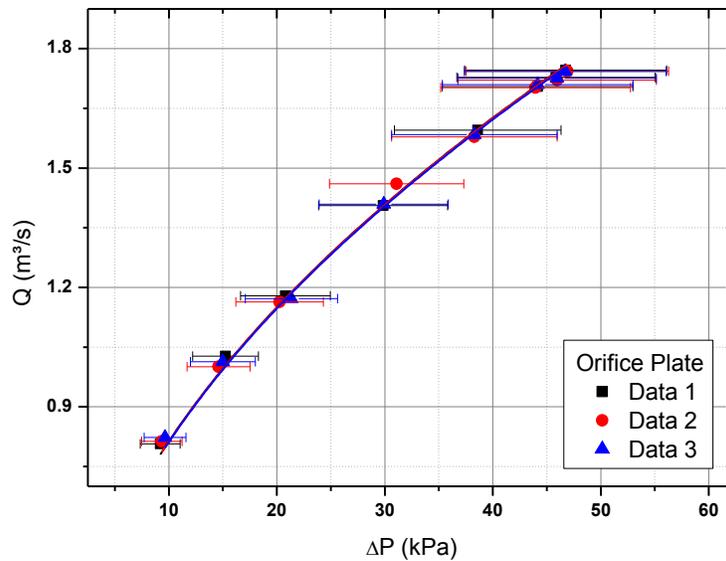

Figure 7: Real flow rate as function of pressure drop across the orifice meter for three data sets.

Table 2: Results concerning the calibration curve fittings for the Venturi tube and the orifice plate.

Data Set	Venturi Tube	Orifice Plate
1	$Q = 1.2506\ (12) \times 10^{-5}.\ \Delta P^{1/2}$	$Q = 8.131\ (3).10^{-6}\ \Delta P^{1/2}$
2	$Q = 1.242\ (8) \times 10^{-5}.\ \Delta P^{1/2}$	$Q = 8.126\ (4).10^{-6}\ \Delta P^{1/2}$
3	$Q = 1.242\ (8) \times 10^{-5}.\ \Delta P^{1/2}$	$Q = 8.110\ (3).10^{-6}\ \Delta P^{1/2}$

Conclusions

The flow rate measurements in a fluid mechanics practical class are influenced by many uncertainties. In addition to that, considering Bernoulli-type devices as Venturi tube and orifice plate, students have to realize of the connection between the mathematical descriptions, concerning the Bernoulli's obstruction theory, and the physics observed at the laboratory, analyzing the uncertainties that could influence the measurements. For engineering undergraduate courses these practical classes help students to understand better the theory and achieve good learning outcomes. To

optimize the data acquisition and help students to become more engaged to the data analysis, digital manometers were specially developed for fluid mechanics laboratories. In the present work, results concerning flow coefficient and the calibration curves for a Venturi tube and an orifice plate are presented and a good agreement between the standard values and the experimental flow coefficients was found for both meters. It is worth noting that, 5% of percent errors is excellent, considering that these values were obtained in a didactic fluid mechanics class and that for standardization processes error around 2% are admissible.

Acknowledgements

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Biography

Iara Batista de Lima is currently professor of Engineering Course (Fluid Mechanics and Physics disciplines) and member of GruPEFE at Universidade Paulista - UNIP. Ms. Lima holds a Bachelor degree in Physics (2008) from Pontifícia Universidade Católica de São Paulo – PUC, a Master of Science degree (2010) and a PhD degree in Science (2014) – nuclear technology – applications - from Universidade de São Paulo (USP), which is a Nuclear Technology Program of the Instituto de Pesquisas Energéticas e Nucleares (IPEN). Her research interests include experimental methods and instrumentation for elementary particles and nuclear physics and practical activities applied to Engineering Course.

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