The Training Methods of Measuring the Velocity and Flow of Gases Using Interactive Systems

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Abstract

Measuring the velocity and flow of fluids, both liquids and gases, has been a daily issue since the beginning of human civilization. Water clock was, for instance a tool used in ancient land of Persia that worked based on measuring the volume of water. In addition, industrial development requires the use of new technologies that are consistent with the methods of measurement of fluid flow and velocity, and therefore various flow meters have been developed since the eighteenth century (e.g. gas flow measuring tools in tubes, and velocity measurement in airplanes and other flying devices). In the present work, an interactive device has been made and presented to teach instruments and methods of measuring the velocity and flow of gases. This device consists of 4 sections; gas meter, anemometer, orifice plate, and Pitot tube. The mentioned project will be used as an educational device at the Science and Technology Museum. One of the main goals of the Science and Technology Museums is the growth and upbringing of the citizens. This device represents technology education which is based on interaction with the visitors of the Science and Technology Museum.

Key words: Measurement, Velocity, Flow, Gas meter, Anemometer, Orifice Plate, Pitot tube, Science and Technology Museum

Nomenclature

English		Greek	
A	cross-sectional area of flow (m^2)	β	diameter ratio
d	orifice plate diameter (m)	ρ	density $(m^3.kg^{-1})$
D	cross-sectional diameter of flow (m)	subscript	
C_d	discharge coefficient	d	discharge
P	Pressure (Pa)	$stagnation$	stagnation
Q	volume flow rate $(m^3.s^{-1})$	$static$	static
V	velocity $(m.s^{-1})$	$1,2$	two points of flow

1. Introduction

Perhaps it is safe to say that the first water meter used 3000 years ago by the Egyptians was a crude form of weir. The knowledge of flow measurement of the Egyptians originated from the understanding of the relationship between time and flow. In fact, the Egyptians, as Chinese and Greeks, were very skilful astronomical observers, and the first devices they made to measure time were shadow-clocks or sundials [1]. From 1500 BC onwards, thanks to many distinguished men of science, the experimental science was established and the understanding of flow phenomena started to develop. Their contributions to flow measurement developments will now be briefly reviewed. Guglielmini was the inventor of the first device for measuring river flows. His current meter was very simple: it consisted of a ball (a float) which was suspended by a string from a quadrant gauge and submerged into the river. The current velocity deflected the ball and the string from their vertical position and the angular deflection was measured by a quadrant scale calibrated in velocity units [2].In 1732 Pitot invented a device which still carries his name, the Pitot tube. He applied this instrument to the measurement of water velocity and the velocity of ships. Pitot's device used "two parallel small-bore tubes mounted on a frame, one straight, and the other with a short right-angle bend at its extremity". Taps and a scale enabled the pressure-head difference to be stored within the device so that the velocity of the stream in which it had been placed could be gauged. Later, Henry D'Arcy (1803-1858), an English scientist, developed the Pitot device in 1848 in the form known today [2]. Venturi did his basic work on a flow meter (the Venturi tube) which was to represent a fundamental contribution to flow measurement, and developed the basis for much of the theory used in modern flow meter computations. In his pioneering work in flow measurement, Venturi postulated that fluids under pressure, passing through converging pipes, gain speed and lose head, the opposite of which happens in diverging pipes. The name of Venturi is to be linked with Clemens Herschel who developed the commercial Venturi tube, using Venturi's basic work, in 1887 [2]. At the beginning of the 20th century, the science of fluid mechanics was established and a variety of a flow meters were commercially available—orifice and Venturi meters, variable area meters, Pitot tubes, inferential meters, and positive displacement meters. Nowadays, there are many kinds of flow measurement principles which might be used for velocity profile measurements, such as ultrasonic flow measurement, magnetic flow metering, and so forth. [3].

Studies performed have shown that the activities other than formal education have positive effects on the improvement of experiences obtained in school [4]. Informal learning environments include many social fields that allow students to have individual relationships with real objects and thus provide them to gain permanent knowledge, values, and points of view, through a positive attitude [5]. Perhaps the most important one of these informal learning environments are science centers, since science centers are among few environments that represent science, technology, and education simultaneously. Science centers have a structure capable of contributing to science education and professional education by building bridges between both science-education and technology-education. Various galleries have been designed and made in science museums with different topics globally - for instance, the Museum of Science in the city of Nagoya has provided a gallery of periodic tables for visitors [6].

In the present work, the device for measuring the velocity and flow of gases is presented with the purpose of teaching and introducing methods and measurement instruments of velocity and flow of gas. This device consists of four sections; gas meter, anemometer, orifice plate, and Pitot tube (Each of these instruments are a method of measurement representative); which have been designed and built to be exhibited in the galleries of the Iranian Science and Technology Museum. In designing and building these devices, safety considerations, interactivity, and attractiveness have been considered.

2. Gases velocimetry and flow measurement Apparatus

The apparatus is shown in Figure 1.Various instruments and methods are also shown for measuring the gas velocity and flow rate. This apparatus is designed and built to be exhibited in the galleries of the Iranian Science and Technology Museum in order to help the scientific upbringing of the citizens. This apparatus includes the following items: a blower (air flow supplier), a gas meter, an anemometer, an orifice plate, and a Pitot tube. Each of these instruments are representative of one of the methods of measurement. The gas meter is a positive displacement flow measurement method representative, the anemometer is a friction velocimetry method representative, the orifice plate represents a method which creates an obstacle against the flow, and the last but not least, the Pitot tube is a pressure difference velocimetry method representative. These four velocity and flow measurement instruments are located in two separate pipelines. Meaning that in order to compare their performance, the gas meter and the anemometer are installed on one pipeline, and the orifice plate and Pitot tube installed on another.

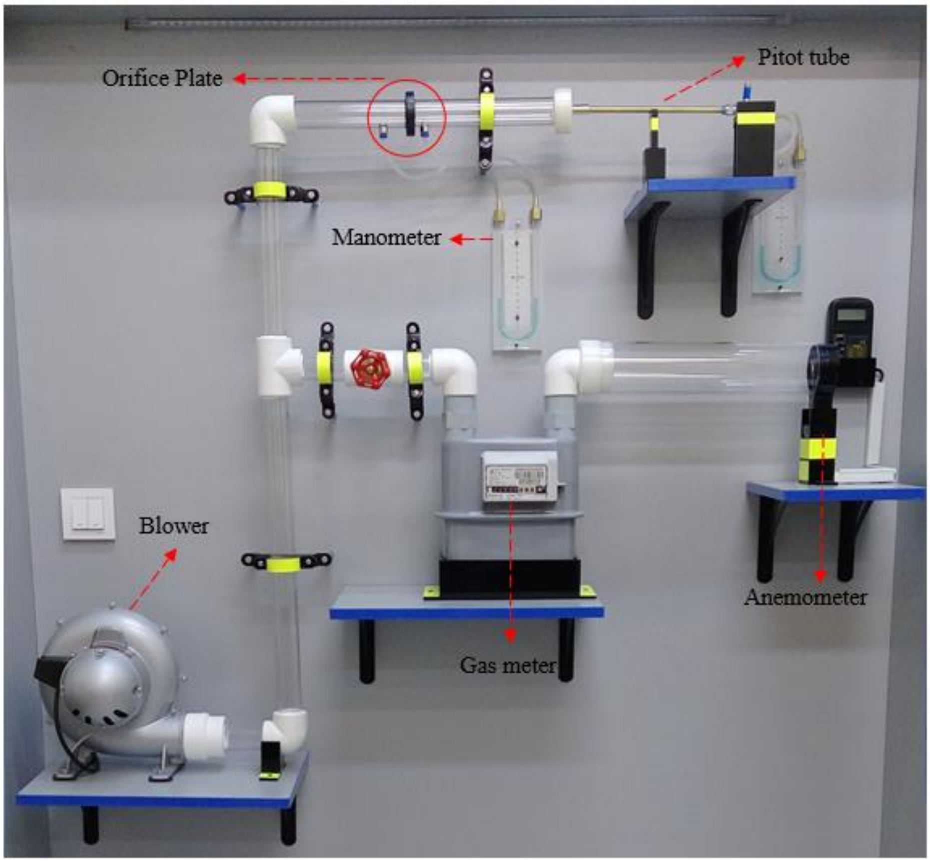

Figure 1: Gases velocity and flow measurement apparatus

2.1. Gas meter

The gas meter used on this apparatus is a diaphragm gas meter, which is a type of positive displacement flow meter. It works based on continuous filling and discharging of the measuring chamber. It operates by trapping a certain amount of incoming fluid, transferring it to the discharge side of the meter, and counting the number of such discharge–recharge cycles to determine the total amount of displaced fluid [7]. Diaphragm meters have remained fundamentally the same for over 100 years and is probably the most common kind of meter in existence. It is used in the United Kingdom for metering the supply of gas to domestic and commercial users [9]. In Figure 2(a), chamber A has emptied and chamber B has filled, and the valve is moving to allow A to fill and B to empty. At the same time, chamber C is filling from the inlet chamber due to the valve's position, and chamber D is emptied into the outlet manifold. In Figure 2(b), gas enters the inlet chamber above the valves and is routed into compartment A, while gas leaves compartment B. At the same time compartments C and D reach the change-over position so that C fills and D empties, and the valve changes over to allow C to empty and D to fill [10].

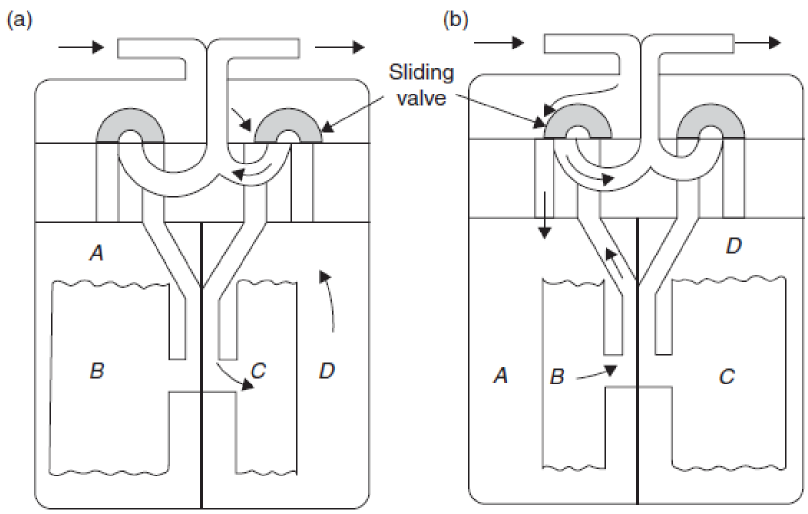

Figure 2: Diaphragm meter. (a) A, empty; B, full; C, filling; D, emptying; (b) A, filling; B, emptying; C, full; D, empty [10]

2.2. Anemometer

A popular type of velocity-measurement device is the turbine meter shown in Figure 3. As the fluid moves through the meter, it causes a rotation in the turbine wheel. In the turbine-wheel body, a permanent magnet is enclosed so that it rotates with the wheel. A reluctance pickup attached to the top of the meter detects a pulse for each revolution of the turbine wheel [11]. As shown in Figure 3, tube diameters and anemometer blades are the same size in order to let flow pass all over the blades.

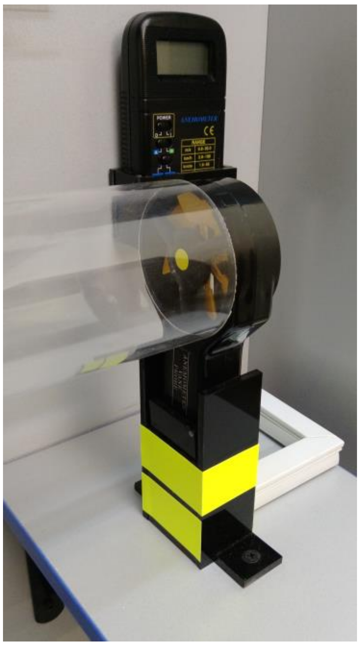

Figure 3: Anemometer for measuring air velocity

2.3. Pitot tube

Pitot probes (also called Pitot tubes) and Pitot-static probes, named after the French engineer Henri de Pitot (1695–1771), are widely used for flow speed measurement. A Pitot tube used for the measurement of both static and stagnation pressures is shown in Figure 4. The opening, at the front of the probe, senses the stagnation pressure, while the small holes around the outer periphery of the tube sense the static pressure. Pitot was the first person to measure velocity with the upstream pointed tube, while the French engineer Henry Darcy (1803–1858) developed most of the features of the instruments we use today, including the use of small openings and the placement of the static tube on the same assembly. Therefore, it is more appropriate to call the Pitot-static probes Pitot–Darcy probes. The Pitot-static probe measures local velocity by measuring the pressure difference using the Bernoulli equation [7]. As shown in Figure 4, Pitot tube consists of a slender double-tube aligned with the flow and connected to a differential pressure meter [7].

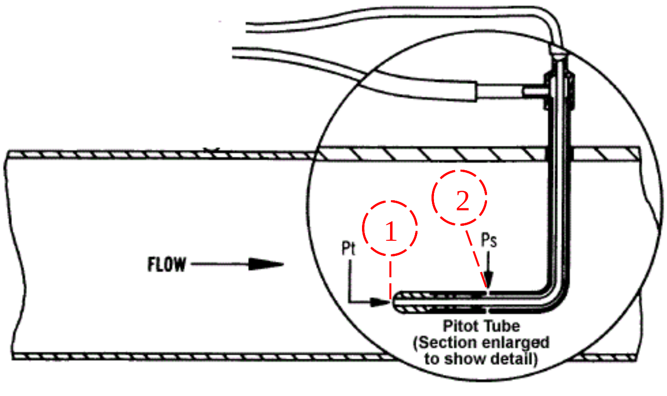

Figure 4: schematic Pitot tube [8]

According to Figure 4, the inner tube is fully open to flow at the nose and thus measures the stagnation pressure at that location (point 1). The outer tube is sealed at the nose, but has holes on the side of the outer wall (point 2) and thus measures the static pressure. For incompressible flow with sufficiently high velocities (so that the frictional effects between points 1 and 2 are negligible), the Bernoulli equation is written according to equation 1 [7].

$$p_1 + \frac{1}{2}\rho V_1^2 = p_2 + \frac{1}{2}\rho V_2^2 \tag{1}$$

Here, p is pressure, ρ is density, and V is velocity. Noting that $z_1 \cong z_2$ since the static pressure holes of the Pitot-static probe are arranged circumferentially around the tube and $V_1 = 0$ due to stagnation conditions, the flow velocity $V = V_2$ is calculated according to equation 2 [7].

$$V = \left(\frac{2(p_{stagnation} - p_{static})}{\rho} \right)^{\frac{1}{2}} \tag{2}$$

The Pitot tube used to measure the air velocity (located in the top pipeline) is shown in Figure 5. The Pitot-static probe is a simple, inexpensive, and highly reliable device since it has no moving parts. It also causes very small pressure drops and usually does not disturb the flow appreciably. However, it is important that it be properly aligned with the flow to avoid significant errors that may be caused by misalignment. It is used to measure velocity in both liquids and gases. Noting that gases have low densities, the flow velocity should be sufficiently high when the Pitot-static probe is used for gas flow, such that a measurable dynamic pressure develops [7].

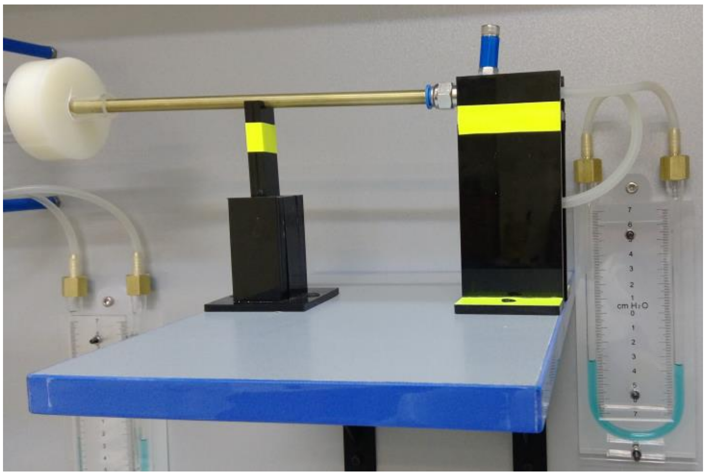

Figure 5: Pitot tube is used in apparatus

2.4. Orifice plate

A simple method for measuring flow rate of fluids is using orifice plate as shown in Figure 6 (it occupies minimal space as it consists of a plate with a hole in the middle). Some orifice meters are sharp-edged, while others are beveled or rounded. The sudden change in the flow area in orifice meters causes considerable swirl and thus significant head loss or permanent pressure loss. In this method, flow rate through a pipe can be determined by constricting the flow and measuring the decrease in pressure due to the increase in velocity at the constriction site as shown in Figure 6. Noting that the pressure drop between two points along the flow can be measured easily by a differential pressure transducer or manometer, it appears that a simple flow rate measurement device can be built by obstructing the flow. Flow meters based on this principle are called obstruction flow meters and are widely used to measure flow rates of gases and liquids [7].

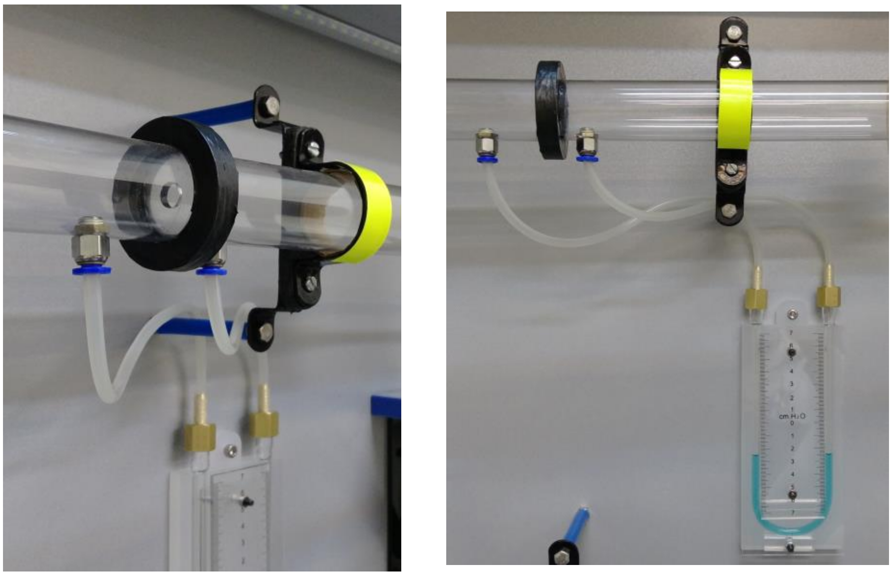

Figure 6: Orifice plate for measuring static pressure

Considering incompressible steady flow of a fluid in a horizontal pipe of diameter D that is constricted to a flow area of diameter d, by combining the mass balance and the Bernoulli equations (between a location before the constriction (point 1) and the location where constriction occurs (point 2)), flow rate of fluid is calculated according to equation 3.

$$Q = A_2 V_2 = (\frac{\pi}{4} d^2)\left(\frac{2(p_1 - p_2)}{\rho(1-\beta^4)}\right)^{\frac{1}{2}} \tag{3}$$

In equation 3, β is the ratio of constriction site diameter to pipe diameter, Q is volumetric flow rate, and A is area of flow cross section. The Flow rate of the fluid is obtained by assuming no loss. Thus, it is the maximum velocity that can occur at the constriction site. In reality, some pressure loss due to frictional effects is inevitable, and thus the actual velocity is less. Also, the fluid stream continues to contract past the obstruction, and the vena contracta area is less than the flow area of the obstruction. Both losses can be accounted by incorporating a correction factor called the discharge coefficient, C_d, which is determined experimentally (less than 1). Then the flow rate for obstruction flow meters is expressed as equation 4 [7].

$$Q = A_2 C_d \left(\frac{2(p_1 - p_2)}{\rho (1-\beta^4)} \right)^{\frac{1}{2}} \tag{4}$$

3. Results

The uncertainty analysis of the experimental data is performed to ensure the validity and accuracy of the measurements. Figure 7 shows the measured volume flow rates by gas meter and anemometer for different velocities. As shown in Figure 7, volumetric flow rates obtained using anemometer have greater values because the velocity value obtained from the anemometer is a mean velocity and is usually higher than the average velocity calculated using the velocity profile.

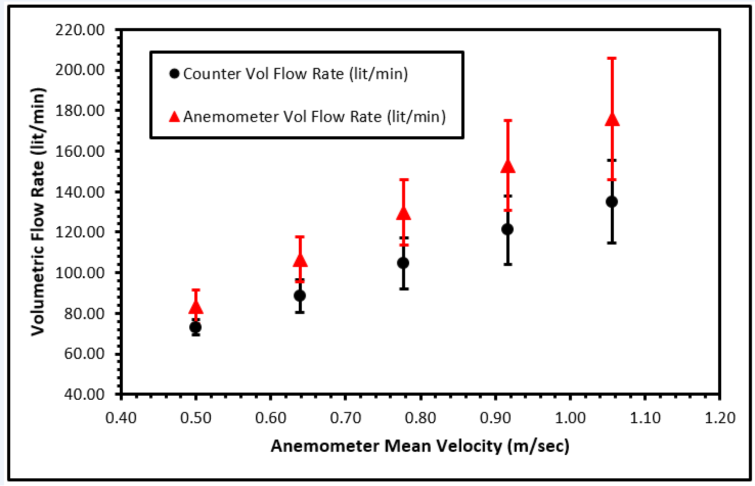

Figure 7: volume flow rate measured by gas meter and anemometer for different anemometer velocities

The percent of relative differences (α) for gas counter (gas meter) and anemometer volumetric flow rates are shown in Figure 8. This relative difference is calculated according to equation 5. According to Figure 8, this relative difference goes up as the velocity increases. The main reason of this is that the mean velocity is obtained base on the fully developed velocity profile (from inlet air to anemometer) assumption. Having noticed that the pipe length of the inlet airflow to the anemometer is constant, as the velocity increases, the inaccuracy of this assumption becomes more important. In general, it can be said that gas meter (counter) values for volumetric flow rates are more accurate since it measures volumetric flow rate directly.

$$\alpha = \frac{Q_{anemo} - Q_{contour}}{Q_{contour}} \times 100 \tag{5}$$

The pressure gradient for orifice plate and Pitot tube is measured and is shown in Figure 9. The pressure gradient is indicated for different flow rates.

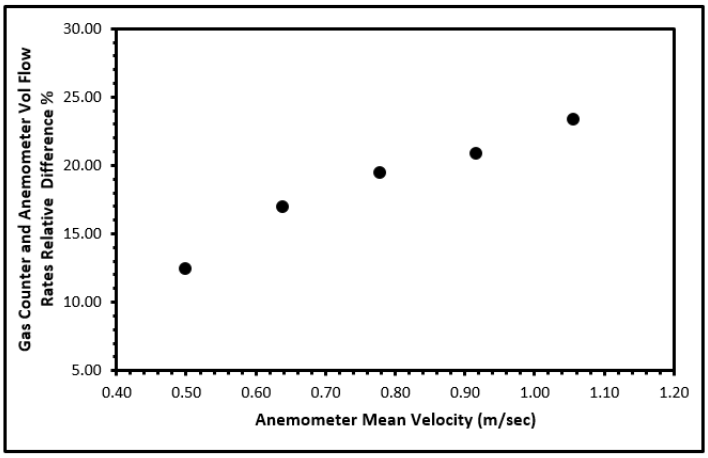

Figure 8: Volumetric flow rate relative error between gas meter and anemometer

As shown in Figure 9, both static and dynamic pressure difference (measured by the orifice and the Pitot tube respectively) increase as the volumetric flow rate increases. Also, the uncertainty of the pressure difference measured by the Pitot tube is greater than that of the orifice plate (maximum 2mm of H_2O) because of the high sensitivity of the Pitot tube.

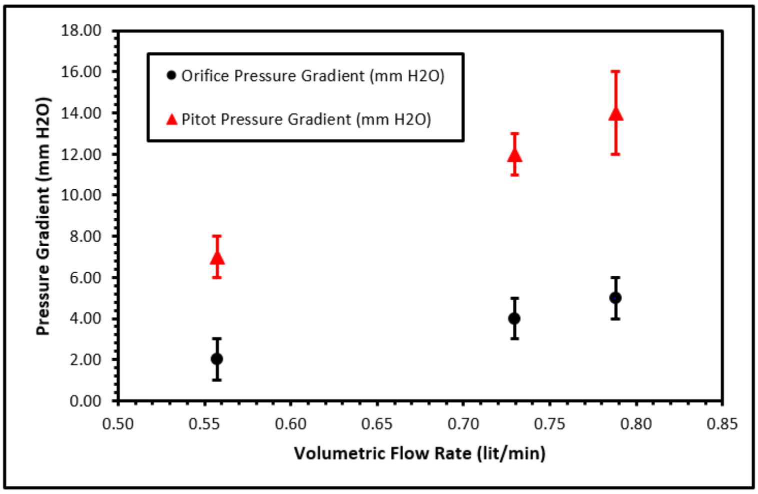

Figure 9: pressure gradient orifice plate and Pitot tube for different volume flow rate

Finally, the orifice plate coefficient, as shown in Table 1, is calculated for various volumetric flow rates. The mean orifice discharge coefficient is 0.79 ± 0.06

Table 1: The calculated orifice plate coefficient for various volumetric flow rates

Volumetric flow rate (lit/min)	Orifice discharge coefficient	uncertainty
0.56	0.84	0.09
0.73	0.78	0.07
0.79	0.76	0.03

4. Conclusions

In the present work, the device for measuring the velocity and flow rate of gases is presented with the goal of teaching and introducing the methods and the measurement instruments for velocity and flow of gases. This device consists of four parts; a gas meter, an anemometer, an orifice plate, and a Pitot tube; which is designed and built to be exhibited in the galleries of the Iranian Science and Technology Museum. Each of these instruments are representative of a method of measurement—the gas meter as a representative of a positive displacement flow measurement method, being the most accurate device and measuring the volumetric flow rate directly, the anemometer as a representative of a friction velocimetry method, the orifice plate as a representative of a method creating an obstacle in the way of the flow, and the Pitot tube as a representative pressure difference velocimetry method. This device was placed on the sight of visiting students and museum users and is capable of showing flow and velocity measurement concepts, along with many other concepts such as pressure drop, static, and dynamic and stagnation pressure differences. According to visitors' feedbacks, this experience increases the awareness and practical knowledge of measuring instruments.

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