Development of a low-cost prototype: Pitot Tube designed to measure the mass and the volumetric flow rates of fluids

Katiane Pereira da Silva, Enoque Coutinho dos Santos, Ramildo Felipe Silva Gonçalves, Antonio T. M. Beirão, Fábio Israel Martins Carvalho, Herson Oliveira da Rocha, Eldilene da Silva Barbosa, Vanessa Mayara Souza Pamplona, Alessandra Epifanio Rodrigues, Fabrício da Silva Lobato

Abstract

This study aims to develop a low-cost prototype to measure the mass and volumetric flow rate of fluids through the construction of a Pitot Tube. This meter must be able to measure the mass flow rate of air for different pressure values using only the water height level variation. For the development of the prototype, low-cost materials were used, in addition to some necessary tools. These experimental models are a didactic proposal for teaching and learning about the flow of fluids discipline, where it was verified that the experimental values found presented satisfactory results correlated with the theoretical concepts of an ideal fluid present in the literature. Thus, the Bernoulli and Torricelli equations were applied to assess the quality of the measurement method, to facilitate the learning of undergraduate students in the Production Engineering Course through conciliation between theory and practice in the Fluid Mechanics Laboratory discipline classes. Finally, the prototype experiment was exposed to other students at the institutional event called "I Integrar Produção" held by UFRA at the Parauapebas Campus.

Keywords: Fluid mechanics; low-cost experiment; prototype; Pitot tube.

1. Introduction

The didactic teaching of fluid physics is considered to be of extreme relevance in the legitimation of fluid flow theoretical concepts (ELGER, 2019). On the other hand, laboratory usage in the contextualization of the subject, through experimental practice, is an important teaching tool in regard to interpreting physical phenomena. Experimental activities must provide conditions for the students to be able to reflect and review their ideas regarding phenomena and covered concepts as a way to promote a self-learning process. (ARAÚJO, 2003; ARRUDA, 1994; VILLANI, 1989; ZYLBERSTAJN, 1983).

Krasilchk (2000), points some didactic modalities, among which are highlighted: demonstrations, expository classes, excursions, practical classes, projects, and debates, as ways to experience the scientific method. In this context, Lima et al. (1999) discusses the role of experimentation in the relationship between learner and knowledge objects, especially when it regards scientific knowledge.

The laboratory teaching environment may be considered a great teaching enhancer. To adhere to a practical teaching proposal it is not necessary to have a specific and structured laboratory available, but it is possible to perform simple experimental activities in any classroom and with low-cost materials, which can be made by the teacher and the students, allowing for quantitative and qualitative experiments to be developed and thus validating physical phenomena (WERLANG, 2008; VENTURA, 1992; MOREIRA, 1992).

The study of fluids flow is obligatory for the formation of future production engineering professionals to act in chemical industries, petrochemistry, and others acting fields. The measurement of rate or flow rate consists in determine the quantity of liquid, gases, and solids that passes through a given area per unit of time (FRANCO, 2008). Measuring fluids flow rate is always present in our day-to-day. For example, a residence hydrometer, the display of a fuel pump, etc. (FOX, 2010).

Throughout history, great names have contributed to the study of fluids flow (BARAÑANO, 2006). In 1502, Leonardo da Vinci observed that the quantity of water per unit of time that flowed through a river was the same in every segment, regardless of width, depth, inclination, and others. (BARAÑANO, 2006). However, the development of practical devices was only possible with the emergence of the industrial era and the work of researchers as Bernoulli, Henri Pitot, and others (CASSIOLATO, 2008).

In various experimental studies regarding fluids flows, it is necessary to determine the module and direction of the fluid velocity in some points of the studied region (FRANCO, 2008). Despite the impossibility of obtaining the velocity value in a point, it is possible to determine the average velocity in a small area or volume using adequate tools (SCHNEIDER, 2007).

The difference between total pressure and static pressure was a method introduced by Henri Pitot in 1732 and it is one of the most utilized presently (FOX, 2010). The Pitot Tube is a measurement instrument that measures fluids speed in physical models, for example, the velocity of airplanes, measuring the velocity of airflow (SCHNEIDER, 2007).

Therefore, and in the absence of a Transport Phenomena laboratory in the Parauapebas campus of the Federal Rural University of Amazon, it was felt necessary to create low-cost prototypes, through which the study could be performed in a more thorough and motivating fashion. The prototypes would be built by the third-period students of the Production Engineering graduation course.

Thus, it is described in this paper a research that had as objective the construction of an educational prototype, with low cost, for volumetric and mass flow rate measurements, through a Pitot Tube.

2. Experimental Methodology

Pitot Tube (PT) is a measurement tool utilized for determining moving fluids' velocity (CASSIOLATO, 2008). This instrument is installed in tubes positioned transversally to the direction of the fluid flow or in a rectangular section pipe. The measurement element, a rod-shaped detector, has one or various slits in the frontal and back parts connected to a differential pressure transmitter by two independent channels. Table 1 presents the description of the utilized material in the prototype elaboration.

Table 1 - Utilized materials

Materials for the Pitot tube prototype
PVC pipe 40 mm
Plastic clamps
Hollow metal rod 15 mm
MDF board 1,15 M x 0,44 M

Silicone Tube 15 mm
Makita Ub 1103 Blower and Vacuum

In the experimental activity proposed in this work, the air was considered the fluid that moves in the PT interior. Thus, it was necessary the usage of specific equipment for this purpose. In this case, it was chosen for the utilization of an air blower/vacuum of the brand Makita Ub1103. For the prototype assembling, the hollow metal rod, which was approximately 20 cm, was folded at 90º. For the Pitot Tube construction, it was used a PVC pipe with 58 cm in length.

In the PVC pipe it was made two holes of approximately 15 mm, 30 cm apart from each other. The silicone tube utilized for the U-shaped tube is about 53,5 cm long, where one of its extremities was fixed in one of the pipe holes. A piece of the L-shaped rod was inserted into the second hole, so that a part of the rod that was inside the pipe could be parallel to the pipe interior and the other rod extremity, in the external portion of the PVC pipe. After the cutting and the insertion of the silicone tube, it was obtained the connections presented in Figure 1.

Figure 1 - Pitot Tube experiment with the U-tube inserted and the Makita Ub1103 blower.

To finish the flow rate meter, a test was performed by putting a given amount of water inside the U-shaped tube. Once that part of the experiment was done, a structure for fixation was prepared. The fixation structure for the Pitot Tube and the U-tube was made from an MDF board with 1,5 cm of thickness, previously drilled accordingly to the prototype measures. Afterward, the air blower was fixed to the board by clamps, as presented in Figure 2.

In Figure 3 is presented the fixation of the Pitot Tube, already connected to the U-shaped tube, on the board. It is noteworthy that this process was achieved by using clamps.

Figure 2 - Blower fixation on the MDF board.

Figure 3 - Pitot Tube being fixed to the MDF board.

The blower serves as the air-flow source inside the PVC pipe. Water, on the other hand, serves to analyze height variation for different pressure levels present at the hose extremities. Therefore, finishing the assembling of the Pitot Tube educational prototype.

2.1 Theoretical Model

According to Schneider (2007), with the pressure values calculated utilizing Pitot Tube and an inclined tube manometer, it is possible to measure a fluid velocity in a point, and the flow rate can be determined from the measurement in different points.

Pitot Tube is an L-shaped hollow tube of a small diameter circular section, of which axis aligns to the flow-velocity direction on the measurement point (Figure 4). The Pitot Tube is connected to a pressure meter, for example, a column manometer, the displayed pressure in such meter matches the one on point 2 of Figure 4, which is called "stagnation pressure" or total pressure on point 1. Stagnation pressure of a fluid particle in a given point is the pressure that would reach the particle if it was slowed down to rest by an isentropic process with no energy loss (SCHNEIDER, 2007; ÇENGEL, 2015).

Figure 4 - Measurement of the velocity of fluid flow inside a tube. The dark part of the U-tube refers to the liquid fluid (water). Source: authors.

Mass flow rate is the quantity of mass flowing in a time interval. Analogously, it is defined the volumetric flow rate. Equations for, respectively, mass flow rate and volumetric flow rate are:

$$Q_m = \frac{\Delta m}{\Delta t} = \rho V_{el} A \quad (1)$$

$$Q = V_{el} A \quad (2)$$

where Q_m is the mass flow rate, Δm is the mass variation, Δt is the time variation, ρ is the density, V_{el} is the velocity, *A* is the transversal section area of the PVC pipe and Q is the volumetric flow rate. Fluid velocity is obtained by the energy and mass conservation equation.

On point 1 of Figure 4, the total pressure is shown, where the mass flow rate is given by:

$$Q_m = \rho_{air} V_{el\,1} A \quad (3)$$

On point 2 of Figure 4, stagnation pressure is given by the equation:

$$Q_m = \rho_{air} V_{el\,2} A_2 \quad (4)$$

Energy conservation law for permanent, incompressible ($\rho_1 = \rho_2 = \rho$), adiabatic, and frictionless flows is given by the Bernoulli equation:

$$P_1 + \frac{\rho_{air} V_1^2}{2} = P_2 + \frac{\rho_{air} V_2^2}{2} \quad (5)$$

Since air velocity on point 2 is null, it follows that:

$$P_1 + \frac{\rho_{air} V_1^2}{2} = P_2 \;\therefore\; V_1 = \sqrt{\frac{(P_2 - P_1).2}{\rho_{air}}} \quad (6)$$

Pressure on point A and B of the U-tube are respectively:

$$P_A = \rho_{air} g h_1 + P_2 \quad (7)$$

$$P_B = \rho_{air} g h_2 + \rho_{water} g \Delta h + P_1 \quad (8)$$

According to the Hydrostatic Principle (Stevin's Law), pressure on point A equals the pressure on point B, so:

$$P_A = P_B \;\therefore\; P_2 - P_1 = g \Delta h (\rho_{water} - \rho_{air}) \quad (9)$$

On the Pitot Tube case, where tube diameter on point 2 (Figure 4) is much smaller than the tube on point 1, the airflow velocity is given by equation (9) substituted into (6):

$$V_1 = \sqrt{\frac{g\Delta h(\rho_{water} - \rho_{air}).2}{\rho_{air}}} \tag{10}$$

Therefore, to calculate the mass and the volumetric flow rate it is only necessary to apply the obtained results by the equation (10) to equations (1) and (2), respectively.

3. Results and discussion

With the purpose of studying fluids flow, through the developed prototype, detailed tests were performed in the classroom, with a total of 50 students. Where students and teachers had the opportunity of analyzing, quantitatively and qualitatively, the relationship between fluid (air) velocity and pressure variation.

The differential pressure meter used was the U-tube, as it is simple and its functioning is easily understandable. The U-tube manometer works accordingly to the hydrostatic principle, that is, it measures pressure through a balance (or equilibrium) of forces on liquid columns confined in a U-shaped tube. The fluid utilized in the U-tube was water, which density and viscosity are known (values presented in Table 2). Differential pressure can be calculated then, as well as the moving gas fluid velocity begins to be determined. Bernoulli equation for incompressible fluids is utilized, as the fluid velocity to be measured is low. It is also essential to know the moving fluid density, in this case, the air, whose values are described in Table 2.

With the intention of achieving the experiment objective and to determine experimentally the mass and the volumetric flow rates, the following procedures were adopted: piezometric pressure was measured by the height differences of the Pitot Tube, obtained through collected data with a measuring tape. And, after that process, other data were collected, such as local temperature, the internal diameter of the tubing and the board hole, the liquid utilized in the manometer, and atmospheric pressure.

For comparison and results analysis purposes, first, the height (h) variation between the two water columns of the U-tube is measured. To only then calculate the flow velocity of the gas that passes through two area sections, given that the PVC pipe area section is approximately 0,00126 m^2.

In possession of those data, it is possible to determine both the mass and the volumetric entry flow rates on the PVC tube. According to the performed test, it is observed that the column height (h) variation of the U-tube between the water columns is 10,5 cm (See Figure 5).

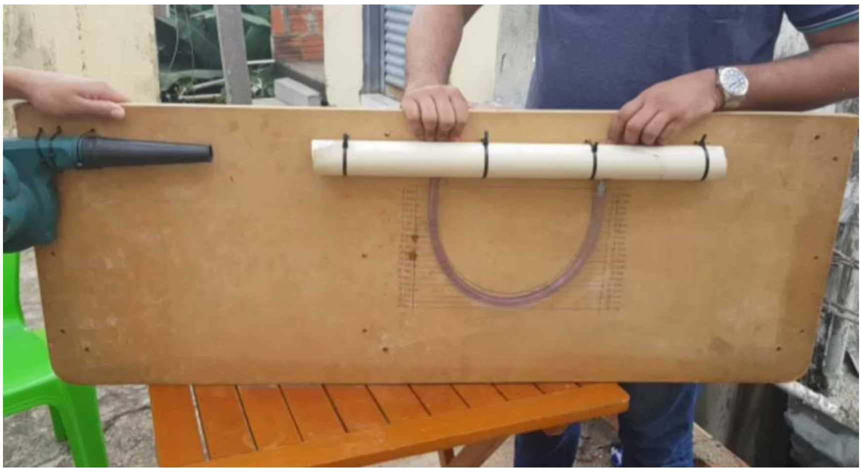

Figure 5 - Finalized Pitot Tube prototype with the blower and the liquid fluid (water) inside the U-tube. Besides the tube columns it can be noted the defined values on the MDF board and, to write these values down the measuring tape was used.

Before the blower was turned on, the liquid was at rest inside the U-tube, each column with an 11 cm height. After the device was activated, the air flux inside the U-tube increases, generating different pressures in each extremity of the fluid present in the hose. Therefore, the extremity to which a stagnation pressure was applied displays now 16 cm while the other displays 5,5 cm. Values of some relevant variables considered are described in Tables 2 and 3.

Table 2: Relevant variables considered at the moment before the activation of the blower.

Variables	Measures
Water columns length	11 cm
Height variation between columns	0 cm
Water density	1000 Kg/m^3
Air density	1,2 Kg/m^3
Air velocity	0 m/s
Mass flow rate	0 Kg/s
Volumetric flow rate	0 m^3/s

From the found data, calculations can be performed according to the equation (10) described in section 3, thus obtaining the following velocity value:

$$V_1 = \sqrt{\frac{g\Delta h(\rho_{water}-\rho_{air}).2}{\rho_{air}}} \quad (10)$$

$$V_1 = \sqrt{\frac{9{,}8 * 0{,}105 * (1000 - 1{,}2) * 2}{1{,}2}}$$

$$V_1 = 41{,}39\ m/s$$

Once the data was obtained, it is possible to find the respective values for the mass and the volumetric flow rates. According to equations 1 and 2, described in section 3, it follows that:

$$Q_m = \frac{\Delta m}{\Delta t} = \rho V_{el} A \qquad (1)$$

$$Q_m = 1{,}2 * 41{,}39 * 0{,}00126$$

$$Q_m = 0{,}0626\ Kg/s$$

To find volumetric flow rate, it is applied:

$$Q = V_{el} A \qquad (2)$$

$$Q = 41{,}39 * 0{,}00126$$

$$Q = 0{,}0521\ m^3/s$$

In table 3 some relevant variables considered are displayed. Regarding the values of the mass and the volumetric flow rates, it is necessary to include the precision uncertainty in the measurement due to the apparatus and all existing physical variables.

Therefore, any difference between the value calculated in the entry and the flow rate meter can be attributed to load losses during the flow. Tube positioning, and the consequent attack angle different from zero, also create a difference between the real stagnation pressure and the measured pressure.

Table 3: Relevant variables considered at the moment during the activation of the blower.

Variables	Measures
Water columns length	16 cm and 5,5 cm
Height variation between columns	10,5 cm
Water density	1000 Kg/m³
Air density	1,2 Kg/m³
Air velocity	41,39 m/s
Mass flow rate	0,0626 Kg/s
Volumetric flow rate	0,0521 m³/s

4. Conclusion

At the end of the study, a prototype of an airflow rate meter was built, capable of operating simply with the aid of a blower. It was developed by using low-cost materials and proved to be relevant for the learning of students during the discipline, given that the institution does not provide a structured laboratory for such experiments.

The experiment result proved itself relevant and satisfactory. As it was possible to determine the mass flow rate of air, with a value of approximately 0,0626 Kg/s, on the Pitot Tube, in addition to that, air velocity was determined, approximately 41,39 m/s, and the volumetric flow rate with a value of 0,0521 m^3/s.

Therefore, any difference between the value calculated in the entry and the flow rate meter can be attributed to load losses during the fluid flow. Furthermore, it was verified that the tube positioning also implies differences between real stagnation pressure and the measured pressure. Yet, the measurements were taken satisfactorily, obtaining measurements values close to the literature ones (DELMÉE, 1983) and, consequently, establishing the low-cost meter prototype as a significant and expressive experiment for experimental classes of the Fluids Mechanics discipline.

It is also expected that, with the creation of low-cost prototypes to aid the teaching-learning process, students show more motivation and it increases the reasoning ability and interaction on physics disciplines.

6. References

ELGER, Donald; LEBRET, Barbara, CROW, Clayton and ROBERSON, John. (2019). **Mecânica dos fluidos para engenharia**, 11. ed.: LTC Editora. Rio de Janeiro-RJ.

ARAÚJO, M.S.T. and ABIB, M.L.V.S. (2003). Atividades Experimentais no Ensino de Física: Diferentes Enfoques, Diferentes Finalidades. **Revista Brasileira de Ensino de Física**, v. 25, n. 2, pp. 176.

ARRUDA, S.M. and VILLANI, A. (1994). Mudança conceitual no ensino de Ciências. Caderno **Catarinense de Ensino de Física**, Florianópolis-SC, v. 11, n. 2, pp. 88-89.

VILLANI, A. (1989). Ideias espontâneas e ensino de Física. **Revista Brasileira de Ensino de Física**, v. 11, pp. 130-147.

ZYLBERSTAJN, A. (1983). Concepções espontâneas em Física: exemplos em dinâmica e implicações para o ensino. **Revista Brasileira de Ensino de Física**, v. 5, n. 2, pp. 3-16.

KRASILCHIK, M. (2000). Reformas e realidade: o caso do ensino de ciências. **São Paulo em Perspectiva**, São Paulo, v. 14, n. 1, pp. 85-93.

LIMA, Maria E.C.C.; AGUIAR JUNIOR, O. G. and BRAGA, S. A. M. (1999).**Aprender Ciências: um mundo de materiais**. 1. ed. Belo Horizonte: UFMG.

WERLANG, R. B.; SCHNEIDER, R. S. and SILVEIRA, F. L. (2008). An experience of teaching of physics of fluids with the use of new technologies in the context of a technical school. **Revista Brasileira de Ensino de Física**, v. 30, n. 1, pp. 1503.1-1503.9.

VENTURA, P.C.S. and NASCIMENTO, S. S. (1992). Laboratório Não estruturado: uma abordagem do ensino experimental. **Caderno Catarinense de Ensino de Física**, Florianópolis-SC, v. 9, n. 1, pp. 54-60.

MOREIRA, M.A. and AXT, R. (1992). **O papel da Experimentação no Ensino de Ciências, Tópicos em Ensino de Ciência**, São Paulo Distribuidora, São Paulo-SP.

FRANCO, B. (2008). **Mecânica dos Fluidos**. 2. ed. São Paulo: Pearson Prentice Hall.

FOX, R. W.; MC DONALD, A. T. and PRITCHAND, P.J. (2010). **Introdução à mecânica dos Fluidos**. 7. ed. Rio de Janeiro: LTC Editora.

BARAÑANO, A. G. (2010). **Utilização de observador de estado em substituição a medido de vazão**. Tese (Doutorado em Engenharia Química) – Programa de Pós-Graduação em Engenharia Química, UFSC, Florianópolis-SC.

CASSIOLATO, C. and ALVES, E. O. (2008). Medição de Vazão. **Controle e Instrumentação**. São Paulo-SP, v. 11, 138, pp. 70-78.

SCHNEIDER, P. S. (2007). Medição de Velocidade e Vazão de Fluidos, **Apostila da disciplina de Medições Térmicas**, Grupo de Estudos Térmicos e Energéticos, UFRGS, Porto Alegre.

ÇENGEL, Y. A. and CIMBALA, J. M. (2015). **Mecânica dos fluidos: Fundamentos e Aplicações**. 3. ed. Porto Alegre: AMGH Editora.

DELMÉE, G. J. (1983). **Manual de Medição de Vazão**, 3. ed. São Paulo: Editora Blücher.