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DESIGN AND MANUFACTURE OF THE SYSTEM MEASUREMENT OF THE AIR FLOW IN THE ALTERNATIVE PULMONARY MECHANICAL VENTILATOR

Felipe Pamplona Mariano
Andreia Aoyagui Nascimento
Anderson Gomes Girardi
João Paulo da Silva Fonseca
Sigeo Kitatani Júnior
Universidade Federal de Goiás (UFG), Escola de Engenharia Elétrica, Mecânica e de Computação (EMC), Laboratório de Engenharia Térmica e de Fuidos (LATEF). Av. Esperança, s/n, Campus Samambaia, Al. Ingá, Prédio B5, CEP: 74.690-900 – Goiânia – Goiás – Brasil. https://latef.emc.ufg.br/
fpmariano@ufg.br
aanascimento@ufg.br
andersongomes@ufg.br
jpsfonseca@ufg.br
sigeo@ufg.br

Abstract. The COVID-19 pandemic, caused by Sars-CoV-2, induces a Severe Acute Respiratory Syndrome (SARS), which can be treated, in part, with the use of Pulmonary Mechanical Ventilator (PMV). The increase in the number of cases induced a lack of PMV in Intensive Care Units. The problem was amplified because there was no availability to import these devices, by generating a global crisis. Therefore, an alternative PMV project was proposed, their key characteristics are the manufacture with materials and instrumentation equipment found in Brazil. The present paper shows the design and manufacture of the system measurement of the air flow in the alternative PMV. For the correct control of the air flow sent to the lungs, the presence of a flowmeter is mandatory, the most conventional used types in PMV are linear resistance pneumotachographs, variable orifice meters, hot wire anemometers and ultrasonic. However, all cited flowmeters have limitations for national manufacturing due to the special materials and high value for their acquisition. The flowmeter proposed for the alternative PMV is of the type orifice plate concentric quadrant edge, which has the advantage of keeping the discharge coefficient constant, even if the flow is laminar. The project of the flowmeter is presented to optimize the pressure difference in the flow, since, on the one hand, the pressure difference has a maximum limit imposed and, moreover, the pressure gauge needs a minimum level of pressure difference to record values with minor errors. Details of the orifice plate fabrication are also presented, highlighting the manufacture of the rounded edge. Lastly, the results of the process of obtaining the discharge coefficients are presented as a function of the Reynolds number to the three orifice plates, the concentric quadrant edge compared with the square edge and square edge recessed. After the installation of the new orifice plate, the alternative PMV worked properly, obtaining satisfactory results when compared with a gold standard PMV in animal clinical tests.

Keywords: biomedical equipment, medical control systems, flowmeter, orifice plate.

1. INTRODUCTION

The COVID-19 pandemic, caused by Sars-CoV-2, induces a Severe Acute Respiratory Syndrome (SARS), which can be treated, in part, with the use of Pulmonary Mechanical Ventilator (PMV). The increase in the number of cases induced a lack of PMV in Intensive Care Units (ICU). The problem was amplified because there was no availability to import these devices, by generating a global crisis.

The PMV are complex machines (Chatburn, 2003), which produce gas displacement to inside the lungs (Wald, 1968). A PMV can assume different models: volume-controlled ventilator (VCV), pressure-controlled ventilator (PCV), synchronized intermittent ventilators (SYNV), pressure support ventilators (PSV) and Continuous Pressure in the Airways (CPAP), (Abba *et at*., 2021, Kwon *et al.*, 2020, Hasan, 2010 and Chatburn and Mirelees-Cabodevila, 2013), but, independent of model, the PMV consisting of many specialized components, which is not produced in Brazil.

Due to the great difficulty in importing PMV, during the pandemic, researchers all the world was motivated to create a simpler, but technically suitable machine that could be produced on a large scale and in a short timeframe and with the mandatory functional characteristics required by technical standards (ABNT), by ANVISA and by the Ministry of Health (NBR ISO 10651-3, NBR ISO 10651-5, NBR IEC 60601-1).

Recent work, Acho *et al.* (2020) described the construction of a low-cost, open-source mechanical ventilator for patients with COVID-19, the method developed by the authors considers pressure measurements at the pulmonary inspiration and alerts clinicians in real-time whether the patient is under a healthy or unhealthy situation. The results show the potential benefits of the developed mechanical ventilator.

García-Castrom *et al.* (2021) proposed a test protocol for low-cost mechanical ventilators in swine models as part of the development of biomedical equipment that can support the health crisis caused by the pandemic. The protocol addresses aspects that include the pre-test phase, anesthetic and airway management, laboratory monitoring, recovery and animal monitoring. As a result, a validation protocol for a prototype mechanical ventilator in swine specimens is presented to the academic community as a reference for its application and revalidation by groups interested in the development of low-cost local technologies.

Another alternative PMV project, model is VCV, was proposed in Brazil (UFG, 2020 and Alcântara *et al.*, 2021), in which the respiratory rate is preset and defines when the trigger occurs. Cycling takes place from the reach of the preset volume and the pressure varies according to the ventilatory dynamics of each patient. Their key characteristics are the manufacture with materials and instrumentation equipment found in Brazil and the present paper, specifically, shows the design and manufacture of the system measurement of the air flow in the alternative PMV.

For the correct control of the air flow sent to the lungs, the presence of a flowmeter is mandatory, the most conventional used types in PMV are linear resistance pneumotachographs, variable orifice meters, hot wire anemometers and ultrasonic. However, all cited flowmeters have limitations for national manufacturing due to the special materials and high value for their acquisition. The flowmeter proposed in the present paper is the orifice plate with concentric quadrant edge (Ismail *et al.*, 1998), which has the advantage of keeping the discharge coefficient constant, even if the flow is laminar.

The project of the new flowmeter is presented to optimize the pressure difference in the flow, since, on the one hand, the pressure difference has a maximum limit imposed and, moreover, the pressure gauge needs a minimum level of pressure difference to record values with minor errors. Three different orifice plates are proposed and manufactured with materials and instrumentation devices found in Brazil. All then are calibrated and the experimental results for obtaining the discharge coefficient under different flow regimes (laminar, transition and turbulent) , show that the new orifice plate with concentric quadrant edge obtain the highest discharge coefficient and it's, practically, constant for a wide range of flows, since laminar to turbulent in comparison with others.

2. MATHEMATICAL FORMULATION

The Bernoulli obstruction theory (White, 2018) is used to obtain the flow rate cross the orifice plate, Figure 1.
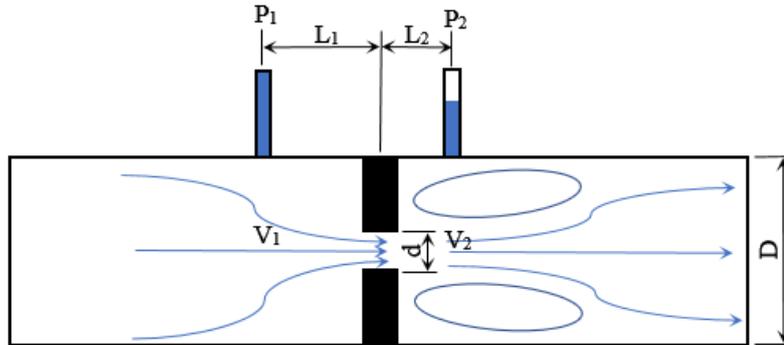

Figure 1. The sketch of pipe flow through the orifice plate in a duct.

At Figure 1 is shown the incompressible flow direction, left to right. The flow changes its velocity V_1 through the orifice plate to V_2, because the continuity equation. At the same time, the pressure is reduced from P_1 to P_2 and location of the pressures taps is given by $L_1=D$ and $L_2=D/2$, where L_1 is the distance between P_1 and the orifice plate and L_2 is the distance between P_2 and orifice plate. D and d are the duct diameter and orifice diameter, respectively.

In practice, due to the inertia flow, the flow cross-section area is smaller than the orifice plate area. The streamlines are restricted to the known area as *venna contracta*, which has the diameter $d_{vc}<d$. Whereas, considering the incompressible, steady state and inviscid flow, the continuity equation is given by:

$$V_1 \pi D^2/4 = V_2 \pi d_v{}^2/4 = Q, \qquad (1)$$

where Q is flow rate [m³/s], V_1 and V_2 are the velocities in [m/s].

Applying the Bernoulli equation between horizontal positions P_1 and P_2:

$$P_1 + \rho V_1^2/2 = P_2 + \rho V_2^2/2, \tag{2}$$

where P_1 and P_2 are the pressures in [Pa] shown in Figure 1 and ρ is the air density in [kg/(m^3)].

Substituting V_1 from Eq. 1 to Eq. 2 and rearranging:

$$V_2 = \sqrt{\frac{2(P_1 - P_2)}{\rho\left(1 - \frac{d_{vc}^4}{D^4}\right)}}. \tag{2}$$

Multiplying the Equation 2 by the area of the *venna contracta*, therefore, the flow rate is obtained in function of $\Delta P = (P_1 - P_2)$:

$$Q = \left(\pi d_{vc}{}^2/4\right)V_2 = \left(\pi d_{vc}{}^2/4\right)\left[\sqrt{\frac{2\Delta P}{\rho\left(1 - \frac{d_v^4}{D^4}\right)}}\right]. \tag{3}$$

However, the inviscid flow condition is correct using of the orifice plate diameter, *d*. Thus, it is not necessary use *venna contracta* diameter, modifying the Equation 3 to:

$$Q = C_d \underbrace{\left\{(\pi d^2/4)\left[\sqrt{\frac{2\Delta P}{\rho(1 - \beta^4)}}\right]\right\}}_{Q_t}, \tag{4}$$

where the diameter ratio, $\beta = d/D$ and C_d is the discharge coefficient.

The discharge coefficient, C_d, is an experimental parameter used to calibrate flow sensors which is based in Bernoulli obstruction theory, for example, the Venturi tubes and orifice plates. Therefore, it is necessary to measure the pressure difference, ΔP, as well as the real flow rate, Q. In the braced bracket, Eq.4, is the theoretical flow rate, Q_t, that would be obtained by respective pressure difference if the flow were inviscid.

Each flowmeter has a specific C_d as a function of the β ratio and Reynolds number, Re_D:

$$C_d = f(\beta, Re), \tag{5}$$

where:

$$Re = \frac{V_1 D}{\nu}, \tag{6}$$

where ν is the air kinematic viscosity coefficient in [m^2/s].

Measuring the pressure difference, ΔP, is possible to obtain the theorical flow rate, Q_t, and the discharge coefficient, C_d, is obtained from a linear regression:

$$Q = C_d Q_t + \varepsilon, \tag{7}$$

where Q is the real flow rate and ε is the experimental error of the linear regression, both in [m^3/s].

3. EXPERIMENTAL METHODOLOGY

The experiment consists to calibrate three different orifice plates. Each one has a certain edge shape, named in the present paper as sharp edge orifice, sharp edge recessed orifice and concentric quadrant edge orifice, and they are schematically shown in Figures 2a, 2b and 2c, respectively.

3.1 Materials

For the experimental setup, the pipeline is connected to a compressed air supply point available at the Laboratory of Thermal and Fluid Flow Engineering of the Universidade Federal de Goiás (LATEF/UFG). The delivered flow is set using a flow control valve while the orifice plate is positioned into an apparatus with flanges.
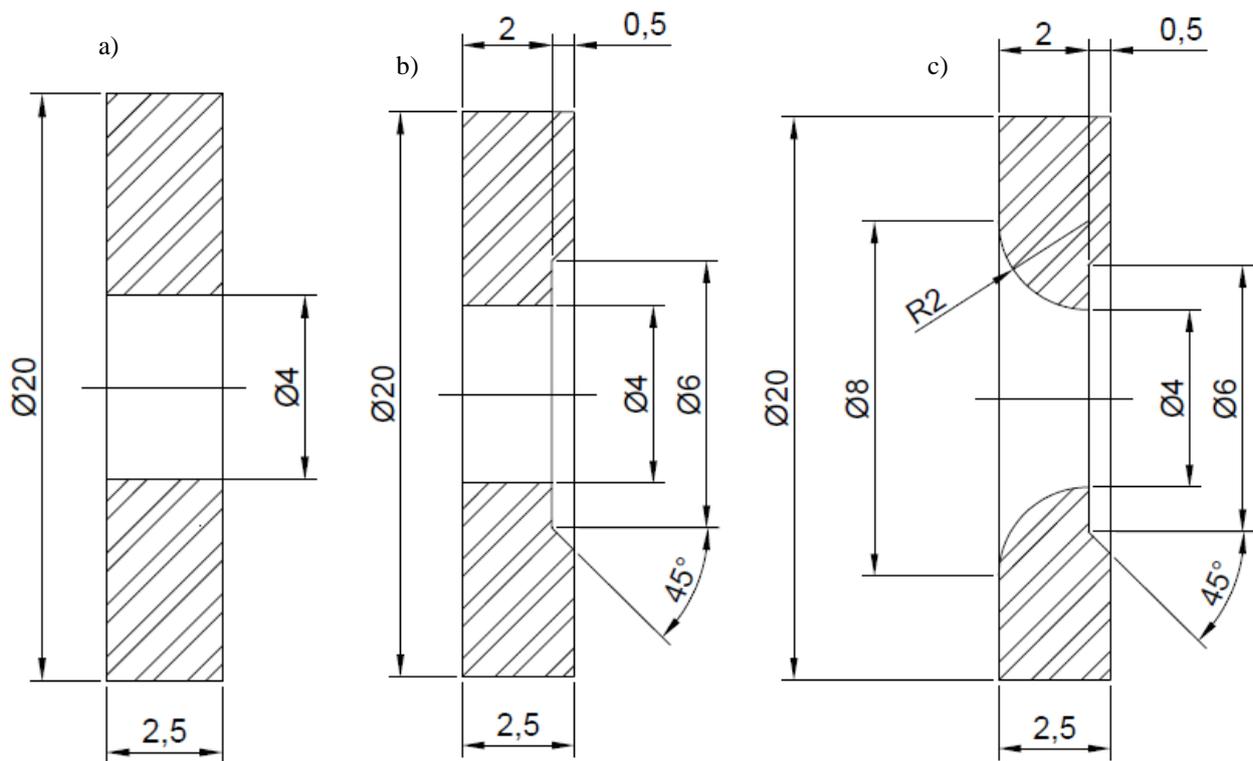
Figure 2. Schematic drawing of orifice plates used in the present work, direction of the flow left to right and measures in [mm]: a) sharp edge orifice plate b) sharp edge recessed orifice plate and c) quadrant edge orifice plate.

In the same apparatus, a pressure sensor is attached to two probes (one upstream and other downstream of the orifice plate) and this signal gives the differential pressure (ΔP) using in Eq. 4. The pipe is then linked to a mechanical ventilation analyzer, used in this experimental setup as a calibrated flow sensor, responsible to read the real flow (Q), presented in Eq. 4. After that, the flow is released to the atmosphere. Details of pipeline are shown in Figure 3.

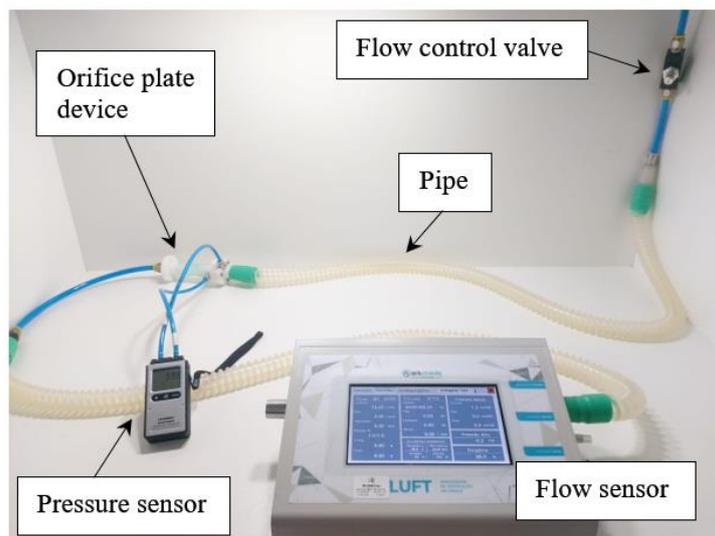

Figure 3. Photo of the complete pipeline.

3.2 Experimental Method

The flow sensor is one of the sensors of the mechanical ventilator analyzer, model LUFT from Arkmeds® (Fig. 4a). This device is used to calibrate commercial Mechanical Ventilators and, in the present work, it is used only its flow sensor. The pressure sensor is a differential manometer, model HHC280 from Omega®, (Fig. 4b).
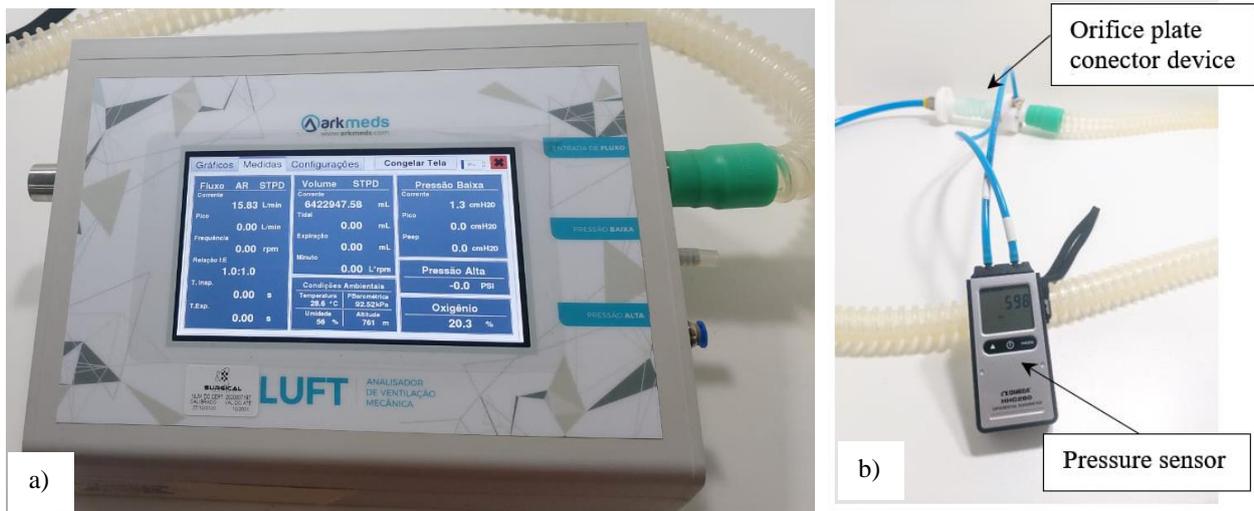
Figure 4. a) Photo of the flow sensor and b) Details of connections of the pressure sensor in apparatus of positioned orifice plate.

The steps for the experimental procedure are:
1) Set the flow rate, opening the flow control valve;
2) Wait 1 minute, until the flow can be considered in steady state, and take note of the flow sensor meter (Q);
3) Acquire 10 measures for the differential pressure (ΔP) every 5 second using the pressure sensor;
4) Return to the step 1, set a new flow rate and repeat it 15 different times;
5) Turn off the flow control valve, change the orifice plate, and return to the step 1.

From the results of the step 3, the ΔP mean is calculated and used in Eq. 4 related to the real flow (Q) obtained in step 2.

All experiments are carried out in the laboratory with controlled temperature at $T=25\ ^oC$ and atmospheric pressure considered $P=1,00\ atm$, which allows to obtain the density and kinematic viscosity coefficient for air $\rho = 1.18\ [kg/m^3]$ and $\nu = 1.55 \times 10^{-5}\ [m^2/s]$, respectively, extracted from White (2018). The pipe diameter is $D = 16.6$ [mm] and of the orifice plate diameter is $d = 4.00$ [mm].

3.3 Orifice plates manufacturing process

The flow measurement set through the method using orifice plate device consists of two flanges also known as plate holder and a plate with an orifice, usually fitted between the two flanges in the pipe, as shown in Figure 5. The material chosen for making the plate holder set was Polyacetal, on the one hand, because it is a polymer resistant to autoclave sterilization and furthermore its ease of internal machining, excellent dimensional stability, and post-machining finishing.

Figure 5. The developed plate holder to positioned orifice plates.

To carry out the fabrication of the measuring system set with orifice plate, the machining process is the most appropriate, which is characterized as a fabrication process with chip removal. According to Machado et al. (2009), it is recognized as the most popular manufacturing process in the world.

The operations used in the machining process of the set will be internal and external cylindrical turning, face milling and drilling. NBR 6175:1971 classifies turning as the mechanical machining process aimed at obtaining revolved surfaces with the aid of one or more single-cutting tools. Therefore, the part rotates around the main rotation axis of the machine and the tool moves simultaneously along a coplanar path with its axis (Brazilian Association of Technical Standards, 2015).

The lathe is one of the oldest and most important machine tools. In a lathe, the tool is clamped on a force-driven transverse carriage in straight paths parallel or perpendicular to the work axis. Lathe is a machine tool that performs turning operations in which the material is removed from a part rotated against a cutting tool (Chiaverini, 1986).

There are conventional lathes that are operated individually by an operator named mechanical lathe, and also Computer Numerical Command (CNC) lathes, which are controlled by a computer and perform operation through pre-programmed codes and their main advantages stand out in the repeatability and machining of complex geometries.

The manufactured orifice plates are shown in Figure 6, all of them are done of brass, because the dimensional characteristics of the piece, the thickness of the t=2.50 mm, would be unfeasible for machining with thermoplastic material.
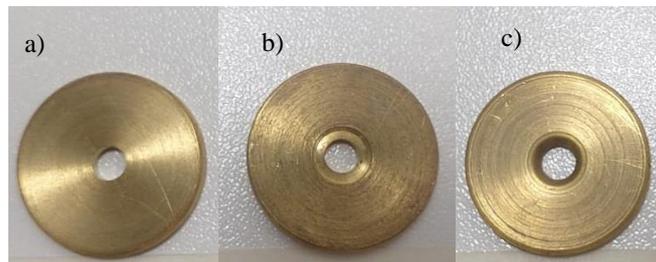

Figure 6. Orifice plates manufactured to the present work: a) sharp edge orifice plate b) sharp edge recessed orifice plate and c) quadrant edge orifice plate.

The three models of orifice plates produced for this the present work (Figures 2 and 6) have a cylindrical profile with an external diameter of *20.0* mm and a concentric hole with a diameter of *4.00* mm. A recess with a diameter of *6.00* mm and a depth of *0.50* mm can be highlighted on plate shown in Figures 2b and 6b. This geometry was obtained in the process of external cylindrical turning, face milling and drilling using a conventional lathe.

The Figure 2c shows the profile of the orifice plate presented in Figure 6c, whose main difference is the curved internal profile (quadrant edge) with a radius of *2.00* mm. Ideally, this profile should be obtained on a CNC computer numerically controlled lathe, to ensure greater precision in obtaining a specific radius. However, this profile was obtained in a conventional mechanical lathe. Highlight the ability of the lathe to perform the bimanual movement on the equipment. This movement is attributed to the displacement of the longitudinal and transverse slides simultaneously and symmetrically. This operation performs the roughing of the material starting from the central part until the end, forming the curved profile. Furthermore, a radius check standard template was used for visual confirmation that the profile is done conforms the dimensions of the orifice plate design.

4. RESULTS

The first set of results is the calibration of each orifice plates (White, 2018). The Figure 7 is accomplished, in *x*-axis, using the ΔP mean to figure out by Q_t in Eq. 4 and using the real Q in *y*-axis. The dashed lines, in each graph, are the linear fit, given by Eq. 7, which the slope is the estimation of the discharge coefficient (C_d) of each tested orifice plate. The parameters of linear fit are given in Tab. 1.

Table 1. Parameters of linear fit, given in Eq. 7, of each orifice plates.

	Sharp edge	Sharp edge recessed	Quadrant edge
$C_d=Q/Q_t$	0.860	0.793	0.914
ε [m³/s]	1.07E-05	3.19E-05	9.54E-06
R^2	0.999	0.999	0.999

The three linear fits presented in Figure 7 have a coefficient of determination (R^2) about 0.999 for all calibration experiments. The orifice plate with sharp edge recessed has C_d=0.793, the smallest of the three, *i.e.*, has the greatest pressure drop. The orifice plate with concentric quadrant edge obtains C_d=0.914, which is the biggest, and highlight it approaches the discharge coefficient of more sophisticated devices, such as Venturi tubes. This is the first important result of the present work, because it shows that is possible to use the orifice plate to control the flow in the alternative PMV prototype.
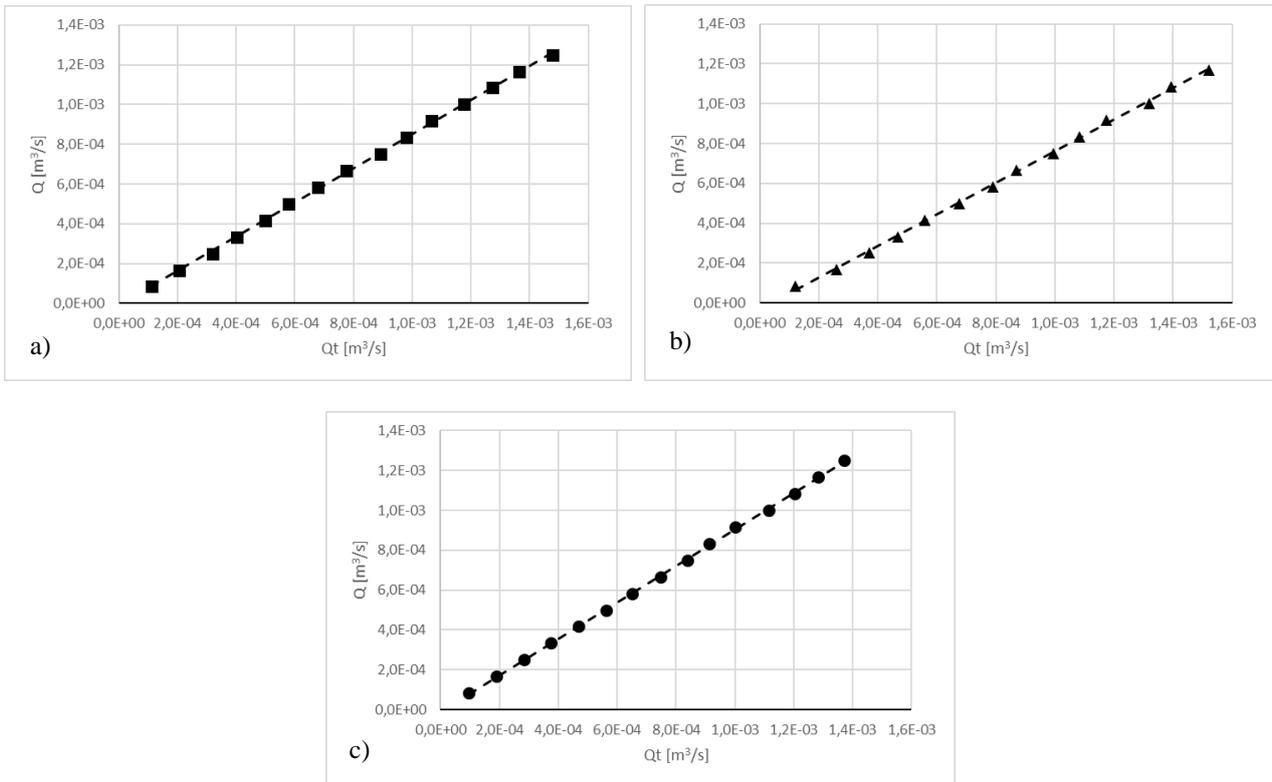
Figure 7. Calibration curves of the orifice plates with a) sharp edge, b) sharp edge recessed and c) quadrant edge.

Figure 8 shows the curves of discharge coefficient x Reynolds number (Eq. 6) for all orifice plates. The C_d of the Sharp Edge and Sharp Edge Recessed orifice plates decrease when $Re < 2100$, *i.e.*, when the flow is in laminar regime. When the flow attains the transition to turbulent ($2100<Re<4000$) and at the turbulent regimes ($Re>4000$), the C_d oscillates around an average value.

The C_d of the concentric Quadrant Sharp orifice plate remains, approximately, constant since laminar to turbulent flow, this concept is commented in Ismail *et al.* (1998) and it is the second important result of the present work, because, in operation of the PMV the flow passes through all flow regimes. Then, a quasi-constant Cd allow better precision readings of measuring instruments, being more appropriate to apply in the PMV flow measurements.
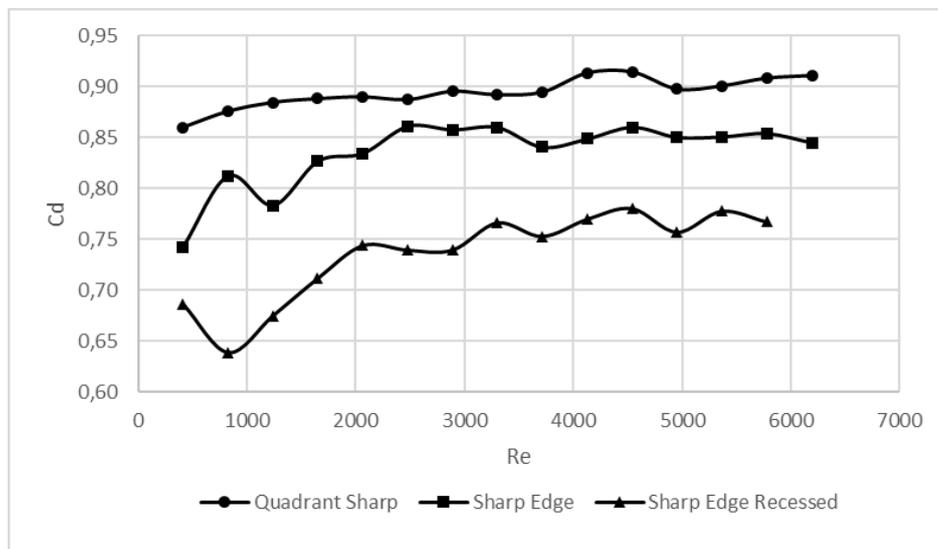

Figure 8. Discharge coefficient to three orifice plates.

5. CONCLUSIONS

In the present paper one shown three important results to design and manufacture of flow measurement system applied to an alternative PMV prototype, in order to facilitate and reduce costs of the manufacturing.

First, the orifice plates with quadrant sharp edge can be used to flow control, because has a high discharge coefficient (C_d) and there is no significant head loss (Figure 8). The second important characteristic observed in this type of orifice plate, it keeps the mean C_d since laminar to turbulent flows (Ismail *et al.*, 1998). Noting that the air flow in pipeline of PMV passes by all regime flow. However, it is necessary making a concentric quadrant sharp in orifice. This is the third important result, in section 3.3 a way to manufacture it is presented.

The new quadrant orifice plate was used in PNEUMA PMV (UFG, 2020), and it worked properly, obtaining satisfactory results when compared with a gold standard PMV in animal clinical tests (Alcântara *et al.*, 2021).

Finally, further testing is needed to improve the statistical data of the orifice plate calibration process and replicate the manufacturing process of the orifice plates. However, it is advisable to use a CNC lathe for manufacturing.

6. ACKNOWLEDGEMENTS

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