INCOMPRESSIBLE FLOW AT LOW REYNOLDS NUMBER IN A CONICAL ENTRANCE ORIFICE PLATE

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Abstract: Incompressible flow at low Reynolds number have a very relevant application that includes the use of orifice plates as a device to determine the fluid flow rate in pipes. This work presents a study about the analysis of the discharge coefficient in orifice plates, using an experimental and numerical approach, the latter being through the Characteristics Method and also through the Finite Volumes Method. The work dealt with situations outside of those contained in the standards, mainly for the flow at low Reynolds number in pipes, the experiments were carried out in a flow bench capable of reproducing the phenomena inside the pipes and the numerical part was done through a one-dimensional software which uses the Method of Characteristics and another three-dimensional that performs the simulations using the Finite Volume Method. The results show that when the inertial effects are not taken into account for the determination of the coefficient of static discharge, the values of the discharge coefficient are higher than expected.

Keywords: Orifice Plate, Discharge Coefficient, Finite Volume Method, Characteristics Method, Experimental Approach.

1. INTRODUCTION

The orifice plate still remains one of the primary elements used in the measurement of flow in the industry and, despite the technological advance that has made flowmeters more and more sophisticated, it is not expected that the participation of this device in the market will be inferior to 40% in the near future. Due to the simplicity of installation and maintenance, good accuracy and relatively low cost, orifice type meters still represent about 80% of the flow measurement systems in the various industrial segments. Among these meters, orifice plates are the most used, besides the advantages already mentioned, they have a wide applicability, even for corrosive fluids Martins (Martins, 1998).

The concentric orifice plate with sharp corners has been extensively studied. For high Reynolds numbers the flow coefficient is well defined arriving to be almost constant. For flows at low Reynolds numbers, as is normally the case for viscous fluids, concentric orifice plates with sharp edges can't be used, because in this case they present a large flow coefficient variation as a function of the Reynolds number. Considering the industrial importance of measuring such fluids, there is a great interest among users of differential pressure flowmeters throughout the device that has a constant flow coefficient at low Reynolds numbers. Several plate profiles have been tried for flow measurement cases which the Reynolds number is relatively low. Among the various forms tested, some are more widespread and commented on in standards such as BS 1042 (1983). The conical entrance orifice plate is the most suitable form for flow measurement of viscous fluids in which the Reynolds number is between 25 and 75, according to the value of β.

Since the publication of BS 1042 (1983) the characteristics of the conical entrance orifice plate have been explored by several researchers (Kastner and McVeigh (1965); Stoll and Zientara (1974); McVeigh (1974); Turton (1975); Ho and Leung (1985)). However, many of the results obtained in these studies were in conical orifice plates that did not meet the sizing specifications recommended by the standard. Thus, few experimental results that meet the specifications of the standard are relatively readily available, requiring further study of their characteristics.

The characteristics of the flow meters are affected by several parameters, among which there is a great variation of the scale in relation to the values found in the practice. Due to the great technological advance in the computational area, numerical simulations can be made with detailed spatial description of the greatness of interest and its evolution over time, speed and low cost, features difficult to obtain in the experimental simulations. The experimental effort can then be greatly reduced. Thus, the use of the appropriate model of turbulence simulation in the computer can be extremely useful in the study of the performance of flow meters.

The need to calculate the flow of fluid flows occurs in many practical situations, from flows in the pulmonary pathways to tidal flow, among the applications in engineering can be highlighted the natural gas pipelines flow, petrochemical, in the admission ducts of internal combustion engines, among others (Grace e Frawley, 2011). The main

parameters that affect the behavior of this type of flow are Reynolds number, velocity gradient, pressure gradient and pulse rate (Metwally, 2009).

This type of flow can be divided into two parts, periodic flow and random flow fluctuation (International Organization for Standardization, 2018a), and can be generated by pumps, compressors, flow control valves, hydrodynamic oscillation, among others (American Petroleum Institute, 2012). Most of the heart pulse investigations have been concerned with the orifice plate flow meter because of its simplicity and frequent use in the industry (Association, 2002; Graves, 2010). Two methods are used to investigate this flow: experimental and numerical.

Novitskii (1996) have emphasized measurement errors in orifice plates by changing the pressure gradient in the orifice plate. Mattingly and Yeh (1994) have analyzed the deviations in the discharge coefficient of an orifice plate, with a diameter ratio of 0.5, installed at various distances downstream of a 90° curve. Morrison et al. (1995) found that some installations that follow API 2530 had errors of the order of 5% (American Petroleum Institute, 1985). Jankowski et al. (2008) developed a model to predict the pressure drop and the discharge coefficient for incompressible flow through orifice with length-to-diameter ratio greater than zero over a wide range of the Reynolds number.

The study of the limit between the steady state flow and the pulsating transient in orifice plate flow meters represents a gap in scientific knowledge. An analysis of the discharge coefficient behavior that includes the pulsating transient parameters is of great interest. The conical entry orifice plate is used in applications where the lower Reynolds number ranges from 25 to 75, according to the value of the ratio β, and its dimensions are given according to BS 1042: Part 1 (1983).

This work approaches experimental and numerically the study of steady, incompressible and low Reynolds number flows through a concentric conical entrance orifice plates with β equal to 0,53; with the experiments realized in a flow bench able to reproduce the pulsating phenomena existing in the flow. Section 1 discusses the introduction, with a brief contextualization of the subject studied and important information about other authors' work on the subject; section 2 reviews the theoretical concepts underlying this work, detailing the norms that govern the field of study; section 3 divide methodology in experimental and numerical, providing the details on the methods of experimental data acquisition and also the numerical models that were used; section 4 presents the results and discussion of the difference between the experimental and numerical values, justifying them with the existing uncertainty, and finally section 5 presents the conclusions and suggestions of future work.

2. THEORETICAL FOUNDATION

One of the oldest ways to measure fluid flow is by using differential pressure meters. Among these, the orifice plate, venturis and flow nozzles stand out. It is estimated that 40% to 42% of the flow meters installed in Europe and the USA are orifice plates (Reader-Harris, MJ and Hodges, D and Rushworth, 2008; Shah *et al.*, 2012).

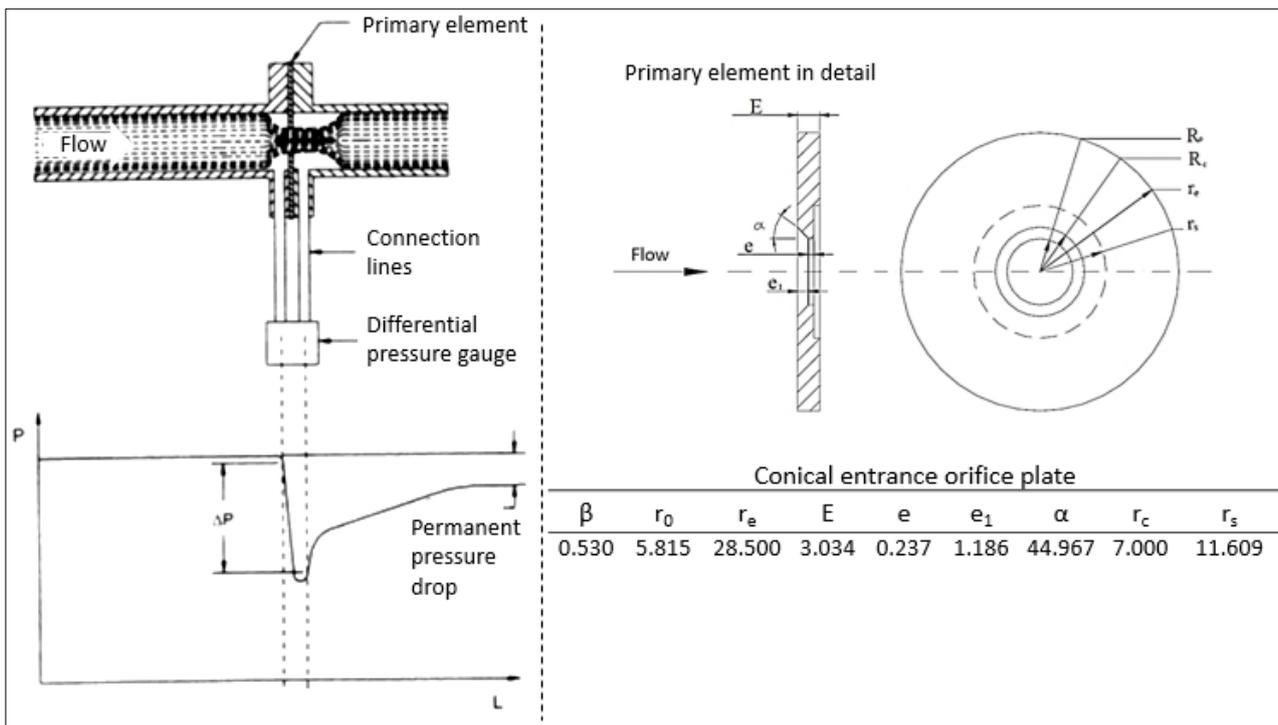| β	r_0	r_e	E	e	e_1	α	r_c	r_s
0.530	5.815	28.500	3.034	0.237	1.186	44.967	7.000	11.609

Figure 1. Scheme for fluid flow measurement through the conical entrance orifice plate.
Adapted from: (Delmée, 2003; Martins, 1998; Reis *et al.*, 2006)

The orifice plate consists of imposing a restriction on the fluid flow in the piping at which the flow rate is measured. This restriction is caused by a hole made in a plate of small thickness, obtaining a change in the speed of the fluid and consequently a pressure differential. The right side of Fig. 1 shows a concentric orifice plate flow meter installed in a fluid flow duct from left to right, the graph immediately below associates the pressure value in each section of the duct. When passing through the orifice plate, the fluid undergoes a pressure drop which is resumed downstream of the plate, but with a certain irreversible loss of charge.

The pressure difference ΔP and the flow rate Q in a pipe with orifice plate can be related through an equation in the form of Eq. (1) (Delmée, 2003).

$$Q = k.\sqrt{\Delta P} \qquad (1)$$

The value of k depends on the orifice plate parameters, the setup physical configuration and the flow characteristics. It is common to use a discharge coefficient, C_d, which takes into account all the factors influencing the flow determination, according to Eq. (2) (Delmée, 2003).

$$Q = C_d.A_0 \sqrt{\frac{2.\Delta P}{\rho}} \qquad (2)$$

Where C_d is the static discharge coefficient, A_0 is the area of the orifice section of the plate (m²), ΔP is the differential pressure at the orifice plate (Pa) and ρ is the specific mass of the fluid (kg/m³).

By Eq. (2), each flow rate corresponds to a coefficient of discharge. From a theoretical point of view, the value of this coefficient is only accurate for the flow used to determine it at the time of calibration.

2.1 Conical entrance orifice plate

The cone-shaped entrance orifice plates keep the discharge coefficient constant even at low Reynolds numbers, making them suitable for measuring viscous fluid flows (International Organization for Standardization, 2018b). Corner sockets must be used for conical entrance orifice plates. Its use is limited to cases where the following situations are present:

a) $0.1 \leq \beta \geq 0.316$;
b) $80 \leq Re_D \geq 2 \times 10^5 \beta$;
c) Orifice diameter, $d \geq 6$ mm;
d) Duct internal diameter, $D \leq 500$ mm.

In which β is the ratio of the orifice diameter to the duct diameter. Figure 1 shows the conical entrance orifice plate, which follows the standard ISO/TR 15377 (International Organization for Standardization, 2018b) and is suitable at low Reynolds number flows.

3. METHODOLOGY

In this section the methodologies used to perform the experiments are discussed: the numerical simulations using the method of the characteristics and also the method of the finite volumes.

3.1 Experimental Methodology

The overall flow bench scheme and the stand where the experiments were performed is shown in Fig. 2. The oil contained in the reservoir (1) is pumped by the vane pump (2) at a constant flow rate. The pump flow is controlled by a pressure regulating valve with pressure and temperature compensation (3), which allows the change of the pump flow, for a mean flow. An accumulator (5) using nitrogen gas at 4 bar pressure is responsible for minimizing the pulsation caused by the pump in the line. The oil flows through the acrylic duct (6) to the static flow measurement system (7). This system consists of a conical entrance orifice plate and two pressure transducers. The purpose of this system is to prove that the straight pipe length used in the dynamic flow measurement system is large enough to not interfere with the flow values found in steady state.

After going through the resonator (8), the oil gets in touch with the flow pulse generator (10) through a branch present in the tubing. The flow pulse generator (10) is driven by an AC motor (9), wherein its rotation being altered by the use of a frequency inverter (11). The oil is then fed into the dynamic flow measurement system (12), consisting of a concentric live-corner orifice plate and three pressure transducers with dynamic characteristics. When the flow pulse generator is switched off, both measurement systems, (7) and (12), send voltage signals corresponding to a pressure difference value

equivalent to the average flow. When the flow pulse generator is actuated, the system (12) indicates a pressure difference which is equal to a mean flow, plus a damped and lagged flow fluctuation that actually passes through the orifice plate. The resonator (8), associated with the inclination of the tube which carries the oil to the dynamic flow metering system, has the purpose of preventing the propagation of this flotation to the measuring system (7).

The fluctuation generated by the flow pulse generator suffers a delay and a damping. After passing through the dynamic flow metering system (12), the oil passes through a directional valve (13) which alternates the path traveled by the oil between the flow metering vessel (14) and the reservoir (1). A timer (15), which acts on the opening of the directional valve, allows the entry of the circulating oil into the vessel during a certain time interval, for the calibration of the steady-state measurement systems and determination of the average flow. The oil temperature is measured inside the tank by a thermostat (16). To maintain the temperature of the oil inside the reservoir (1) at the desired temperature, the heat exchanger (17) is started.
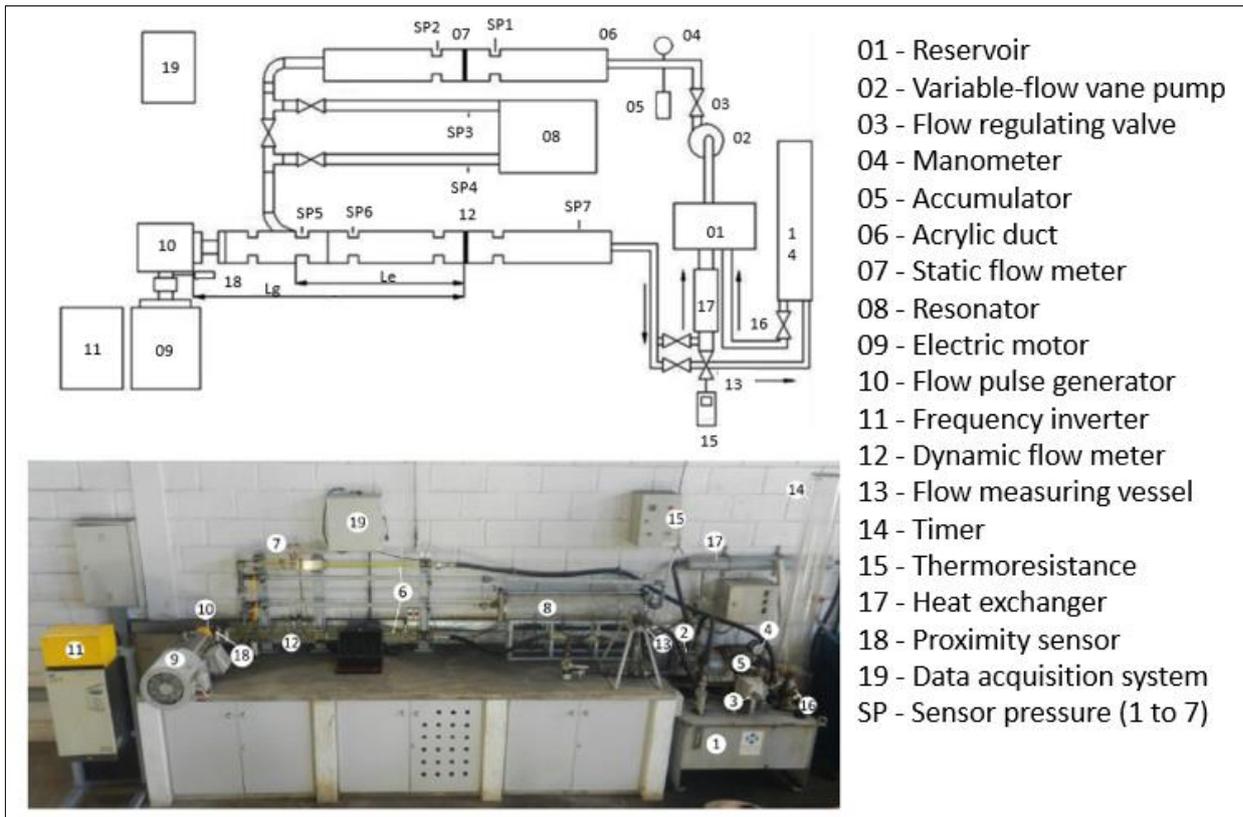

Figure 2. Flow bench's overall scheme
Adapted from: Reis (2013).

The oil's specific mass and the kinematic viscosity are 857, 61 kg / m³ and 31.5 cSt, respectively [20]. The oil temperature was maintained at $(40 \pm 1)\,^\circ$ C.

3.2 Numeric Methodology – Characteristics Method

In this section we will present the mathematic and numerical methods employed, besides the software used during the simulations.

The characteristic method is a numerical (Claro Romão, Felipe Mendes de Moura e Batista Campos Silva, 2008)and analytical (Sarra, 2003) method of solving partial differential equations. The 1-D analysis of transient flows is the most common and popular way to treat transient flows, using the characteristic method as a tool.

The equations to be considered in the resolution of transients in pipe networks are the continuity equation (Eq. (3)) and the momentum equation (Eq. (4)) whose development and application were based on Miller (1978).

Continuity equation:

$$\frac{\partial H}{\partial t} + \frac{c^2}{g\,A}\frac{\partial Q}{\partial x} = 0 \tag{3}$$

Momentum equation:

$$\frac{\partial Q}{\partial t} + g.A.\frac{\partial Q}{\partial t} + \frac{f.Q.|Q|}{2.D.A} = 0 \tag{4}$$

The friction factor (f) given in terms of the shear stress (τ_W), according to Eq. (5) (Benson, Horlock e Winterbone, 1982), and the velocity of propagation of the pressure wave in the fluid given by Eq. (6) (Miller, 1978).

$$f = \frac{\tau_W}{\frac{1}{2}\rho u^2} \tag{5}$$

$$c = \frac{\sqrt{\frac{k}{\rho}}}{\sqrt{1 + \frac{k.D.C}{e.E}}} \tag{6}$$

In which k represents the volumetric elastic modulus of the liquid (N/m²), ρ is the specific mass of the fluid (kg/m³), D is the internal diameter of the tube (m), e the wall thickness of the tube (m), E the Young's modulus of tube material (N/m²), A is the cross-sectional area of the tube (m²), g is the acceleration of gravity (m/s²), H is the pressure expressed as the height of the liquid column or piezometric charge (m), Q represents the volumetric flow rate (m³/s), t the time (s), x the tube length (m) and finally C is a dimensionless number depending on the elastic characteristics of the tube. Its value is taken as the unit without significant error in many cases.

Equations (3) and (4) are transformed into four ordinary differential equations by the characteristic method. Solving these equations describing the transient propagation of pressure and flow in a tube (Miller, 1978), we have the solutions C+ (Eq. 7) and C- (Eq. 8) represented in the graph of the characteristic equations (Fig. 3). The term B represents the impedance and the term R is the coefficient of resistance.

$$C^+: H_p = H_A - B.(Q_p - Q_A) - R.Q_A.|Q_A| \tag{7}$$

$$C^-: H_p = H_B + B.(Q_p - Q_B) - R.Q_B.|Q_B| \tag{8}$$
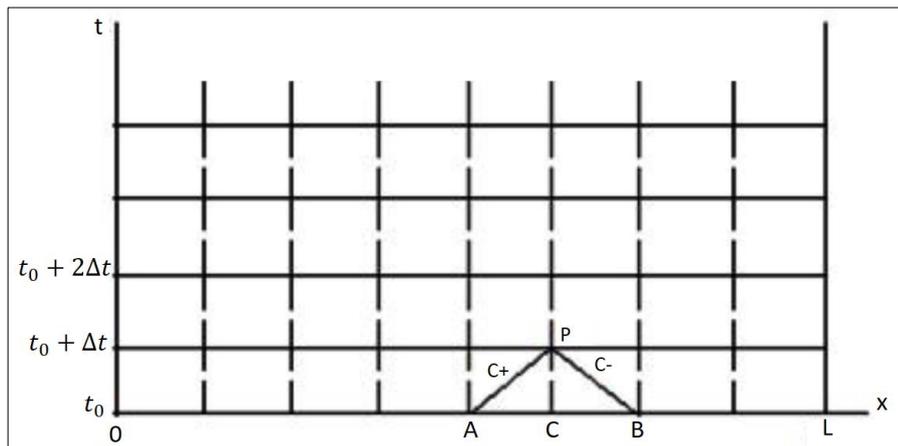

Figure 3. Characteristics lines graph.
Available from: Wylie and Streeter (Wylie e Streeter, 1978).

The Characteristics Method has been successfully used in several works, in the steady three-dimensional isentropic flow (Frohn, 1974) , supersonic rotational flow (Holt, 1956), coronary blood flow (Rumberger e Nerem, 1977), among others.

3.3 Numerical Methodology – Finite Volumes

The conical entrance orifice plate is essentially used under the low Reynolds number conditions. Therefore, a turbulent model at low Reynolds number would be required for the study of its characteristics. One of the advantages of

the k-ω formulation is the near wall treatment at low Reynolds number computations, a model developed by Wilcox (1986). The model does not involve the complex nonlinear functions required for the k-ε model and is consequently more accurate and more robust. A low Reynolds k-ε model would typically require a close definition of the highly refined mesh, while a k-ω model requires tenfold refinement. In industrial flows, even ten times smaller refinements cannot be guaranteed in most applications and for this reason a new near-wall treatment was developed for the k-ω models. It allows smooth displacement of a low Reynolds formulation to a wall function formulation (Campregher, Silveira Neto, da e Said Mansur, 2004).

The flow coefficient or flow velocity is the most important parameter for a differential pressure type meter. Consequently, a correct model could be said to have been obtained when the choice of straight portions 55D upstream and 16D downstream of the orifice plate were sufficiently large, so that any additions in these stretches did not affect the flow velocity result. Further refinement of the mesh was done so that the coefficient of flow remained unchanged.

The STAR-CCM+ Siemens software is a commercial CFD package for multiphysics. The program enables the user to import complex CAD program geometries and also has an internal CAD tool for less detailed geometries. STAR-CCM + is able to generate different types of meshes automatically and allows to choose several physical characteristics of the real problem, such as turbulence model, for example.

The S.S.T. model, developed by (Menter, 1993), consists of a transformation of the k-ε model into a k-ω formulation and a subsequent addition of the corresponding equations. The k-ω model is multiplied in this way by a coupling function F_1 and the transformed model k-ε by a function 1-F_1. The equation F_1 becomes equal to one near the surface and zero in the boundary layer. At the edge and outside the boundary layer, the standard k-ε model is retrieved. The model takes into account the transport of turbulent stresses and gives highly accurate predictions of the start and amount of flow separation under adverse pressure gradients. The final model equations are the turbulent kinetic energy (Eq. (9)) and specific dissipation rate (Eq. (10)).

$$\frac{\partial(\rho k)}{\partial t} + \nabla.(\rho U k) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_{k3}}\right)\nabla k\right] + (P_k - \beta'\rho k\omega) \tag{9}$$

$$\frac{\partial(\omega)}{\partial t} + \nabla.(\rho U \omega) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_{\omega3}}\right)\nabla\omega\right] + (1-F_1)2\rho\frac{1}{\sigma_{\omega2}\omega}\nabla k\nabla\omega + \alpha_3\frac{\omega}{k}P_k - \beta_3\rho\omega^2 \tag{10}$$

Wherein k is the turbulent kinetic energy, P_k is the turbulent product due to viscosity and thrust forces, ω the specific dissipation rate, ρ the density of the fluid and U the velocity vector. The coefficients of the new model are a linear combination of F_1 and 1-F_1, according to Eq. (11), (12) and (13); where Φ_1 and Φ_2 are the coefficients of the model k-ω and k-ε, respectively.

$$\Phi_3 = F_1\Phi_1 + (1-F_1)\Phi_2 \tag{11}$$

$$F_1 = tanh\left\{min\left[max\left(\frac{\sqrt{k}}{\beta'\omega y}, \frac{500v}{y^2\omega}\right), \frac{4\rho k}{\sigma_{\omega2}y^2.max\left(2\rho\frac{1}{\sigma_{\omega2}\omega}\nabla k\nabla\omega, 10^{-10}\right)}\right]\right\}^4 \tag{12}$$

$$F_2 = tanh\left\{max\left(\frac{2\sqrt{k}}{\beta'\omega y}, \frac{500v}{y^2\omega}\right)\right\}^2 \tag{13}$$

4. RESULTS

The numerical model S.S.T. was used to simulate the flow through the orifice plate. Figure 4(a) shows the geometry and dimensions used for the numerical simulation using the Finite Volume Method (3D) applying commercial software STAR-CCM+. Figure 4(b) shows the mesh used in the discretization, which has a base size of 0.1 mm and 906671 volumes in total. A greater refinement was built near the walls with 7 layers of prismatic mesh that better computes the viscous effects, and also a twofold refinement in the region comprised of 5D downstream and 5D upstream in relation to the orifice plate, with D equals to 21,89 mm. Figure 4(c) illustrates the conical entrance orifice plate mesh.

Table 1 shows the Reynolds number values calculated based on the orifice diameter and pipe diameter, Re_d and Re_D respectively. The experimental discharge coefficients (Cd - Exp.), using the Characteristic Method (Cd - Num. Car.) and

the Finite Volume Method (CFD) were calculated using Eq. (2) for the hydraulic lubrication oil Mobile DTE 24 (ISO VG 32) with specific mass of 864 kg/m³ and absolute viscosity of $26,78 \times 10^{-3}$ Pa.s (Lubrificantes, 2012).
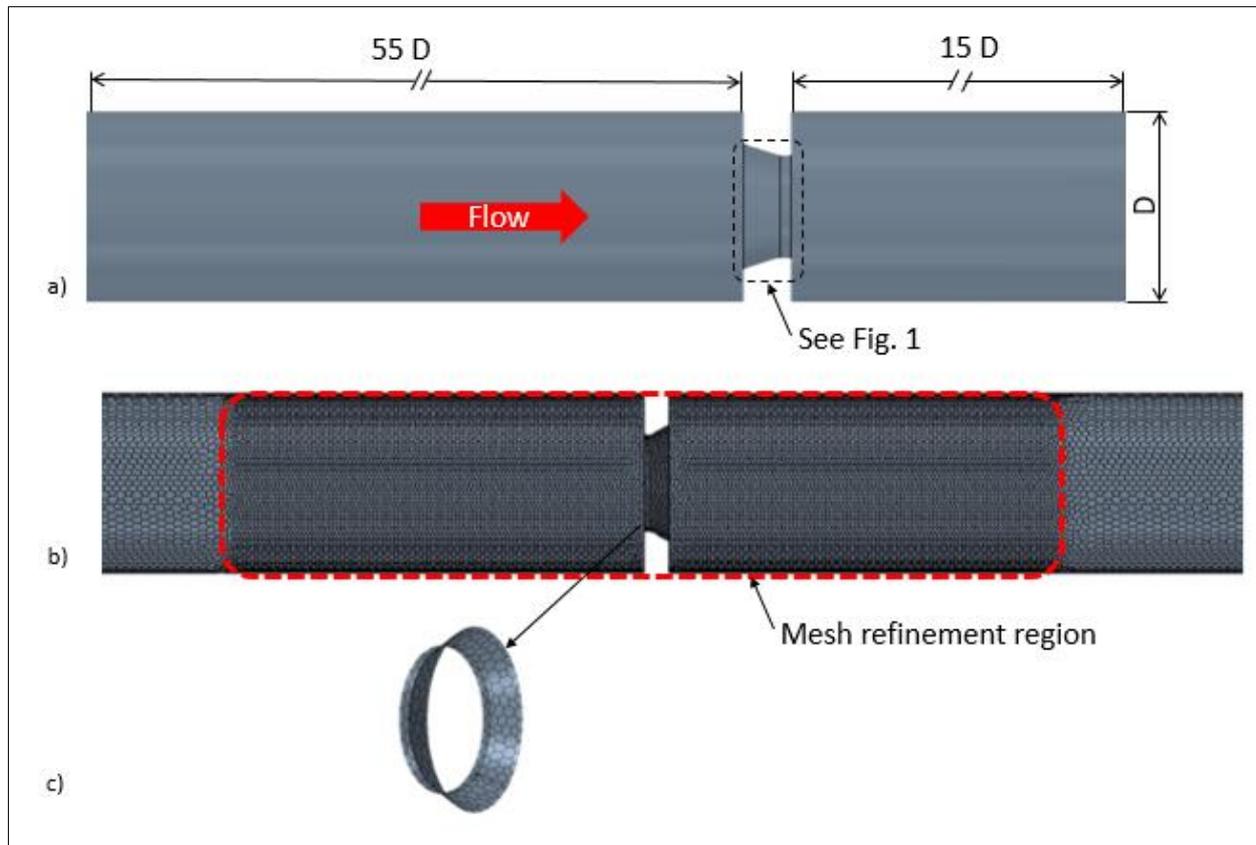

Figure 4. Geometry and mesh for the CFD

Table 1. Flow, Reynolds numbers and Discharge Coefficient.

$Q \times 10^{-3}$ (m³/s)	Re_d	Re_D	Cd - Exp.	Cd – Num. Car.	Cd – Num. CFD
0.430 ± 0.005	1498	794	0.774 ± 0.023	0.741	0.827
0.620 ± 0.005	2160	1145	0.812 ± 0.023	0.790	0.832
0.810 ± 0.005	2822	1496	0.845 ± 0.023	0.830	0.836
1.020 ± 0.005	3554	1883	0.879 ± 0.023	0.867	0.839
1.250 ± 0.005	4356	2308	0.914 ± 0.023	0.901	0.842

As one can see in the Fig. 5, it is observed a good agreement between the values obtained experimentally (the lozenge-shaped points) and through the Characteristics Method (the red square points) and the only discharge coefficient value that remained outside the uncertainty of 0.023 was the first value, with an error 4,26% regarding the experimental result. Concerning to the results obtained through STAR-CCM + Software (the cross-shaped points), the second and third discharge coefficient values remained within the experimental uncertainty, the first and the last point presented an error in relation to the experimental ones of 6,89% and 7,85%, respectively.

The orifice plate's chamfer angle influences the discharge coefficient (Singh, Singh e Seshadri, 2010). The average discharge coefficient value for the 45 degrees' chamfer angle was greater than the corresponding value for the 30 degrees' chamfer angle (concentric sharp-edge orifice plate). In the literature, there are few studies related to the discharge coefficient for viscous fluids at low Reynolds numbers, especially in laminar regime. The values of the discharge coefficient presented in the literature and in the standards consulted are for high Reynolds numbers and for turbulent regime.
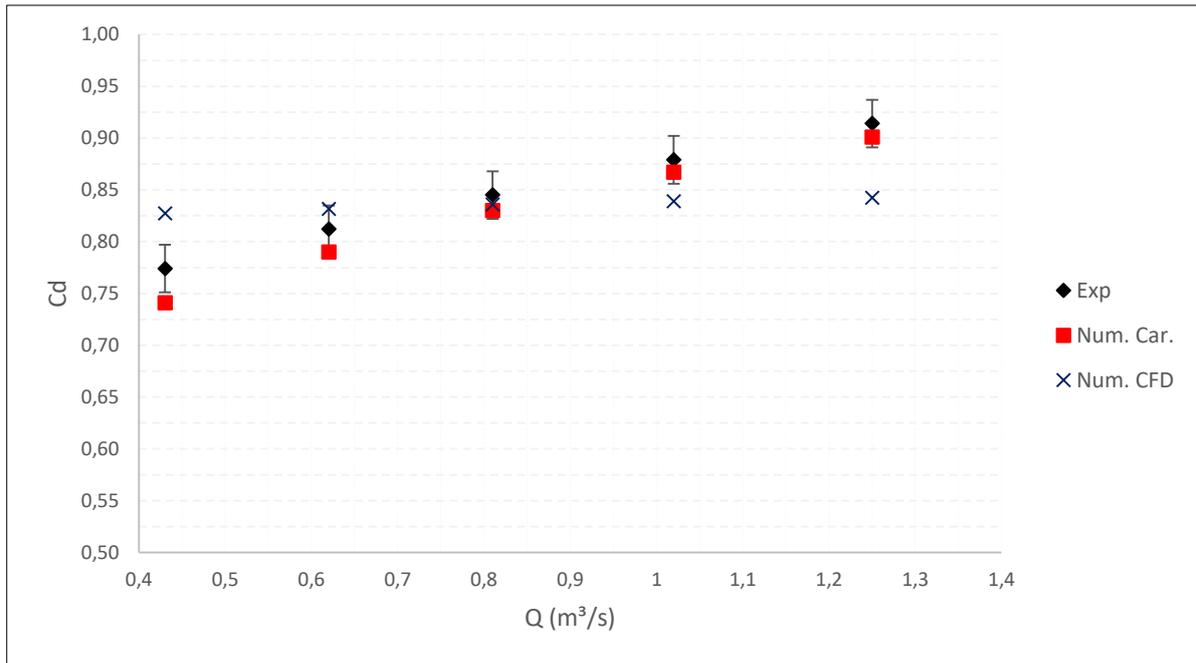
Figure 5. Discharge coefficient obtained numerical e experimentally.

As a stopping criteria, the minimum value of residuals smaller than 10^{-4} (Dias, 2011) was assumed for all equations, that is, continuity equation, the momentum equations in the three directions, turbulent kinetic energy equation and viscous dissipation rate equation. Figure 6(a) and 6(c) illustrate the general velocity field near the orifice plate, respectively. One can observe the existence of two recirculation zones downstream of the orifice, as was to be expected. Figure 6(b) shows the residue values for the above-mentioned equations, in relation to the interactions it is observed that there was good convergence.
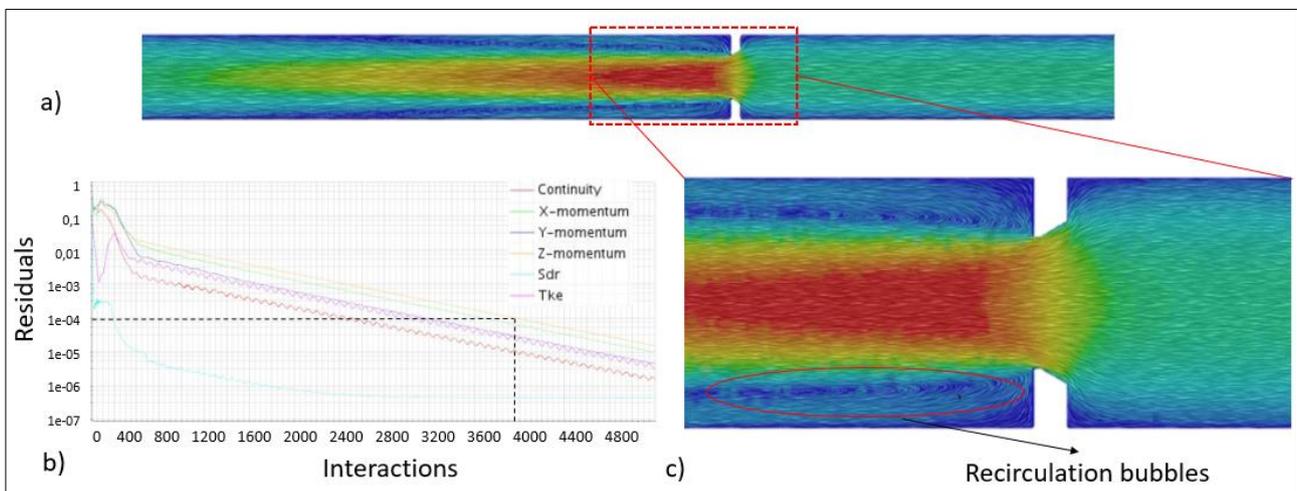

Figure 6. Velocity field and residuals of the CFD simulation.

5. CONCLUSION

The work presented in this document shows the application of the S.S.T. model, for the flow simulation through the conical entry orifice plate. The numerical model developed shows that it is able to predict the value of the flow coefficient of the conical entry orifice plate with an error up to ±3% of the value established in the standard and the one found experimentally. Since there are a limited number of experimental results available on the characteristics of the conical entrance orifice plate, numerical modeling can be very useful in providing more data on these characteristics.

The characteristics method proved to be effective for what was proposed, since it was within the experimental uncertainty range of ±0.023 for four of the five flow rates. The second and third values from the 3D simulation on the

STARCCM+ also kept inside the uncertainty range, whereas the first and last discharge coefficient did not agree very well with the experimental ones, mostly due to the chamfer angle abruptness.

Since there are a limited number of experimental results available on the features of the conical entrance orifice plate, numerical modeling can be very useful in providing more data on its influence in the discharge coefficient. Thus, the use of the appropriate turbulence model in the simulation can be extremely useful in the study of the conical entrance orifice plate performance. Furthermore, the experiments carried out will help to better understand the obtained data, resulting in a better use of the orifice plate at low Reynolds numbers flows.

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7. ACKNOWLEDGEMENTS

8. COPYRIGHTS