INFLUENCE OF DIMENSIONAL AND GEOMETRIC PARAMETERS ON ORIFICE PLATES TO FLOW DETERMINATION

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Abstract. *This work aims to evaluate the influences of macro-geometric (circularity), micro-geometric (surface roughness) and dimensional quantities on orifice plates to the flow determination. Dimensional and geometric quantities are extremely important and also necessary when we have in mind the accomplishment of any project being directly linked with several areas of the engineering. All designs of machines or pieces are represented through drawings containing their nominal dimensions with the respective dimensional and/or geometric tolerances. After it had been manufactured the dimensional and geometric control will prove if the pieces or machines were made in agreement with the project. Therefore, the orifice of an orifice plate can come oval for effect of deformation and the measure of its diameter can result in two: the maximum and minimum diameters. Then, taking big flows into consideration it can mean large wastes of liquid and gas. The work will also present the tolerances imposed to the dimensional and geometric parameters related to orifice plates according to the norms and technical regulations. The measurements are performed using a coordinate measuring machine (CMM) and a profilometer. Finally, we will express the uncertainty sources associated to flow meters, especially to the orifice plates.*

Keywords*: Orifice plates; Flow measurement; Tolerances*

1. INTRODUCTION

Dimensional and geometric quantities are extremely important and necessary when we have in mind the accomplishment of any project. They are directly linked with several areas of the engineering as well as the flow, which has many applications since water flow measurement in treatment plants until measurements of industrial and fuel gas, passing through more complex ones as the blood flow in circulatory systems.

All designs of machines or pieces are represented through drawings containing their nominal dimensions with the respective dimensional and/or geometric tolerances. After it had been manufactured the dimensional and geometric control will prove if the pieces or machines were made in agreement with the project. In the flow measurement the orifice plates are devices of low cost at installation and maintenance, therefore, they are the most used in the majority of industrial applications. At an orifice plate with an orifice with a nominal diameter of 25 mm, in practice we can find bigger and lower values than 25 mm besides geometric variations. Therefore, the orifice of an orifice plate can come oval for effect of deformation and the measure of its diameter can result in two: the maximum and minimum diameters. Then, taking big flows into consideration it can mean large wastes of liquid and gas. Those geometric and dimensional deviations must be determined by sophisticated measurements. So, the measurements were performed using a coordinate measuring machine (CMM) and a profilometer.

As we know, the flow of oil and natural gas production occurs by trucks, trains, ships and pipelines which connect wells to refineries and terminals. The pipeline network, however, is widely used and suitable for transporting large volumes of oil and natural gas, so the calibration of flow meters is essential for an accurate measurement in order to ensure the correct charge ordered, and also to prove that it will effectively reach its destination. To have an idea of the commercial importance in flow measurement, we can take into consideration the Bolivia-Brazil gas pipeline as an example. This pipeline carries natural gas from Bolivia to São Paulo, and it was designed to carry up to 30 millions square meters a day of natural gas. If it was considered a cost of sales of U$ 0.50 per square meter, we could see that a bias of just 1% on a flow meter is associated to an amount at about U$ 150.000 a day according to Fernando (PUC-RJ).

Currently, there is an effort form several international laboratories to improve the flow meters and also to reduce measure uncertainties.

2. DEVELOPMENT

2.1 Equating to incompressible flow

The theory of flow measurement by differential pressure is based on known physical laws. The theoretical equations must be supplemented by practical coefficients, so that flow can be measured accurately. The theory considers the continuity equation and Bernoulli's equation. From these equations can result an expression which is used on this work:

$$Q = CE\beta^2 A_t \sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

Substituting A_t for $\pi D^2/4$ and considering that $\pi/4\sqrt{2} = 1,1107$, we have Eq. (1):

$$Q = 1{,}1107 \cdot CE\beta^2 \cdot D^2 \cdot \sqrt{\frac{(p_1 - p_2)}{\rho}} \qquad (1)$$

Where: $Q = m^3/s$; p_1 and $p_2 = Pa$; $D = m$; $\rho = kg/m^3$.

Product $CE\beta^2$ can be treated together, being C a characteristic of each primary element and the product EB^2 representing geometric dimensions. The discharge coefficient's equation C which is used on this work is according to the norm ISO 5167*98. It is given bellow:

$C= 0,5961 + 0,0261\beta^2 - 0,216\,\beta^8 + 0,000521 \times (10^6\,\beta/R_D)^{0,7} + (0,188 + 0,0063A)\,\beta^{3,5} \times (10^6/R_D)^{0,3} + (0,043 + 0,08e^{-10L1} - 0,123e^{-7L1}) \times (1 - 11A) \times \beta^4/(1 - \beta^4) - 0,031[M'_2 - 0,8M'^{1,1}_2]\,\beta^{1,3}$.

2.2 Inspection of manufacture parameters on classic plates

Independent of the type of tap classic orifice plates (by norms ISO 5167 and AGA3) have to be manufactured and installed in agreement with certain minimum specifications. To values once out of these specifications can influence in flow measurement. Because of that it is necessary to follow severely certain limits imposed by norms.

An inspection of an orifice plate implicates on verification or measurement of fifteen items where in the Laboratory of Metrology (UFRN) we are able to analyze the followings:

- Flatness analysis;
- Superficial roughness measurement;
- Measurement of at least four orifice diameters;
- Average of the previous item;
- Temperature during the plate measurement;
- Identification of who has performed the service and its date of inspection;
- Has the plate conic aperture, or not? What is the cone's angle?

a) Upstream and downstream faces

The upstream face has to be plain. It will be considered plain when a straight line binding any two points of its surface has inferior inclination lower than 1%. The upstream face must not present wire edges, burrs, risks or other imperfections (Delmée, 2003).

On the other hand, the downstream face has to be parallel to the upstream face. There is no need to reach the same quality of state of the surface that is demanded for the upstream face. The flatness and the state might be judged by a simple visual examination, according to (Medeiros; Lima et al, 2006).

b) Roughness of the plate

The roughness of the upstream face of the orifice plate has to be inferior to 0.0001d, being determined radially in a concentric circle to the orifice. The circle diameter not being inferior to 1.5d as it is seen in the Fig.1 (Martins, 1998 cited by Medeiros, Lima et al (2006).

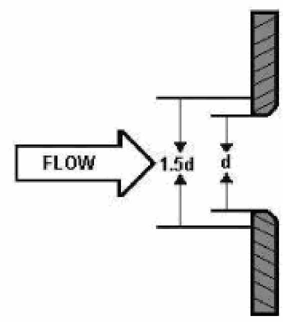

Figure 1 – Indication of the diameter 1.5d to be considered for determination of roughness of the plate

Superficial roughness of the upstream and downstream faces must not exceed 50 µin of R_a measured with a cut-off value not lower than 0,03 inches according to (Araújo and Link, 2004). Superficial roughness measurements on orifice plates which were used in this work were performed in the Laboratory of Metrology from UFRN. It is shown in Fig. 2:

Figure 2 - Superficial roughness measurement on orifice plates

c) Orifice diameter

Orifice plate diameter *d* is given by arithmetic mean of four or more measurements equally spaced in the perimeter of the orifice. None of these measurements differ from the value of the calculated diameter, nor from any another measured diameter beyond the limits shown in table 1 in agreement with (Medeiros, Lima et al, 2006). The process of measuring the diameter of an orifice of a plate is shown in Fig. 3:

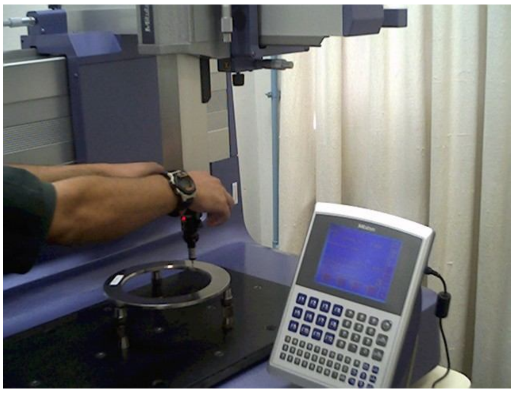

Figure 3 – Process of measuring the orifice of a plate through a Coordinate measuring machine.

Tab. 1 – Allowed tolerances for orifice diameters

Orifice diameter (d), mm	Maximum deviation (%)
d ≤ 12	± 0.1
12 < d ≤ 16	± 0.08
16 < d ≤ 20	± 0.07
20 < d ≤ 25	± 0.06
d > 25	± 0.05

Diameter d is always limited among 0.1D and 0.8D. However, to calculate the value of the orifice diameter of the plate, the reference diameter (d_r) is determined, calculated to the reference temperature (t_r) using the following equation according to (Araújo and Link, 2004).

$$d_r = d_m\left[1+\alpha_1\left(t_r - t_m\right)\right]$$

Where:

α_1 = coefficient of linear expansion of the material of the plate;
d_r = orifice diameter of the plate, calculated to the reference temperature (t_r);
d_m = orifice diameter of the plate, measured to the temperature (t_m);
t_m = temperature of the plate during the measurements;
t_r = reference temperature of the orifice plate.

Based on (Araújo and Link, 2004), tolerances about circularity errors found at measuring the orifice of an orifice plate are shown in table 2 bellow.

Tab. 2 – Circularity tolerance for the orifice of a plate (d_m).

Orifice diameter (in)	**Tolerance (± in)**
≤ 0,250 [a]	0,0003
0,251 a 0,375 [a]	0,0004
0,376 a 0,500 [a]	0,0005
0,501 a 0,625	0,0005
0,626 a 0,725	0,0005
0,726 a 0,875	0,0005
0,876 a 1,000	0,0005
> 1,000	0,0005 in/(in of diameter)

[a] The use of lower diameters is not prohibited, but measurement uncertainties would be bigger than the usual.

d) Entrance edge G

The edge G at the upstream should not show imperfections, burrs or visible peculiarities by rough estimate. It shall be sharp (Fig. 4). This will happen if the edge radius is not larger than 0.0004d.

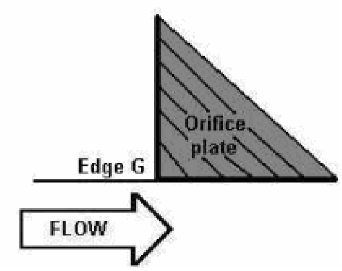

Figure 4 – Detail of the orifice edge G

e) Exits H and I

The edges H and I (Fig. 5) at the downstream are inside the region of exit of the flow. Therefore, the requirements for its quality are less rigorous than those for edge G; so, in this case, small defects are acceptable.

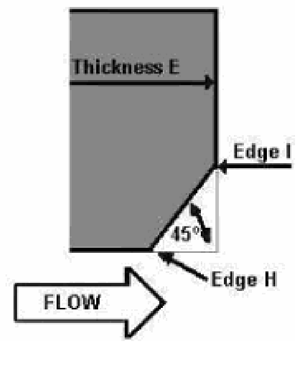

Figure 5 – Details of the edges H and I

f) *E* and *e* thicknesses

The plate thickness *E* should be kept among the orifice thickness *e* (see Figure 6) and 0.05D. A careful attention should be paid so that the plastic or elastic deformation of the plate, due to the differential of pressures in operation, does not exceed the flatness limit that is specified by norm (Delmée, 2003).

The orifice cylindrical part *e* must have thickness within D/200 and D/50. When by reason of robustness, plate thickness *E* is bigger than the orifice cylindrical part *e*. So the downstream face must receive a bevel of 45º (Delmée, 2003). See Fig. 6:

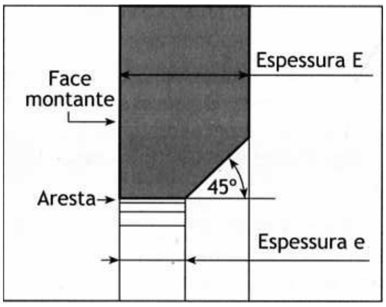

Figure 6 – Plate and orifice thicknesses

g) Verification of flatness

The verification of flatness can be performed in a practical way, with the aid of a straight scale of approximately equal length to the internal diameter of the pipe, at the temperature of 20 ºC (Araújo and Link, 2004), as it can be seen in Fig. 7.

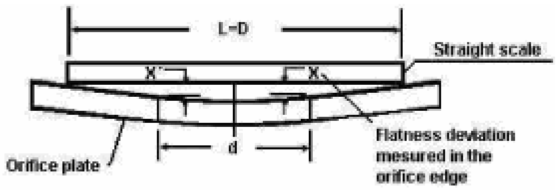

Figure 7 – Verification of flatness

The allowed maximum deviation in the flatness can be determined by 0.005(D-d), and also found by the equation specified below:

$$P = \frac{x + x'}{D}$$

h) Angle of bevel

When the plate thickness *E* is superior to the orifice thickness *e*, the plate will have to be beveled at the downstream edge (Fig. 8). The angle of bevel should range between 30 and 45º. And the plate could not be beveled if its thickness is inferior or equal to 0.02D.

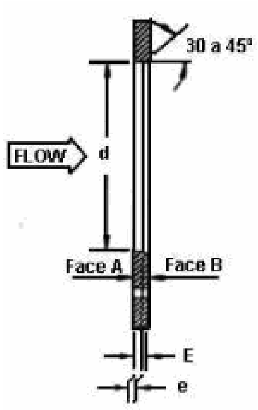

Figure 8 – Plate with bevel angle

3. METHODOLOGY

Initial proceeding consisted firstly of measurement and analysis of several parameters as circularity, flatness, orifice diameter, plate thickness, etc. These parameters are important for calibration of orifice plates which we receive in Laboratory of Metrology form UFRN (Fig. 9). The measurement is done through a Coordinate Measuring Machine (CMM) we have in the laboratory. Besides new orifice plates that recently arrived for calibration, used in this work, we also verified recent documents of orifice plate calibrations as data sources.

As it was seen on the beginning of this work it was done an "inspection" in orifice plates and an analysis of several parameters which involves this kind of flow meter. Then we could see that these parameters can influence directly or indirectly in flow rate measurement. Thereby, we can use these data to have wider notion as its uses in future essays and calculations.

Following, it was created a *spreadsheet program* in Microsoft Excel to be able to evaluate circularity error on the orifice plates which were measured for analysis (Fig. 10). In this spreadsheet are done suppositions about differential pressure, pipe diameter and fluid flow velocity. All these values fit this type of application. For the discharge coefficient calculations we used the equation from the norm ISO 5167.

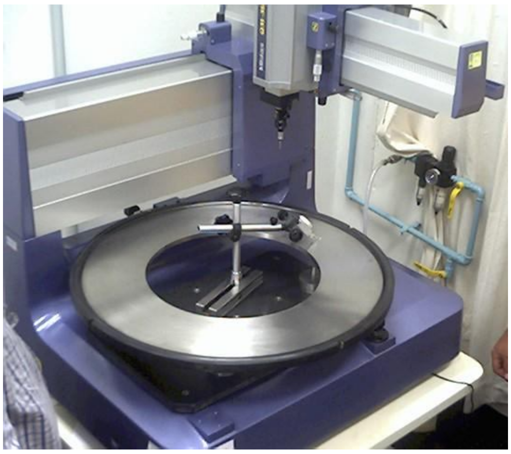

Figure 9 - Orifice plates' calibrations performed in the Laboratory of Metrology from UFRN.

Circularity Evaluation on Orifice Plates							
Data Input		Units		Analyzed Substance:	Water at 20ºC		
Pipe diameter (D):	0,7	m	*				
ΔP:	2,50E+04	Pa	*	Orifice plate calibrated in Laboratory of Metrology from UFRN			
Orifice diameter (d):	0,3767	m					
Density (ρ):	1000	kg/m^3		Customer 1	(mm)		
Reynold's Number (R_D):	3990000	-		Orifice diameter	376,702		
β = d/D:	0,5381429	-		Plate thickness	11,887		
E = $1/(\sqrt{(1-\beta^4)})$:	1,04477	-		Circularity Error	0,019	0,0000095	
Flow velocity (V):	5,7	m/s	*	Flatness Error	0,437		
"A" Parameter:	0,0084517	m^2		Roughness	0,59x10^{-3}		
Viscosity (μ):	0,001	Pa.s					
Discharge Coefficient (C):	0,6106203	**					
Volumetric flow rate (Q):	0,5027475	m^3/s		D'	0,3767095	β'	0,538156429
Flow rate':	0,5027729	m^3/s		d'	0,3766905	β''	0,538129286
Flow rate'':	0,5027221	m^3/s					
* Assigned considerations							
** According to the norm ISO 5167							
*** Corner taps						Error	
				Nominal	0,50274750	-	
A = $((19000\beta)/R_D)^{0,8}$				to D'	0,50277286	0,00152147	m^3/min
D' e d' = diameters due to the oval orifices				to d'	0,50272215	-0,00152144	m^3/min
			%	0,005043865	Estimation	0,00003837	l/min
			%	-0,005043738			
Student: João Batista de La Salles Junior							

Fig. 10 – Spreadsheet image

Other data come from performed measurements as circularity, flatness, orifice diameter, etc. These data are entered in the program indicating possible error estimations that probably could be being measured due to oval orifices (see Fig. 11).

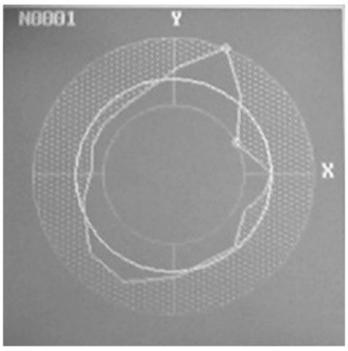

Fig. 11 – Circularity error on orifice plates

Thereby, we know that circularity error would be: D_{max} - d_{min} as it is seen above. In the spreadsheet it is calculated three values for volumetric flow rates by using Eq. (1) and different diameter ratios β. The first is considering the diameter ratio β as the nominal value of orifice plate which is being analyzed divided by the pipe diameter assigned previously. It means:

$$\beta = d/D$$

The second is considering the diameter ratio β as the nominal value of orifice plate which is being analyzed plus half the circularity error and after divided by the pipe diameter assigned. They were called D' and β':

$$\beta' = D'/D$$

The third value for volumetric flow rate we considered the diameter ratio β as the nominal value of orifice plate minus half the circularity error and after divided by the pipe diameter assigned. They were called d' and β'':

$\beta'' = d'/D$

Now we have three values of volumetric flow rates due to different diameter ratios. Calculating the difference between flow rate values found to β' and β" and the flow rate value when using β, we will be able to find two error estimations for the flow rate. Approximately, we can see that one error can compensate failures of the other. Thereby, it is also calculated the difference between these values obtaining a final error estimation which is shown in *l/min*. The calculations were made with values measured on two plates with different orifice diameters. For the first plate it was considered water and for the second plate ethylic alcohol 100% both at 20ºC.

4. RESULTS AND DISCUSSION

The performed measurements on orifices plates and the obtained results are shown by graphics bellow, as already explained on methodology:

a) **Plate 1** (Considered fluid: Water at 20ºC)

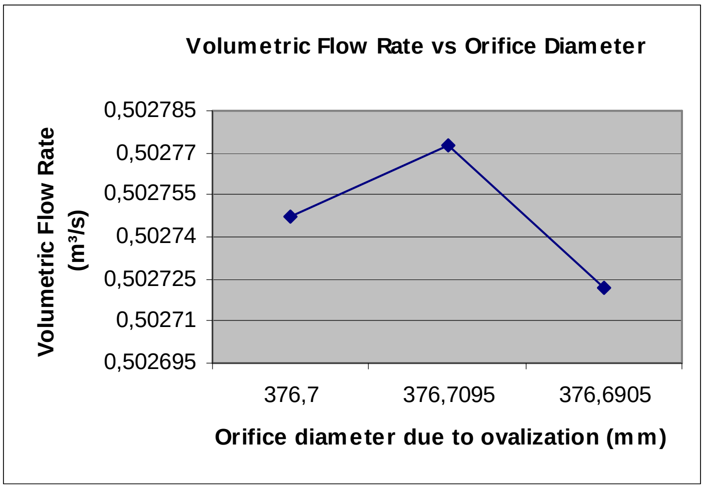

Figure 12 – Graphic: volumetric flow rate *vs* Orifice diameter (plate 1)

For this first plate we could find errors of ± 0,0050% to the volumetric flow rate when considering the ovalized diameter.

b) **Plate 2** (Considered fluid: Ethylic Alcohol at 20ºC)

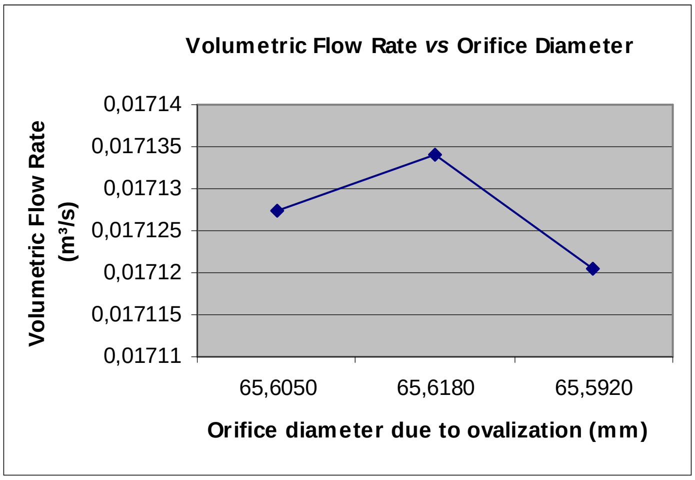

Figure 13 – Graphic: volumetric flow rate *vs* Orifice diameter (plate 2)

For the second one we found errors of ± 0,0396% to the volumetric flow rate value when considering the ovalized diameter.

Analyzing the obtained data we can see that value from flow rate measurement using orifice plates is affected by circularity errors. But it is tolerable when the plates are within limits of tolerances imposed by norms. As the measured plates are within important requirements as roughness, thickness, flatness, the data shown error estimation at about 0,0000807 l/min for plate 1 and 0,0000384 l/min for plate 2 (this last value can be seen on Figure 10). Thereby, they are little significant in a way that can not affect the result of a real measurement.

5. CONCLUSION

It is concluded that according to the analysis of results, values of flow measurement using orifice plates are affected by their circularity errors. However, this influence is negligible when it is perceived that the parameters from the analyzed orifice plates such as upstream roughness, plate thickness, circularity, flatness, among others, are within tolerance limits imposed by the norms. Based on (Link and Araújo, 2004) we see in table 3 circularity tolerances for orifice plates, and then we can notice that both plates are considered compliant. The same are also within the limits of upstream roughness (which should be up to 10^{-4}d) and thickness (should be found inferior to D/20 to tubes exceeding 3 inches). Thereby, we observe that these tolerances imposed by norms, which deal with flow meters such as the ISO 5167, must be strictly followed in order to have more accurate measurement. Any process of manufacture of these types of flow meters, which are extensively used in the oil industry, may be subject to some sort of problem happening during its execution. This can happen when this process is performed by people who are not able to do this type of work, or when those responsible do not follow exactly the related tolerances. Such situation may be leading to waste of liquids or gases and incorrect measurements.

6. ACKNOWLEDGEMENTS

CT-UFRN, Laboratório de Metrologia (UFRN)

7. REFERENCES

Fox, R.W. e McDonald, A.T.. “Introdução à Mecânica dos Fluidos”, 5ª Edição, Editora LTC, 2001.
Gerard, Jean Delmée. “Manual de Medição de Vazão”, 3ª edição, São Paulo: Edgard Blucher, 2003.
Agostinho, Oswaldo Luiz, 1943 – “Tolerâncias, ajustes, desvios e análise de dimensões”, por Oswaldo Luiz Agostinho, Antônio Carlos dos Santos Rodrigues [e] João Lirani. São Paulo, Edgar Blucher, Ed. da Universidade de São Paulo, 1977.
Frank, M. White. “Fluid Mechanics”, Fourth Edition. University of Rhode Island, Kingston. November 1998.
Husain, Zaki D.. Theoritical Uncertainty of Flow Meter Measurement, Houston, Texas, 1995.
Ibars, Rubén Alcides Franco. “Desenvolvimento e avaliação de tubos Venturi para medição de vazão”. Piracicaba-SP, 2004.
Schneider, Paulo. “Medição de velocidade e vazão em fluidos”. Porto Alegre-RS, 2003.
Azevedo, Luís Fernando A.. “Introdução à medição de vazão - Métodos experimentais para engenharia mecânica”. Rio de Janeiro – PUC-RJ. Ano desconhecido.
Araújo, L.P. de; Link, W.. “Inspeção de placas de orifício. Rede Cooperativa de Pesquisa Norte-Nordeste em Instrumentação e Controle”, REDIC, 2004.
França, Fernando A.. “Instrumentação e Medidas: grandezas mecânicas”. UNICAMP 2007.
Medeiros, A.K. de A.; Lima, J.F. de; Medeiros, G.G. de; Silva, N.F. Junior; Felipe, R.N.B; Felipe, R.C.T. dos S.. “Parameters for dimensional inspection of orifice plates and roughness of the straight stretches of the tubing”. Braz. arch. biol. technol. vol.49 spe Curitiba Jan. 2006.
ABNT - NBR 13225 –“ Medição de Vazão de Fluidos em Condutos Forcados Utilizando Placas de Orifício e Bocais em Configurações Especiais”.
ABNT NBR ISO 5167-1 – “Medidores de Vazão - Placas de Orifício, Venturis”.

8. RESPONSIBILITY NOTICE