DEVELOPMENT OF A TEST RIG FOR SONIC NOZZLES

Maria Luiza Moraes dos Santos
CETEC - Technological Center Foundation of Minas Gerais
Av. José Cândido da Silveira, 2000 - Cidade Nova
Belo Horizonte - Minas Gerais
maria.luiza.moraes@cetec.br

Geraldo Campolina França
Federal University of Minas Gerais
Departament of Mechanical Engineering
Av. Antônio Carlos, 6627 - Pampulha
Belo Horizonte - Minas Gerais
gacf@ufmg.br

Antônio Carlos de Andrade
Federal University of Minas Gerais
Departament of Mechanical Engineering
Av. Antônio Carlos, 6627 - Pampulha
Belo Horizonte - Minas Gerais
andrade@ufmg.br

***Abstract.**. The performance of a test rig for sonic nozzles using air as working fluid was evaluated. Throat diameters of 0,8mm, 1,1mm and 2,2mm were tested. The experimental work was accomplished for stagnation absolute pressures ranging from 0,32MPa to 0,70MPa at stagnation temperatures near to room values. For these operational conditions, the rig presented values of mass flow rate from 1,3kg/h to 32kg/h. The discharge coefficient of each meter was evaluated experimentally through a primary standard meter, the "bell prover", coupled to the rig exit. The sonic nozzles were connected to distribution and collection chambers in a parallel way. This work shows that rig calibration becomes unnecessary when the nozzles are previously calibrated. The methodology proposed, as well as the main results will be used for designing a rig with larger capacity (500kg/h), which could become a link in the traceability chain in the country for gas flow measurements close to atmospheric pressure values.*

***Keywords**: sonic nozzles, flow measurement, test rig.*

1. Introduction

Primary calibration systems, in spite of their accurate measurements of gas flow, lose in flexibility and are onerous. The complexity of the operational procedures, the sophisticated instrumentation and the long time requested in the accomplishment of the reference data in a primary calibration system results in high infrastructure and operational costs. Since there is some reduction in the accuracy of the measurement each time that a calibration is transferred to a secondary standard, the ideal secondary standard would be that which presents the best commitment between operational flexibility and minimum reduction in the transfer of the calibration primary standard. Arnberg et al (1973) consider that the sonic nozzle approaches this ideal more than any other meter.

The sonic nozzle can transfer, by a practical and safe way, the accuracy of the inflexible and expensive primary calibration methods of gas flow measurements. A sonic nozzle with an relative standard uncertainty as low as 0,095% can provide measurements with an standard uncertainty relative to the discharge coefficient of approximately 0,105% (Wright & Mattingly, 1998). In addition to represent an excellent value in the metrology field of gas flow measurement, this gathers all their operational advantages.

Recent analytical studies carried out at the National Research Laboratory of Metrology of Japan, NRLM, reported that multidimensional effects contribute with only 0,1% for the value of Cd, which is, practically, dependent on the boundary layer (Ishibashi & Takamoto, 2000). For Reynolds numbers in the throat, Red, above 1,7 x 10^5, the discharge coefficient obtained with the nozzles in this work, with throat diameters varying from 1 to 2mm, was found to be larger than 0,99.

With an uncertainty resulting from its repeatability of approximately 0,05% (Paik et al, 2000), the sonic nozzle requests a short time for adjustment and it possesses an excellent stability within its discharge coefficient, presenting an average time variation of only +0.003% (Wright, 1998). Before these advantageous characteristics, the meter sonic nozzle has been increasingly used at the National Metrology Institutes - NMI as a secondary standard in order to improve the traceability chain of the flow pattern measurement among the metrology laboratories in their countries, and also as a transfer standard for its international counterparts. Being a secondary pattern, its usage as a gas flow meter is, therefore, quite advantageous. The industrial gas distributors and users may employ it as a work standard, either as meter and flow controller, or as pressure insulator.

A worldwide trend is observed in the use of calibration systems integrating sonic nozzles rigs and primary calibration standards. NMI's of several countries already adopt this device, such as the National Engineering Laboratory-NEL, Scotland, National Research Laboratory of Metrology-NRLM, Japan, Physikalisch Technische Bundesanstalt-PTB, Germany and Korea Research Institute of Standard and Science-KRISS.

The consolidation and definitive international acceptance of the gas sonic nozzle flowmeter came in 1990 with the publication by ISO - International Organization Standardization, of the 9300 standard (ISO 9300, 1990). This standard specifies the geometry, methods and the theoretical equation of sonic nozzles for measurement of gas mass flow. Corroborating the importance of this meter, in scientific events, such as FLOMEKO(5,8,9,12,13,14,15), IMEKO(3), FLUKOME, the subject gas flow measurement using sonic nozzle meters was made invariably present. In the year 2000, the December edition of the magazine Flow Measurement and Instrumentation was exclusively dedicated to the publication of works concerned with sonic nozzle meters.

More recently, several research works have been focused on the study of small meters with throat diameters inferior to 2 mm. The influence of the boundary layer in smaller meters is accentuated, due to the smallest throat Reynolds number, *Red*. The standard ISO 9300 is limited to Reynolds number in the throat, Re_d, above 10^5. Numerical studies associated to experimental work have demonstrated that flows with $\mathrm{Re_d}$ smaller than the limit established by the ISO 9300 standard present periods of instability of the critical condition, thus resulting in intermittent decreasing of the mass flow. However, this instability occurs at high frequency and lasts for miliseconds, not being perceptible macroscopically and, therefore, not affecting the use of this meter as reference in the measurement of gas flow, even for smaller mass flow values (Dietrich et al, 2000).

Another trend observed in recent published works is the use of combined sonic nozzles forming a rig of meters. The importance of this technique stands out for the fact that the primary patterns used in the calibration of gas flow are, in many cases, limited to maximum flow varying from 60 to 400 m^3/h. Using this approach becomes possible to enlarge the range of laboratory measurements with uncertainty levels closer to that obtained with primary patterns. The combined use of sonic nozzles is not mentioned in ISO 9300 standard.

Several experimental studies are being carried out at the National Metrology Institutes in order to provide reliable data for the accomplishment of a revision of ISO 9300 standard, owing to the importance that the sonic nozzle have acquired.

The principal aim of this work is to analyze flow measurement in small individual sonic nozzles, and when used in an integrated way, composing a rig of sonic nozzles.

2. Formulation

The mass flow equation in a sonic nozzle, under real conditions and in terms of the throat diameter, is:

$$\dot{m} = Cd\,\frac{\pi d^2}{4}C^*\frac{P_0}{\sqrt{RT_0}} \tag{1}$$

The expression for the discharge coefficient of the sonic nozzle, in calibration processes is derived of Eq. (1) is:

$$Cd = \frac{4\dot{m}_{padrão}\sqrt{RT_0}}{\pi d^2 P_0 C^*} \tag{2}$$

where $\dot{m}_{padrão}$ is the mass flow in the critical condition, measured by the pattern, for the conditions of P_0 and T_0.

The Reynolds number in the throat of the sonic nozzle, under critical condition is defined by ISO 9300 as:

$$Re_{d\,iso} = \frac{\rho^* V^* d}{\mu_0} = \frac{4\dot{m}}{\pi d \mu_0} \tag{3}$$

The critical flow function (to air), C *, for the established stagnation conditions was determined in all experiments using the polynomial expression

$$C^* = \sum_i n_i (P_0/P_c)^{p_i}(T_0/T_c)^{t_i} \tag{4}$$

where: Pc = 3,786 MPa, Tc = 132,5306 K. The coefficients n_i, p_i and t_i are provided, for i varying from 1 to 14. Equation (4) was obtained from the National Metrology Laboratory of Scotland-NEL, being considered by their authors the most exact for the determination of C * (Steward et al, 1999).

For hypothesis: T_0, Cd, C * were considered approximately constant for the 3 sonic nozzles, for the same stagnation pressure. In this case, the relation between mass flows of the 3 sonic nozzles should be the same and proportional to the sum of the square of the respective throat diameters, d, of each nozzle meter, i.e.,

$$\dot{m} = \left[\frac{Cd\, \pi\, C^* P_0}{4\sqrt{R}\sqrt{T_0}} \right] d^2 \tag{5}$$

in which the term between brackets can be considered constant for the 3 sonic nozzles, for the same stagnation condition. Taking this into account, the discharge coefficient of the sonic nozzle rig was calculated for different pressure conditions and stagnation temperature, P_0 and T_0, established by the expression below,

$$Cd = \frac{4\dot{m}\sqrt{(\Re / M)T_0}}{\pi P_0 C^* [(d^2)_{Bs0,8} + (d^2)_{Bs1,1} + (d^2)_{Bs2,2}]} \tag{6}$$

3. Methods

3.1. Experimental Data Treatment

The discharge coefficient of each one of the 3 sonic nozzles was calculated for different pressure conditions and stagnation temperature (P_0 *and* T_0) established in the experiments by the expression:

$$Cd = \frac{4\dot{m}\sqrt{(\Re / M)T_0}}{\pi d^2 P_0 C^*} \tag{7}$$

The term in Eq. (8) is the experimental critical mass flow that crosses the meter, obtained with the pattern "bell prover" thus $\dot{m}_{banco} = \dot{m}_{bell}$. The mass flow was obtained in the "bell prover" multiplying the volumetric flow measured by the specific mass, specified in the medium conditions of temperature and pressure of the measurement in the "bell" and calculated using the ideal gases equation corrected for the real conditions by the compressibility factor, Z.

The absolute pressure, P_{bell}, and the temperature, T_{bell}, were measured directly. The compressibility factor, Z_{bell}, was calculated in function of P_{bell} and T_{bell}. The molar mass of the air flow, M, was constant and calculated considering its humidity.

The mass flow of the nozzles rig corresponds to the sum of the mass flow of the 3 sonic nozzles, under the condition of critical flow, i.e.:

$$\dot{m}_{banco} = \dot{m}_{Bs0,8} + \dot{m}_{Bs1,1} + \dot{m}_{Bs2,2} \tag{8}$$

Considering the critical condition for each sonic nozzle the mass flow can be obtained from Eq. (13),

$$\dot{m} = Cd\, A^* C^* \frac{P_0}{\sqrt{RT_0}}\,, \tag{9}$$

the mass flow in the sonic nozzles rig under critical condition can be obtained from the expression:

$$[\dot{m}]_{banco} = \left[Cd \frac{\pi d^2}{4} \right]_{Bs0,8} \frac{C^* P_0}{\sqrt{RT_0}} + \left[Cd \frac{\pi d^2}{4} \right]_{Bs1,1} \frac{C^* P_0}{\sqrt{RT_0}} + \left[Cd \frac{\pi d^2}{4} \right]_{Bs2,2} \frac{C^* P_0}{\sqrt{RT_0}} \tag{10}$$

which, when simplified, results in

$$[\dot{m}]_{banco} = \left[(Cd\,d^2)_{Bs0,8} + (Cd\,d^2)_{Bs1,1} + (Cd\,d^2)_{Bs2,2}\right] \frac{\pi C^* P_0}{4\sqrt{RT_0}} \tag{11}$$

3.2. Uncertainty Analysis

The uncertainty associated with R, C * and d can be neglected in determination of the discharge coefficient uncertainty, if the same sonic nozzle and fluid are used (Wright & Mattingly, 1998).

The uncertainty in the value of the discharge coefficient was calculated for each group of 5 consecutive measurements, for each established stagnation pressure.

Equation (16) presents the expanded relative uncertainty of the discharge coefficient, U_{Cd}, under the experimental conditions used in this work

$$U_{Cd} = ku_{Cd} = k\sqrt{(u_{\dot{m}})^2 + (u_{P_o})^2 + (0,5u_{T_0})^2 + (u_R)^2} \tag{12}$$

where:
k is the abrangency factor
U_{Cd} is the combined uncertainty pattern of the Cd
$u_{\dot{m}}$ is the relative uncertainty pattern in the medium value of the mass flow for the pattern "bell prover"
u_P is the relative uncertainty pattern in the measured stagnation pressure medium value
u_T is the relative uncertainty pattern in the measured stagnation temperature medium value
u_R is the repeatability of the sonic nozzle under test

4. Materials

4.1. Sonic Nozzles

The three sonic nozzles present toroidal profile and throat diameters of approximately 0,8 mm, 1,1mm and 2,2 mm, manufactured in stainless steel by the American Company Cox Instrument.

Fig.1 shows a picture of two meters. Externally, they are similar (55,6 mm long and 33 mm wide), and as it can be observed in the illustration, they resemble each other to a nipple. The screw is the special connection AN-16.

The meters possess the following common geometric characteristics:
-angle of the divergent section with a tangency point to the toroidal surface equal to 5°;
-diameter of the nozzle entrance equal to 3d (throat diameter).

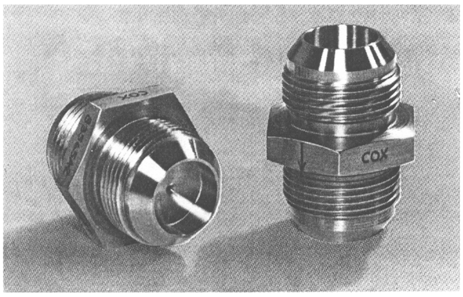

Figure 1 - Picture of sonic nozzles of COX Instrument - SOURCE - the manufacturer's catalog

4.2. Sonic nozzle rig

Prior to the construction of the rig the following basic premises were observed:
-Assembly and disassembly of one to three sonic nozzles in parallel.
- Variation and fine manual adjustment of the upstream pressure by valves.
-Reference flow accomplished by a primary standard meter.
-Evaluation of mass flow through a single sonic nozzle or up to three sonic nozzles in parallel.
-Direct measurement of the pressure and stagnation temperature upstream of the sonic nozzles.

-Variation and adjustment of the downstream pressure.

The final configuration is shown in Fig.2

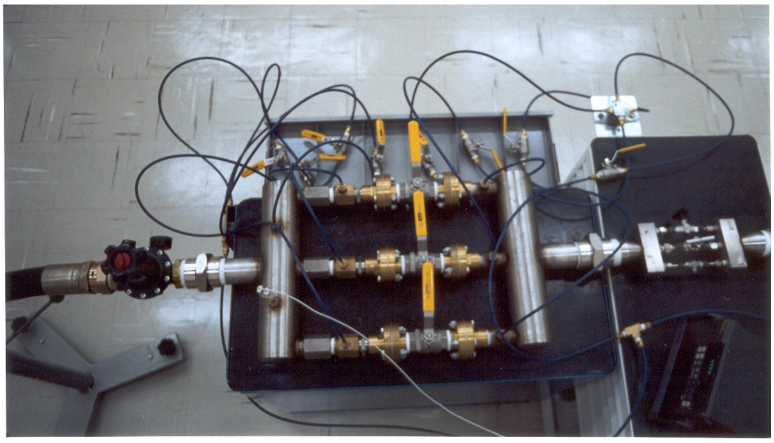

Figure 2. Sonic nozzles rig installed in the test circuit with pressure and temperature sensors.

4.3 Rig calibration

In the experimental analysis of the combined operation using the 3 sonic nozzles, the same operational procedure was adopted in the individual analysis of each one. The experimental results presented in this section refer to the average value of 5 consecutive measurements, for a determined mass flow value, established by the chosen upstream stagnation pressure. Six stagnation conditions were selected close to those established during the calibration of the individual sonic nozzles.

4.4. Mass flow in the critical condition

The discharge coefficient and the critical flow function, C *, were obtained from sonic nozzles rig under distinct stagnation conditions. It is observed that, for the same stagnation pressure, the values of C * obtained from the rig approached those obtained for each one of the sonic nozzles and the *Cd* values were among those obtained for the nozzle Bs1,1 and the nozzle Bs2,2.

5. Results

The spreadsheet for calibration of the experiments is shown in Tables 1 to 4.

TABLE 1. Spreadsheet of the Calibration Results
Relative standard uncertainty
Sonic nozzle Bs0,8 - confidence level ≅95%

P_0 (kPa)	T_0 (K)	C *	$\dot{m}$ (kg/h)	Red	Cd	Uncertainty (%)
320 816	295,500	0,68575	1,325	32 352	0,9847	0,33
400 721	295,922	0,68596	1,656	40 389	0,9857	0,30
450 575	294,947	0,68612	1,868	45 658	0,9861	0,34
500 813	295,741	0,68625	2,076	50 619	0,9865	0,29
600 785	295,260	0,68654	2,497	60 942	0,9872	0,29
700 817	297,911	0,68676	2,906	70 397	0,9878	0,31

TABLE 2. Spreadsheet of the Calibration Results
Relative standard uncertainty
Sonic nozzle Bs1,1 - confidence level≅ 95%

P_0 (kPa)	T_0 (K)	C *	$\dot{m}$ (kg/h)	Red	Cd	Uncertainty (%)
320 845	296,073	0,68574	2,629	45 523	0,9862	0,29
400 625	296,117	0,68596	3,289	56 920	0,9870	0,36
450 765	296,901	0,68609	3,700	63 875	0,9873	0,30
500 490	296,573	0,68623	4,111	71 058	0,9878	0,32
600 668	294,624	0,68655	4,965	86 168	0,9884	0,30
700 677	294,946	0,68683	5,794	100 461	0,9887	0,29

TABLE 3. Spreadsheet of the Calibration Results
Uncertainty pattern relative
Sonic nozzle Bs2,2 - confidence level=95%

P_0 (kPa)	T_0 (K)	C *	$\dot{m}$ (kg/h)	Red	Cd	Uncertainty (%)
320 865	294,923	0,68575	10,760	92 570	0,9885	0,29
400 651	295,422	0,68597	13,439	115 458	0,9891	0,30
450 536	294,992	0,68612	15,126	130 120	0,9894	0,29
500 574	294,817	0,68627	16,829	144 789	0,9896	0,29
600 530	295,277	0,68654	20,192	173 507	0,9901	0,30
700 350	296,663	0,68679	23,480	201149	0,9903	0,29

TABLE 4. Spreadsheet of the Calibration Results
Relative standard uncertainty
Sonic Nozzles Rig - confidence level=95%

P_0 (kPa)	T_0 (K)	C *	$\dot{m}$ (kg/h)	Cd	Uncertainty (%)
320 714	296,29	0,68573	14,670	0,9871	0,30
400 515	296,63	0,68595	18,337	0,9880	0,30
450 641	294,78	0,68612	20,691	0,9875	0,30
500 555	296,60	0,68623	22,949	0,9886	0,30
600 533	296,71	0,68651	27,560	0,9889	0,30
700 459	296,85	0,68678	32,157	0,9898	0,30

A comparison between the values of critical condition mass flow measured directly using the pattern "bell prover" and the values obtained from the calibrated discharge coefficients of the sonic nozzles is presented in the Table 5. The deviation in the results varies from (- 0,003)%, for a stagnation pressure of 700.459Pa , to (+ 0,121)%, for a stagnation pressure of 450.641Pa.

The maximum cited deviation, (+ 0,121)%, is smaller than the expanded relative uncertainty, which was 0,31%, obtained from the average of the individual sonic nozzles discharge coefficients. Considering this, the obtained results demonstrated the efficiency and the viability of the measurement of air flow using sonic nozzle meters in parallel arrangement composing a rig.

TABLE 5. Measurement of the actual critical flow: (rig) X (calibrated sonic nozzles)

Absolute Stagnation Pressure P_0 (kPa)	Stagnation Temperature T (K)	Nozzle Meter	Discharge Coefficient Cd	Actual Mass Flow (kg/h)
320 714	296,29	Bs0,8	0,9847	1,323
		Bs1,1	0,9862	2,627
		Bs2,2	0,9885	10,730
		Total		14,680
		Bell Prover		14,670
400 515	296,63	Bs0,8	0,9857	1,653
		Bs1,1	0,9870	3,285
		Bs2,2	0,9891	13,407
		Total		18,345
		Bell Prover		18,337
450 641	294,78	Bs0,8	0,9861	1,869
		Bs1,1	0,9873	3,712
		Bs2,2	0,9894	15,135
		Total		20,716
		Bell Prover		20,691
500 555	296,60	Bs0,8	0,9865	2,072
		Bs1,1	0,9878	4,112
		Bs2,2	0,9896	16,777
		Total		22,960
		Bell Prover		22,949
600 533	296,71	Bs0,8	0,9872	2,490
		Bs1,1	0,9884	4,946
		Bs2,2	0,9901	20,142
		Total		27,578
		Bell Prover		27,560
700 459	296,85	Bs0,8	0,9878	2,910
		Bs1,1	0,9887	5,772
		Bs2,2	0,9903	23,474
		Total		32,156
		Bell Prover		32,157

6. Conclusions

The theoretical and experimental analysis of the performance of a sonic nozzles rig designed and built in this work, allow to following conclusions:

- The use of a upstream chamber and three downstream valves was shown effective in the distribution of the flow for one or more meters. The chamber also constitute a reservoir for direct measurement of pressure and temperature stagnation values.
- The total rig flow operating with the three sonic nozzles together was measured in the "bell prover" pattern. The total theoretical flow was also obtained using a combination of the discharge coefficients from each meter. The deviation among the two results was inferior to the uncertainties associated to the direct flow measurements.
- The sonic nozzles rig constitutes a reliable gas flow meter and it can be employed as a secondary pattern with small reduction in the accuracy relative to the primary calibration system used in the determination of individual discharge coefficients nozzle meters.
- The nozzles rig, compared to primary patterns, presents lower cost, higher measurement capacity, in addition to provide a simpler and fast calibration.

7. Acknowledgements

Authors would like to thank the Gas Flow Measurement Laboratory - CETEC for the provision of technical support and Mr. Ramon Zeferino for the valuable assistance during the whole work, especially in the experimental investigation.

8. References

1. ARNBERG, B. T.; BRITTON, C. L.; SEIDL, W. F. *Discharge coefficient correlations for circular-arc Venturi flowmeters at critical (sonic) flow*. Journal of Fluids Engineering, Transactions of the ASME, ASME Paper N 73 - WA/FM-8, New York, 1973.
2. DIETRICH, H. et al. *Flow meter calibration with sonic nozzles in high-pressure natural gas*. In: THE 10^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT. FLOMEKO'2000, Salvador.
3. DIETRICH, H. et al. *High-accuracy test rig for gas flows from 0.01* m^3/h *up to 25000* m^3/h*.* In: INTERNATIONAL CONFERENCE IMEKO'99. Osaka, 1999. p. 13-18.
4. ISO 9300. INTERNATIONAL ORGANIZATION OF STANDARDIZATION: *measurement of gas flow by means of critical flow Venturi nozzles*. Geneva, 1990. 66 p.
5. ISHIBASHI, M. et al. *Precise calibration of critical nozzles of various shapes at the Reynolds number of* $0.8\text{-}2.5 \times 10^5$. In: FLOW MEASUREMENT IN THE MID 90'S. THE 7^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT. "FLOMEKO'94". 1994, Glasgow.
6. ISHIBASHI, M.; TAKAMOTO, M. *Theoretical discharge coefficient of a critical circular-arc nozzle with laminar boundary layer and its verification by measurements using super-accurate nozzles*. Flow Measurement and Instrumentation, v. 11, p. 305-313, Dec. 2000.
7. PAIK, J. S.; PARK, K. A. ; PARK, J. T. *Inter-laboratory comparison of sonic nozzles at KRISS*. Flow Measurement and Instrumentation, v. 11, p. 339-344, Dec. 2000.
8. PARK, K. A. et al. *Characteristics of small sonic nozzles*. In: The 10th International Conference on Flow Measurement. In: THE 10^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT FLOMEKO, 2000, Salvador.
9. SCHLEY, P. et al. *Simulation of critical nozzle flow considering real gas effects*. In: THE 10^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT. FLOMEKO'2000, Salvador. Proceedings.
10. STEWART, D. G. .; WATSON, J. T.; VAIDYA, A. M. *Improved critical flow factors and representative equations for four calibration gases*. Flow Measurement and Instrumentation. v.10, p. 27-34, 1999.
11. VALLET, J. P.; WINDENBERGER, C. *Thermodynamic calculations used for the flow rate of sonic nozzles*. In: THE 10^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT. FLOMEKO'2000, Salvador.
12. von LAVANTE, E. et al. *Effects of various geometric parameters on flow behavior in sonic nozzles*. In: THE 10^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT. FLOMEKO'2000, Salvador.
13. von LAVANTE, E.; ISHIBASHI, M.; WENDT, G. *Investigation of flowfields in small sonic Venturi-nozzles*. In: THE 10^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT. FLOMEKO'2000, Salvador.
14. WENDT, G.; von LAVANTE, E. *Influence of surface roughness on the flowrate behavior of small critical venturi nozzles*. In: THE 10^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT. FLOMEKO'2000, Salvador.
15. WINDENBERGER, J. P. V. C. et al. *Improvement of thermodynamic calculations used for the flow rate of sonic nozzles*. In: THE 10^{TH} INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT. FLOMEKO'2000, Salvador.
16. WRIGHT, J. D. *The long term calibration stability of critical flow nozzles and laminar flowmeters*. In: NCSL WORKSHOP & SYMPOSIUM. 1998, Albuquerque,p. 443-462.
17. WRIGHT, J. D.; MATTINGLY, G. E. *NIST measurement services: NIST calibration services for gas flow meters. Piston Prover and Bell Prover gas flow facilities*. NIST Special Publication 250-49, Washington, 1998.

9. Responsibility notice