IMPROVEMENT OF THERMODYNAMIC CALCULATIONS USED FOR THE FLOW RATE OF SONIC NOZZLES

Authors :

J.P. Vallet, C. Windenberger
CESAME LNE Ouest, France

F. Vulovic
Gaz de France / Research and Development Division, France

R. Bouard
UMR CNRS 6609, Université de Poitiers, France

ABSTRACT

Nozzles operating under sonic conditions are already used widely as reference flowmeters in many countries to measure gas flow rate under pressure. These Nozzles are calibrated, in each of the countries concerned, on approved primary test rigs. The techniques used in these countries today are the fruit of R&D carried out on nozzles for more than twenty years. The outcome has been standard ISO 9300, published in 1990, on the technique for measuring gas flowrates using a sonic nozzle.

In the past years, it was decided to revise the ISO 9300 in order to improve the values of the thermodynamic coefficients used to calculate the mass flow rate through the sonic nozzles.

The paper describes the results of the comparison on the thermodynamic calculations used by the participants to establish the critical mass flow rate through a sonic nozzle. It was initially conducted in line with the activities of EUROMET, a grouping of European flow metering laboratories which were subsequently joined by NOVA, CEESI, and NIST.

The comparison was more specifically made between the methods used by those laboratories to calculate the critical flow function C*. The calculation methods considered were the ISO 9300 standardized equations for dry air and natural gaz, the different versions of the AGA8 method, as well as several other methods developed by the laboratories, some of them based on the free energy equations.

The 1992 version of the AGA8 calculation method appreciably improves the calculation uncertainty of the critical flow coefficient C* for natural gas. The most recent thermodynamic values obtained for dry air using the NEL / Panasati method is more reliable than the method developed on the basis of the Johnson data (basis in ISO 9300 for air).

From this study, the most accurate calculation methods are selected in order to re calculate the results obtained from sonic nozzle international intercomparisons and thus to improve significantly the accuracy of the experimental discharge coefficient equation obtained from all calibration results.

All these results will be used for the revision of ISO 9300.

1 INTRODUCTION

The sonic venturi nozzles are widely used as references and transfer standards in gas flow measurement in a number of European countries (U.K., Germany, France, Norway). This technique is also in use in Japan (NRLM) and in North America (NIST, CEESI, SWRI, NOVA).

Easy traceable to mass and time, the sonic venturi nozzle is one of the most accurate device to achieve gas flowrate standards, both for high and / or low pressure. In addition its physical concept based on the product of the sound velocity at the throat (universal constant) by the cross throat section (dimensional size) is near of the definition of a flow standard.

With no moving parts the sonic nozzles are not affected by flow disturbances. They are reliable, static an robust devices very stable and repeatable during the time.

For more than twenty years a number of research programmes about the metrology and the use of sonic nozzles have been carried out in the major NMI's and Gas Companies around the world.

The main results about this work has been the achievement of ISO / DIS 9300 standard – 1990 [1] and AGA n° 8 (1986-1992) reports [2]. Some research programmes are still under way and are mainly focussed on the improvent of the design (type and quality of curvature of the convergent) and the development of new equations of state improving the calculations of the critical fow coefficient C*. [2] [8] [9] [11] [13].

A more recent and larger intercomparison carried out between 1995 and 1999 both in western Europe and in North America has shown the influence of the different thermodynamic calculations employed [3].

The aim of this paper is to present which method appreciably improves the calculation uncertainty of the critical flow function for different type of gases.

2 PRESENTATION OF THE INTERCOMPARISON

This intercomparison was carried out between 1995 and 1999, first in the EUROMET frame project n°307 [3]. Then after North America (NOVA – CEESI – NIST) joined the programme (see figure 1).

The transfer standard used was a venturi cylindrical throat nozzle manufactured according to ISO 9300 standard requirements [1].

The diameter of the throat was equal to 12.3 mm allowing to generate a flowrate close to 100 m^3 per hour and per bar under pressure ranging from 1 to 60 bar.

The participants (see figure 1) calibrated the nozzle according to their own operation procedure and calculation method.

Name of the Laboratory	Type of Calibration	Type of gas	Calculation method, C*
CEESI, USA	A and B	Air	ISO 9300
Exa Débit (CESAME LNE Ouest), France	B	Air	ISO 9300
Force Institutes, Denmark	B	Air	ISO 9300
Gaz de France, France	A	NG	ISO 9300
K-Lab, Statoil, Norway	A	NG	AGA 8
NEL, Great Britain	A	Air	ISO 9300
NMI, Netherlands	B	NG	ISO 9300
NOVA, Canada	A	NG	AGA 8
PTB, Braunschweig, Germany	A	Air	Own method
Swiss Federal Office, Switzerland	B	Air	ISO 9300
NIST, USA	A	Air	ISO 9300

A : Primary method   B : Comparison method   NG : natural gas

Figure 1 :   List of paricipants in the flow intercomparisons using a sonic nozzle with type of calibration, type of fluid, and calculation methods used by participants.
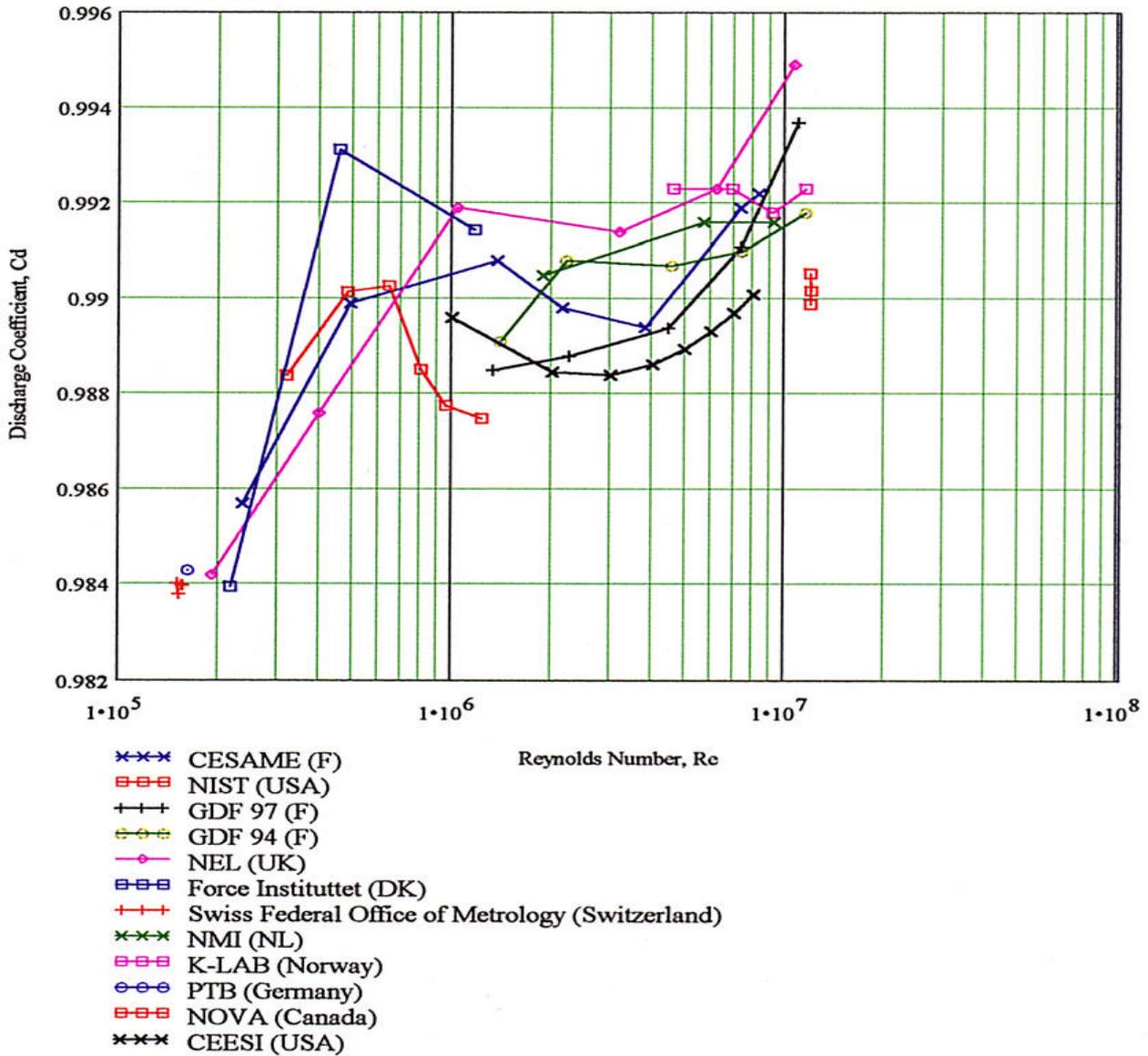
The chart legend:
- CESAME (F)
- NIST (USA)
- GDF 97 (F)
- GDF 94 (F)
- NEL (UK)
- Force Instituttet (DK)
- Swiss Federal Office of Metrology (Switzerland)
- NMI (NL)
- K-LAB (Norway)
- PTB (Germany)
- NOVA (Canada)
- CEESI (USA)

Figure 2 : Results of the intercomparison using a sonic nozzle TF 100E in which the laboratories used their own operating procedure and calculation methods.

Some of them used a primary method (PVT, t or mass-time), the others used a comparison method with their own reference flowrate standard. Depending on the laboratories the fluid employed was air or natural gas.

The results found (see figure 2), covering a very large Reynolds number range, were very consistant and complementary despite differences in operating and calculating procedures, type of fluid used and covered ranges (low and / or high pressure tests).

The deviation observed between the different participants remained within the uncertainty channel of each laboratory which was near by 0.2% depending on the operating method used.

These raw results confirmed clearly the very good transfer standard ability of sonic nozzles allowing to link results obtained under low and high pressure with different natures of fluid. The contribution and the complementarity of each laboratory was also essential to ensure the quality of the transfer standard.

The project is still under way, planed to join by Japan (NRLM) and open to any other country for enrichying the data base.

3 THE INFLUENCE OF DIFFERENT METHODS OF CRITICAL FOW FUNCTION CALCULATION (C*)

The mass flowrate passing through a nozzle functioning at a critical regime is only function of the upstream condition of the flow. As a result the accuracy on the mass flow depends only on the measurement uncertainties of the sensors (pressure – temperature – density) associated with the nozzle and on the sensitivity of method used for the calculation of the critical fow function C*.

The characteristic equation of critical sonic nozzles can be summarized as follows.

$$Q_m = A.C_D.C*.\frac{P}{\sqrt{r.T}} \qquad \text{or} \qquad Q_m = A.C_D.C_r.\sqrt{r.P}$$

with $$C_r = C*.\sqrt{Z}$$

Where

Q_m	:	massflowrate (kg/s)
C_D	:	discharge coefficient (dimensionless)
C*	:	critical flow function
r	:	ratio of gas constant to molecular wheight (J/kg K)
C_r	:	Real gas critical flow coefficient
Z	:	Compressibility factor
A	:	Cross section of the throat (m^2)
P	:	upstream pressure (Pa)
T	:	upstream temperature (K)
ρ	:	density (kg/m3)

Depending on the laboratories and the type of fluid used (see figure 1) several methods of C* or C_r calculation have been used (ISO 9300 – Johnson method [1] [4], AGA n°8 - 86 or 92 method [2], Jacobsen method [8] NEL – Panasati method [9], own laboratory method).

Eleven different laboratories from nine different countries calibrated the nozzle. Consequently the data base contains results obtained with different fluids, with different C* calculation with different levels of pressure (1 to 60 bar).

From this important data base it was also interesting to compare and analyse the effects of the different methods used for the C*, or C_r calculation.

This is why a new Euromet project n°470 [15] has been launched.

This project consisted in identifying the deviations in the calculation methods used by the participating laboratories to calibrate the sonic nozzle, and more specifically the values of the thermodynamic critical flow function C* or real gaz critical flow coefficient C_r.

The objective of the comparison was two fold : First of all, its purpose was to compare the calculation methods found in the different bibliographical references. It was further aimed in

comparing for the same reference the libraries of programms for computing the thermodynamic quantities as well as the iterative programms for computing critical quantities used by the participating laboratories.

Previous results [16] showed clearly the influence of the different methods of calculation if using ISO 9300 – Johnson or Nel / Panasati or Jacobsen or AGA n°8 1986 or 1992 methods. From these results it was decided to complete only the comparison between ISO 9300 and AGA n°8 – 1992 methods for natural gas and between Nel / Panasati and ISO 9300 methods for air.

3.1 Comparison of results between AGA n°8 and ISO 9300 – 1992 method for natural gas

The comparisons were made for four compositions of natural gas which are given in figure 3.

Composition	Gas A	Gas B	Gas C	Gas D
C1 (methane)	82.916	93.301	88.360	94.330
C2 (ethane)	13.665	3.585	8.550	1.250
C3 (propane)	1.052	0.567	2.040	0.320
iC4 (iso-butane)	0.044	0.327	0.360	0.060
nC4 (normal butane)	0.066	0.073	0.010	0.010
iC5 (iso-pentane)	0.004	0.055	0.000	0.010
nC5 (normal pentane)	0.004	0.019	0.000	0.000
C6 (hexane)	0.002	0.052	0.000	0.000
C7+ (heptane +)	0.003	0.073	0.000	0.010
N2 (nitrogen)	1.242	1.637	0.680	3.640
CO2	1.002	0.311	0.000	0.370

Figure 3 : Compositions of four standard gases used to compare calculation methods.

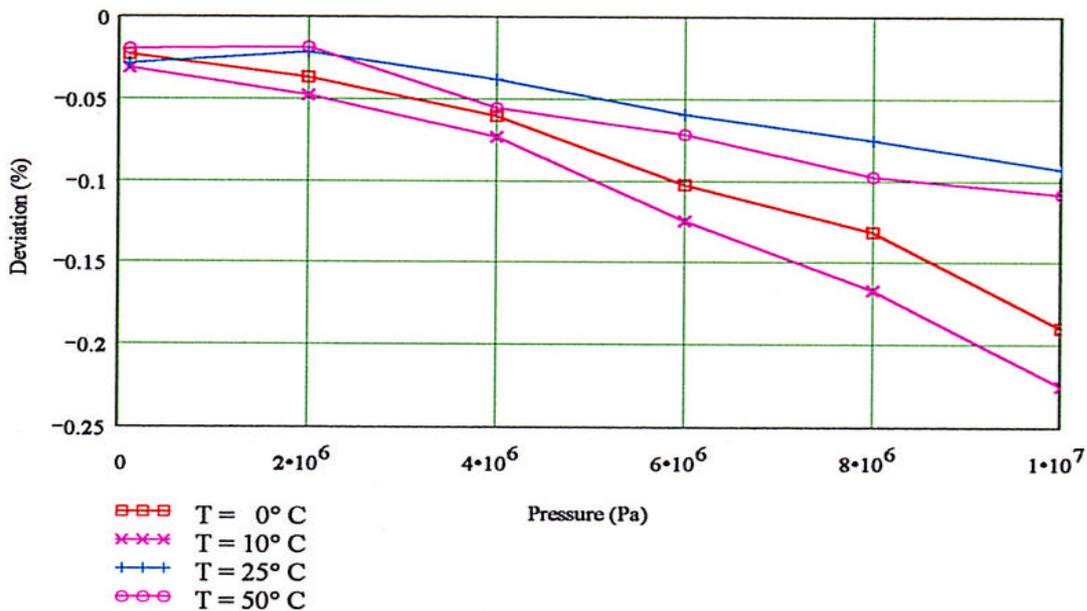|	
⊟⊟⊟	T = 0° C
✕✕✕	T = 10° C
＋＋＋	T = 25° C
⊝⊝⊝	T = 50° C

Figure 4 : Deviations in results for C_r between AGA n°8 – 1992 method and ISO 9300 method

The results found at different temperatures between 0 and 50°C are given in figure 4.

They show the deviations between the value of real gas critical flow coefficient C_r found by the laboratories using the AGA n° 8 - 1992 method and the same value found by applying the ISO 9300 standard method.

They decrease with pressure, showing significant deviations around 0.2%, at 40 bar for example. This deviation becomes lower when the temperature of the gas rises. The results found for the other gas compositions followed the same pattern by roughly ±0.03%.

Taking in consideration that the uncertainty of the calibration method is better than 0.1%, it must be assumed <u>that deviations must be taken in account when the level of pressure becomes significant</u> (around 15 to 20 bar for natural gas).
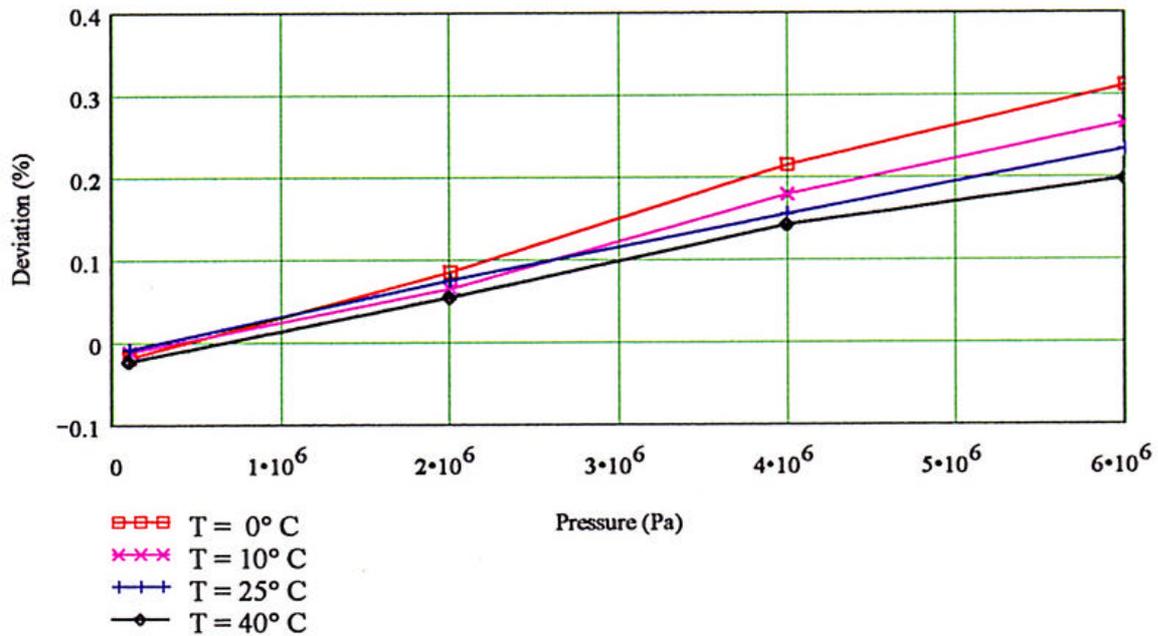

Figure 5 : Deviations in results for C* between NEL / Panasati and ISO 9300 method

1.2 Comparison of results between NEL / Panasati and ISO 9300 method for air

The results found at different temperatures between 0 and 50°C are given in figure 5.

They show the deviation between the value of critical flow function C* found by the laboratories using NEL / Panasati method and the same value found by applying the ISO 9300 method.

The NEL / Panasati method used for these calculations more recent state equations associated with an iterative method based on the convergence of the throat flow velocity [9].

The C* deviation between the two methods is for example of the order of 0.05% at 40 bar and increases significantly when the pressure rises. Temperature effects are also significant and increase more than 0.05% between 1 and 60 bar.

Consequently for air it must be also assumed <u>that the deviations must be taken in account when the level of pressure becomes significant</u> (around 20 bar).

4   RE-ANALYSIS OF THE INTERCOMPARISON RESULTS

In light of these considerations the raw results of the intercomparison have be re-analysed and re-calculated.

The figures 6 and 7 show the impact of this re-calculation.

The figure 6 shows the results where the values of the discharge coefficient C_d have been re-calculated by using the ISO 9300 critical flow function method for all laboratories both with natural gas and air.
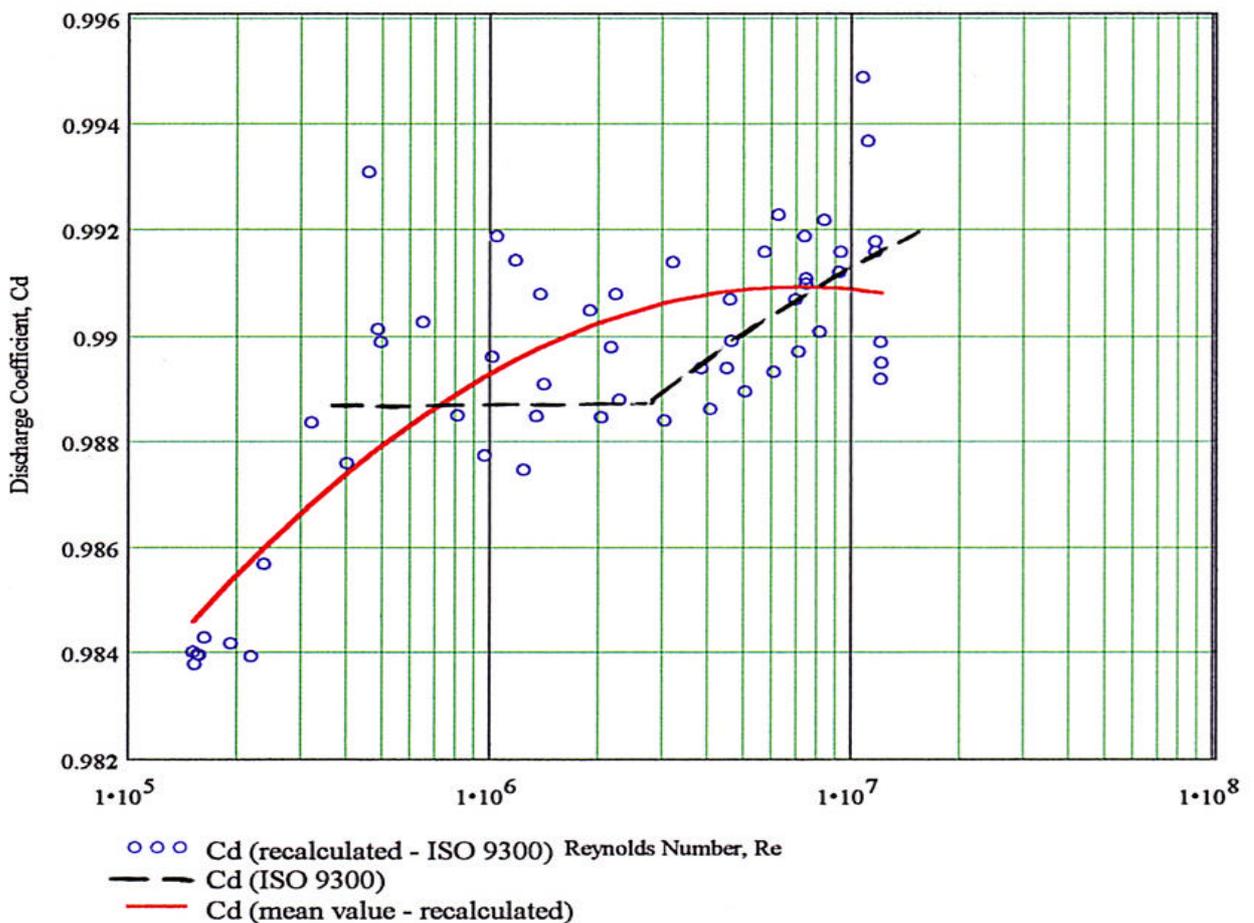

Figure 6

The figure 7 shows the results where the values of the discharge cofficient C_d have been re-calculated by using the AGA n°8 –1992 critical function calculation method for the laboratories working with natural gas and the NEL / Panasati critical function calculation method for the laboratories working with air.
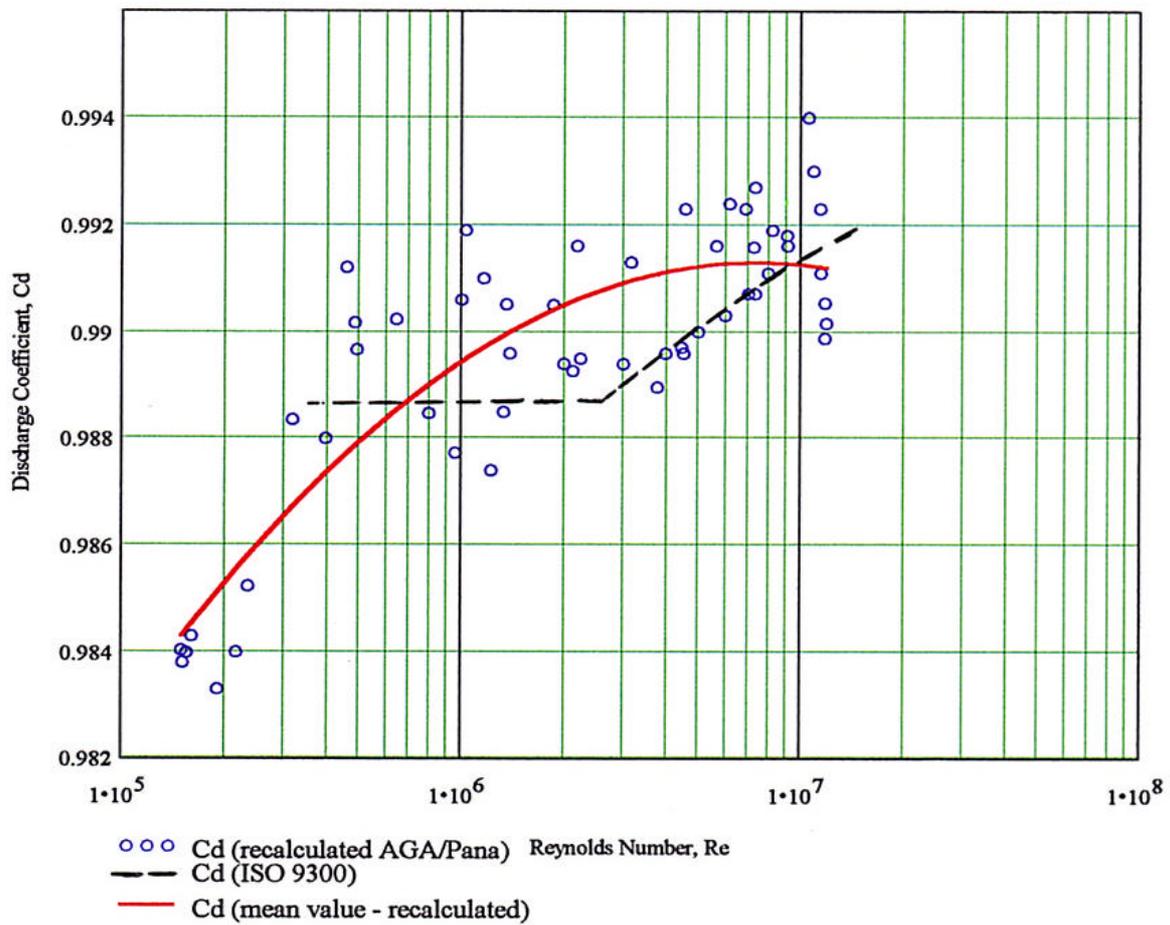

Figure 7

As it can be seen the scattering of the results (fig.7) is reduced significantly in comparison of the raw results (fig.2) and the results calculated using ISO 9300 (fig.6).

The following table (fig.8) gives the mean value of C_d and the associated standard deviation σ for raw results (a) , ISO 9300 results (b) , AGA N°8/NEL Panasati results (c).

The deviation between the mean value of σ for the raw results (σa) and for the AGA N°8/Nel Panasati results (σc) reaches 5.5% showing this general tendency

	a	b	c
Mean C_d value	0.9895	0.9894	0.9895
σ (mean)	2.67.10-3	2.60.10-3	2.53.10-3

Figure 8

5   CONCLUSION

The results presented here concerned only one type of sonic nozzle i.e. The venturi sonic nozzle with cylindrical throat. They can be incomplete depending on different nozzle designs (toroidal throat for example).

Meanwhile several conclusions can be drawn from this study.

For pressure levels below 20 bar and Reynolds numbers between $3.5\ 10^5$ to 10^6, the calculation method used for the determination of the critical flow function has strictly no effect on the C_d value.

For this nozzle design, it must be noted that the C_D value decreases dramatically below Reynold number equal to $3.5\ 10^5$ (ISO 9300 limit). This tendency is confirmed by laboratories working at atmospheric pressure for very low Reynolds numbers ($1.5\ 10^5$).

For natural gas and at significant pressure levels (higher than 20 bar), the 1992 version of the AGA n°8 calculation appreciably improves the calculation uncertainty of the real gas flow coefficient C_R.

For air and from a comparable level of pressure (around 20 bar), the NEL / Panasati slightly improves the calculation uncertainty of critical flow function C^*.

Depending on fluid used and pressure level an improvement of roughly 0.05% to 0.1% can be expected C_d value if AGA n°8 – 1992 method is used for natural gas and NEL / Panasati method is used on air.

Hence, these results may be used to revise the C_D values proposed in the actual version of the ISO 9300 standard.

This project is still under way and open to any new interesting laboratory for enriching the data base and confirm these tendencies. In a future work an other design of nozzle (toroidal throat) could be used to complete this intercomparison or better , a toroidal throat nozzle associated in tandem with the present one…

REFERENCES

EUROMET DIRECTORY, 1998

[1] ISO 9300, Measurement,of gas flow by means of critical flow Venturi nozzles

[2] J.L. Savidge, K.E. Starling, Compressibiliy factors for natural gas and related hydrocarbon gases, Transmission Measurement Committee Report n°8, American Gas Association, 2nd Edition, November 1992

[3] F. Vulovic, EUROMET PROJECT n° 307, Report on the Intercomparison Carried Out on Eight European Benches Using a Sonic Nozzle as Transfer Standard, Gaz de France, M. CERMAP VUL/SZ 97/I/129, 1997

[4] R.C. Johnson, Calculations of the Flow of Natural Gas through Critical Flow Nozzles, ASME publication, paper n° 69-WA/FM-4, December 1969

[5] R.C. Johnson, Real Gas Effects in Critical Flow through Nozzles and Tabulated Thermodynamic Properties, NASA Technical Note D-25, Lewis Research Center, Cleveland, January 1965

[6] R.C. Johnson, Real Gas Effects in Critical Flow through Nozzles and Thermodynamic Properties of Nitrogen and Helium at Pressures to 300 10^{5} Newton pr. Square Meter (approximately 300 atm.), NASA-SP2046

[7] J.L. Savidge, J.J.S. Shen, Evaluation of Critical Flow Factor and Speed of Sound Methods for Gas Measurement, IGRC, Tokyo, Japan, 1989

[8] R.T. Jacobsen, S.G. Penoncello, S.W. Beyerlein, W.P. Clarke and E.W. Lemmon, A Thermodynamic Property Formulation for Air, Fluid Phase Euilibria, 79 (1992) 113-124

[9] M.D. Panasati, E.W. Lemmon, S.G. Penoncello, R.T. Jacobsen, D.G. Friend, Thermodynamic properties of air from 60 to 2000K at pressures up to 2000 Mpa, 13th Symposium on Thermophysical Properties, Boulder, June 1998

[10] U. Setzmann, W. Wagner, A New Equation of State and Tables of Thermodynamic Properties for Methane Covering the Range from the Melting Line to 625 K at Pressures up to 1000 Mpa, Journal of Physical and Chemical Reference Data 20 (1991), 1061-1155

[11] D.G. Steward, J.T.R. Watson, A.M. Vaidya Improved critical flow factors and representative equations for four calibration gases, Flow Measurement and Instrumentation, Volume 10, Number 1, 27-34, March 1999

[12] B. Schmidt, R. Martin, C. House, Behaviour of high pressure air in critical flow through nozzles, Journal of Thermophysics and Heat Transfer (1) 1990,37-41

[13] M. Ishibaski, M. Takamoto, Discharge coefficient of super accurate critical nozzle at pressurized conditions, 4th international symposium on fluid flow measurement, Denver, June 1999

[14] M. Takamoto, Flow measurement technology for the next century, Flomeko'96, Beijing

[15] F. Vulovic, Intercomparison of C* calculation, Euromet Agreed Project n° 470

[16] F. Vulovic, E. Vincendeau, J.P. Vallet, C. Windenberger, O. Willanger, J. Bosio, Influence of thermodynamic calculations on the flowrate of sonic nozzles, 4th international symposium on fluid flow measurment, Denver, June 1999