Flow coefficients of critical flow venturi nozzles calibrated with hydrogen and other gases

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Abstract

Critical flow Venturi nozzles (CFVNs) are very stable and widely used secondary standards for gas flow rate measurements. The current study presents the first step in introducing CFVNs in the traceability scheme for gaseous hydrogen. The study was arranged in the framework of a Joint Research Project (EMPIR – MetHyInfra) and deals with the characterisation of the hydrogen discharge coefficient and the identification of a potential alternative gas for calibration of nozzles. The presented experimental study was made for two CFVNs with throat diameters of 0.175 mm and 0.436 mm. Tests were carried out using six different gases including hydrogen for the inlet pressures between 200 kPa and 700 kPa thereby covering the *Re* number range from 2×10^3 to 6×10^4. The results for both tested nozzles demonstrate the dependence of the discharge coefficient on the isentropic coefficient of the gas. With the exception of nitrous oxide, this behaviour can be explained by the theoretical model accounting for the isentropic coefficient, which presents good prospects for calibrating the nozzles intended for hydrogen processes with alternative inert gases.

1. Introduction

Hydrogen technologies are gaining momentum, because they provide the opportunities to decarbonise industrial processes and economic sectors. This, in turn, requires to ensure the metrological traceability for the hydrogen flow rate in the entire distribution chain. Due to already available inert gas calibration infrastructure and high flammability of hydrogen it is desired that to replace hydrogen with some other gas in the calibration process.

Critical flow Venturi nozzles (CFVNs) are very stable and widely used secondary standards for gas flow rate measurements with their geometries and calculation methodology for flow rate thoroughly described in ISO 9300 [1]. Unfortunately, their behaviour in hydrogen flows has not been extensively studied, and many crucial pieces of information are still missing, especially for high-pressure flows.

The experimental study of hydrogen flow in CFVNs presented by Tan and Fenn [2] for Reynolds numbers up to 1×10^4 showed that the discharge coefficient can be satisfactory predicted by using analytical models accounting for the isentropic gas coefficient, e.g., [3]. Johnson et al. [4] showed strong correlations between the discharge coefficient obtained with their numerical model and the experimental data. Some newer numerical studies [5-7] show that the real gas effects become essential in high-pressure hydrogen nozzle flows.

In order to introduce CFVNs in the traceability chain for the gaseous hydrogen flow rate, the present study, prepared in the framework of a Joint Research Project (EMPIR – MetHyInfra), deals with the characterisation of the hydrogen discharge coefficient and the identification of a potential alternative gas for calibration of nozzles in the laminar boundary layer regime. The experimentally obtained discharge coefficients for different gases will also be checked against ISO 9300 model.

The experimental study is based on a comparison of the discharge coefficients (C_d) of two toroidal critical flow venturi nozzles (CFVNs) of different dimensions with six different gases: dry air, argon, helium, hydrogen, nitrogen, nitrous oxide. Based on the comparison and analysis of the results, the study will try to identify a potential alternative to hydrogen gas in the calibration process.

2. Definition of the discharge coefficient

The discharge coefficient C_d of the nozzle is in general defined as

$$C_d = \frac{q_m}{q_{m,id}}, \qquad (1)$$

where q_m is the actual mass flow rate and $q_{m,id}$ is the ideal critical mass flow rate (assuming the one-dimensional isentropic flow of ideal gas). The ideal mass flow rate is defined by

$$q_{m,id} = \frac{AC^* p_0}{\sqrt{R_m T_0}}, \qquad (2)$$

where A is the cross-section at the nozzle throat, C^* is the critical flow function, R_m is the specific gas constant, and p_0 and T_0 are the stagnation pressure and temperature, respectively. The cross-section at the throat is defined as $A = \pi d^2/4$, where d is the nozzle throat diameter. The stagnation temperature (T_0) and pressure (p_0) are calculated as:

$$\begin{aligned} p_0 &= p_1\left(1+\frac{\kappa-1}{2}Ma_1^2\right)^{\frac{\kappa}{\kappa-1}}, \\ T_0 &= T_1\left(1+\frac{\kappa-1}{2}Ma_1^2\right), \end{aligned} \qquad (3)$$

where κ is the isentropic exponent and Ma_1 is the Mach number at the inlet conditions (at upstream pressure tapping).

The value of the discharge coefficient is related to the viscous effects of the boundary layer (C_{d1}) and the core flow, which is defined by the geometry of the nozzle (C_{d2}) [3,8]. Since the coefficients are almost independent of each other, the discharge coefficient can be approximated as:

$$C_d \approx C_{d1} C_{d2} = a - \frac{b}{Re^n}, \qquad (4)$$

where the coefficients a, b and n are related to the geometry of the nozzle and the type of the gas. The throat Reynolds number (Re) is based on the ideal mass flow rate of the gas:

$$Re = \frac{4 q_{m,id}}{\pi d \eta_0}, \qquad (5)$$

where η_0 is the dynamic viscosity of the gas at stagnation inlet conditions.

The expression for the discharge coefficient (4) has the form also used in ISO 9300 [1] for standardized nozzle shapes; for toroidal nozzles the value of $n = 0.5$, while for cylindrical nozzles $n = 0.2$. However, the values of coefficients a and b are different for laminar and turbulent boundary layers [8]. Figure 1 shows a typical variation of C_d with Re for a standard venturi nozzle with the characteristic transition from laminar to turbulent boundary layer regime at about $Re = 1\times10^6$. Note, that all tests performed in the scope of the current study fall in the laminar boundary layer regime ($Re < 6\times10^4$).

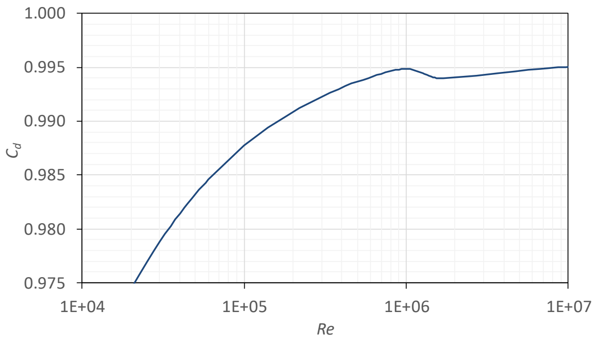

Figure 1: Typical variation of the discharge coefficient with Re for a venturi nozzle

3. Test setup and test procedure

The measurements were carried out for two toroidal critical flow venturi nozzles with two different throat diameters, both part of a 5-nozzle array (Tetratec) with the inlet manifold diameter of $D = 10$ mm:

- nozzle 1; $d_1 = 0.175$ mm,
- nozzle 2; $d_2 = 0.436$ mm,

where the given diameters are the values measured by the manufacturer of the nozzles. The setup used for tests is shown schematically in Figure 2. High pressure cylinders (50 L) were used as a gas source. The pressure regulator (stage 1) was mounted at the outlet of the gas cylinder and was set to approximately 1 MPa. In order to achieve suitable temperature stabilisation, the gas passed through a tube coil before reaching the pressure controller (Bronkhorst, EL-PRESS P-502C), which was used to set the inlet absolute pressure of CFVNs in the interval between 200 kPa and 700 kPa. The pressure (Mensor, CGP2500 & CPR2550, $U(k = 2) = 0.02$ % MV or 80 Pa) and the temperature (Tetratec & PicoTechnology; 535T 161 & PT-104, $U(k = 2) = 0.2$ °C) of the gas were measured at the inlet manifold of the CFVNs. The piston prover (Sierra Instruments (Bios), Cal=Trak SL-800 & SL-800-44, $U(k = 2) = 0.14$ %), which was used as a flow standard, was connected to the outlet of the CFVNs. All components were connected to the PC with the control program realised in LabVIEW programming environment. The program permitted the control of the pressure at the CFVNs inlet and saving of all necessary data for further processing.

The measurements for each CFVN were carried out at six measurement points; at nominal inlet pressures p_1 equal to (200, 300, 400, 500, 600, 700) kPa. Three repetitions were carried out at each measuring point. The reference mass flow rate is determined as the mean of ten consecutive readings of the piston prover. The results at each measurement point consist of three main parameters: the reference mass flow rate ($q_{m,ref}$), the pressure (p_1) and the temperature (T_1) at the inlet of the CFVN.

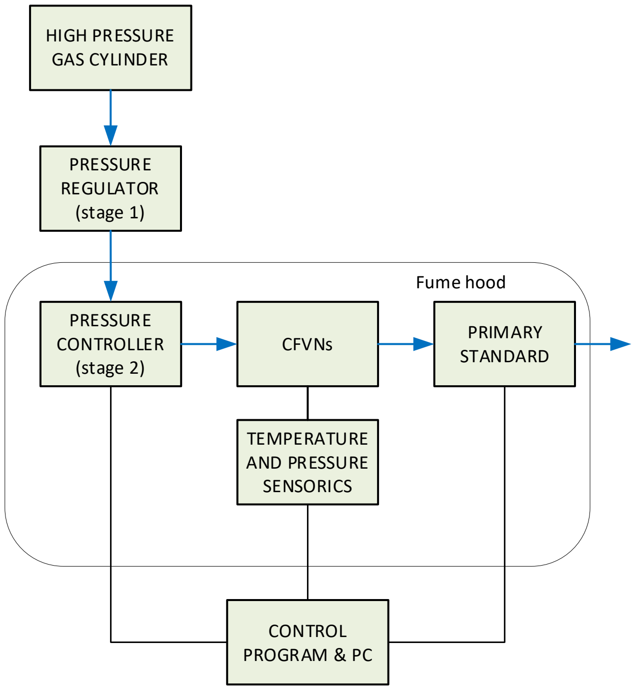

Figure 2: Scheme of the test setup

The calibration of the nozzles was carried out with six different gases (the grade of purity of each gas is shown in parentheses):

- dry air,
- Ar - argon (5.0),
- He - helium (5.6),
- H_2 - hydrogen (5.5),
- N_2 - nitrogen (5.0),
- N_2O - nitrous oxide (2.5).

All properties of the gases were defined using REFPROP v9.0 database [9].

Special precautions were made for working with hydrogen. First, prior to working with hydrogen the leak-tightness of all connections was tested with helium using a He-sniffer device. During the hydrogen flow measurements, the part of the measuring system (CFVNs, the pressure controller and the piston prover) were put under the fume hood as shown in Figure 3. Using the suitable ventilation system, the gas under the fume hood was exhausted into the outdoor environment.

The discharge coefficient at each measurement point is calculated according to eq. (1) using $q_{m,ref}$ as the reference flow rate determined by the piston prover. The coefficients *a, b* and *n* are determined by fitting the calculated discharge coefficients vs *Re* according to ISO model (4). The value of *n* was, in all cases, rounded to two decimal places.

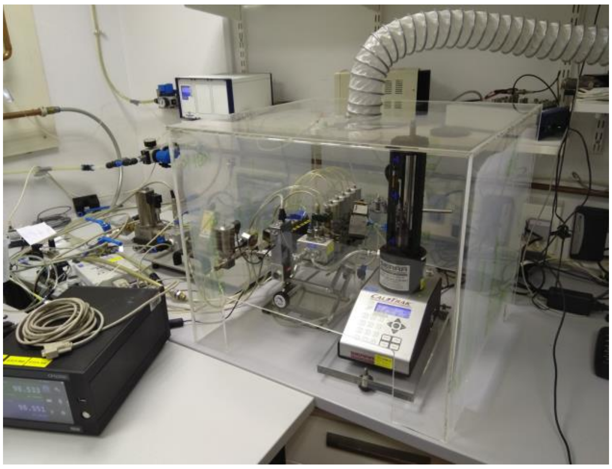

Figure 3: Measuring system with the fume hood

The expanded measurement uncertainty ($k \approx 2$) of the calculated discharge coefficient is given by:

$$\frac{U(C_d)}{C_d} \approx 2\left[\left(\frac{u(q_{m,ref})}{q_{m,ref}}\right)^2+\left(\frac{u(p_1)}{p_1}\right)^2+\left(\frac{u(T_1)}{2T_1}\right)^2+\left(\frac{u(C_d)}{C_d}\right)^2_{fit}\right]^{1/2} \qquad (6)$$

where the last term represents the uncertainty of the approximation.

4. Results

The experimentally obtained values of discharge coefficients for both nozzles and all the gases under consideration are shown in Figures 4 and 5, together with their approximations (4) and the C_d values for accurately machined toroidal nozzles (a = 0.9985, b = 3.412 and n = 0.5) according to ISO 9300 [1]. The values of coefficients *a*, *b* and *n* of the C_d models obtained from tests for both nozzles are also listed in Table 1. The expanded uncertainties of the resulting discharge coefficients were approximately 0,2 % in all cases.

Similar trends of discharge coefficients for different gases are observed for both nozzles. There is a relatively small range of *Re* where the determined discharge coefficients could be directly compared. However, the values of discharge coefficients of air, nitrogen and hydrogen almost overlap for both nozzles. The results also show that compared to nitrogen (or air or hydrogen) the discharge coefficient for argon and helium is about 0.5 % lower, while it is about 1 % higher for nitrous oxide. Having in mind the stated uncertainties for C_d, the observed differences are significant. Slightly smaller values of C_d for helium and argon correlate with some earlier experimental data published in [4,10].

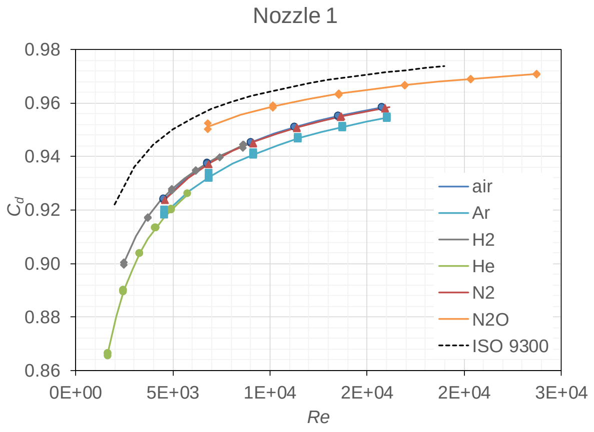

Figure 4: C_d for different gases for nozzle 1 – experiments (symbols) & C_d model (lines)

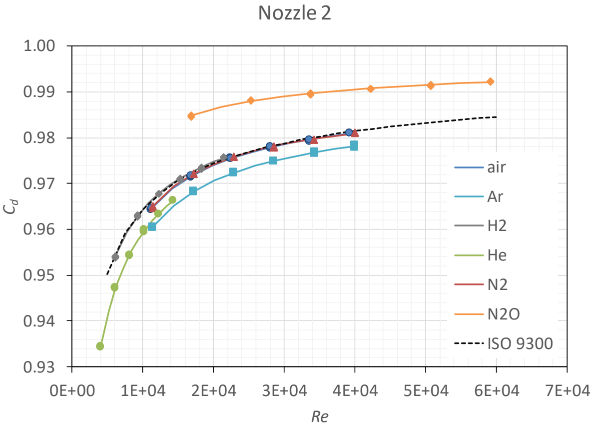

Figure 5: C_d for different gases for nozzle 2 – experiments (symbols) & C_d model (lines)

For nozzle 2 the ISO 9300 model almost exactly matches the values of air, nitrogen and hydrogen, whereas for nozzle 1 the ISO 9300 model predicts higher values of C_d compared to those obtained in the tests. Note, that ISO 9300 only states the validity of the C_d model for $Re > 2.1\times10^4$. In addition, the observed difference for nozzle 1 could also be the result of an error in the value of the throat diameter. Our analysis shows that the actual diameter of nozzle 1 is likely to be about 0.001 mm smaller than its specified value.

The ISO 9300 model, which agrees reasonably well with the experimental trends of the discharge coefficient, does not explain the differences between different gases. Based on the measured values of the discharge coefficients, the gases can be classified into three groups (from lowest to highest values of C_d): (i) helium and argon, (ii) air, nitrogen and hydrogen and (iii) nitrous oxide. As given in Table 1 the gases belonging to one of these three groups can be characterised by a similar value of the isentropic exponent; for helium and argon around 1.67, for air, nitrogen and hydrogen about 1.4 and for nitrous oxide its value is about 1.3.

Table 1: Values of coefficients *a*, *b* and *n* for both nozzles and different gases

Gas	*a*	*b*	*n*
Nozzle 1			
air	1,00118	4,0332	0,47
Ar	1,00040	3,9571	0,46
H_2	0,99907	3,8839	0,47
He	0,98907	6,2386	0,53
N_2	1,00231	3,7804	0,46
N_2O	0,99779	2,2615	0,44
Nozzle 2			
air	0,99170	26,987	0,74
Ar	0,98833	49,051	0,80
H_2	0,99556	6,5126	0,58
He	1,00020	5,3843	0,53
N_2	0,98956	62,938	0,84
N_2O	0,99696	16,254	0,74

This can be partly explained by the comparison of the experimental values with the C_d model, which considers the isentropic coefficient. According to Ishibashi and Takamoto [3]:

$$a = 1 - \frac{\kappa+1}{(2R/d)^2} \times \left(\frac{1}{96} - \frac{8\kappa+21}{4608(2R/d)} + \frac{754+1971\kappa+2007}{552960(2R/d)^2}\right) \qquad (7)$$

and

$$b = \frac{4a}{\sqrt{m}}\left(\frac{\kappa+1}{2}\right)^{\frac{1}{2}\cdot\frac{1}{\kappa+1}}\left(3\sqrt{2}-2\sqrt{3}+\frac{\kappa-1}{\sqrt{3}}\right), \qquad (8)$$

where

$$m = \sqrt{\frac{2d}{R}\left(\frac{\kappa+1}{2}\right)^{\frac{3\kappa-1}{\kappa-1}}}, \qquad (9)$$

and $R = 2d$ is the wall curvature of the nozzle throat. The comparison for hydrogen, helium and nitrous oxide is shown in Figure 6 for nozzle 2. It is evident that the difference between measured C_d values for gases from group (i) and group (ii) can be well explained by Ishibashi&Takamoto model. This is accordance with [3] where the experimental data for hydrogen, nitrogen and argon agreed reasonably well with the Ishibashi&Takamoto model. Also, Tang and Fenn [2] showed that C_d for nitrogen, hydrogen, argon and helium coincide with their proposed model at $Re > 1\times10^3$, which also exhibits dependence of C_d on κ.

On the other hand, higher C_d for nitrous oxide cannot be explained by the Ishibashi&Takamoto

model, which predicts increase of C_d of only about 0.1 % compared to hydrogen. A greater difference observed in the tests results could stem from the relatively low purity (99.5%) of nitrous oxide or from the effects of vibrational relaxation; the latter is more likely. See e.g., [10-12] for vibrational relaxation effects in CO_2 and SF_6.

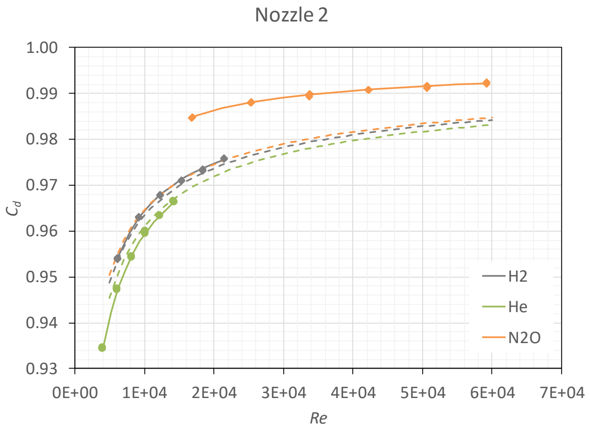

Figure 6: Comparison of C_d for different gases for nozzle 2 (—●— experimental data; --- Ishibashi&Takamoto model [3])

6. Conclusion

The discharge coefficients (C_d) were experimentally determined for six different gases: air, argon, helium, hydrogen, nitrogen and nitrous oxide and two different toroidal CFVNs with throat diameters of 0.175 mm and 0.436 mm. The measurements for each CFVN were carried out at absolute inlet pressures in the interval from 200 kPa to 700 kPa, which covers the range of *Re* numbers from about 2×10^3 to 6×10^4. The results obtained are as follows:

- values of C_d were found to be dependent on the isentropic coefficient of the gas, which agrees with the predictions of the theoretical model [3];
- values of C_d for hydrogen, air and nitrogen agree well with the standard ISO 9300 model. However, it might not be possible to achieve comparable ranges of *Re* number for hydrogen and air or nitrogen for the given CFVN;
- for helium and argon, the values of C_d were found to be about 0.5 % smaller than for air, nitrogen or hydrogen. However, this difference can be explained using the model, which takes into account the isentropic coefficient. Besides, the *Re* number range of helium is comparable to that of hydrogen;
- the highest values of C_d were observed for nitrous oxide (about 1 % higher than for air) and this deviation cannot be explained solely by the influence of the isentropic coefficient.

The results show that CFVNs in the tested range of Reynolds numbers in the laminar boundary layer regime, can potentially be calibrated with alternative gases. The next goal of the project is to carry out the comparison for nozzles with inert gases (air, nitrogen, helium) at higher pressures using existing calibration facilities. Finally, these nozzles will be tested with hydrogen using a primary standard developed in the course of the MetHyInfra project.

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