

Performance Evaluation of Critical Flow Venturi Nozzle with Primary Standard Calibration Facilities at FCRI and Validation with ISO Standards

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Abstract

A 2" NB Critical Flow Venturi Nozzle (CFVN) of Nominal Flow capacity 25m³/h was designed at Fluid Control Research Institute (FCRI), India as a transfer standard for undertaking calibration of smaller capacity flow meters. The Nozzle fabricated was of Toroidal throat design and was assembled as per the general guidelines of ISO 9300:2005 "Measurement of gas flow by means of Critical flow Venturi nozzles". The Air Flow Measurement facilities at FCRI is equipped with Primary Standards Pressure-Volume-Temperature-time (PVTt) facility of 2m³ Nominal volume and 90 m³/h maximum flow capacity and a Bell Prover of 500 ltr volume and with a maximum flow capacity of 40m³/h. The performance of the Critical Flow Venturi Nozzle assembly was tested and analyzed with both PVTt facility and Bell Prover. PVTt facility can be used as a collection tank for estimation of mass flow rate during operation of CFVN during suction mode.

To establish dynamic traceability in measurements and compare the test results with other proven primary standards, the same CFVN assembly was calibrated both under pressure mode and suction mode using the Primary standard Bell Prover system available at the Primary Standard Air Flow Laboratory at FCRI. During filling mode operation of Bell Prover, the Throat Reynolds number of nozzle was about 1.24E+05 and in Discharge mode of flow test the Throat Reynolds number of nozzle was about 8.61E+04.

Cd of the nozzle was established at different Reynolds numbers with both PVTt facility and Bell prover. The results obtained with the above methods were validated using ISO equation given in ISO 9300: 2005.

Keywords: Critical flow venturi nozzle, PVTt facility, Validation, Bell prover, Uncertainty

1. About FCRI

The Fluid control Research Institute (FCRI) an autonomous R&D Institute was established in 1987 with active assistance and participation from UNDP and UNIDO, under the Ministry of Industry (Govt. of India). The Institute is accredited by different

National/International bodies such as National Accreditation Board for Testing and Calibration Laboratories (NABL, India); Underwriters Laboratory, USA; Chief Controller of Explosives, Nagpur-India; Bureau of Indian Standards (BIS); NMI, Netherlands; Department of weights and measures, India; Central Pollution Control Board(CPCB, India); Department of Science and Technology, India; etc. FCRI regularly participates in International round robin proficiency test programs in association with NIST, USA; CEESI, USA; NEL, UK; DELFT, Holland; DTI, Denmark; and KRIS, Korea etc. Other than flow laboratories with Air, Water and Oil as media, FCRI has got supporting laboratories like metrology section, Noise and Vibration section, and Electronics and Instrumentation section etc. FCRI regularly conducts National/International level Conferences/Training programs. FCRI also develops software in the field of flow meter design and selection valves/pumps, natural gas metering etc.

1.1 Facility at Secondary Air Flow Laboratory (SAFL)

The SAFL of FCRI is equipped with critical flow venturi nozzles (sonic nozzles) of capacity 11.25-2880 m³/h. This facility is used for model studies, calibration/testing of flow products upto 10,000 m³/h at near ambient conditions using three cyclo blowers connected to the test loop. The reference critical flow venturi nozzles are assembled in parallel and are connected to the device under Calibration/test in series. The laboratory is maintained at a temperature of 25±1 °C and humidity of 55±5 %. Positive pressure is ensured inside the facility by means of Air Handling units which supplies conditioned air to the laboratory. The schematic of SAFL is given in Fig. 1.

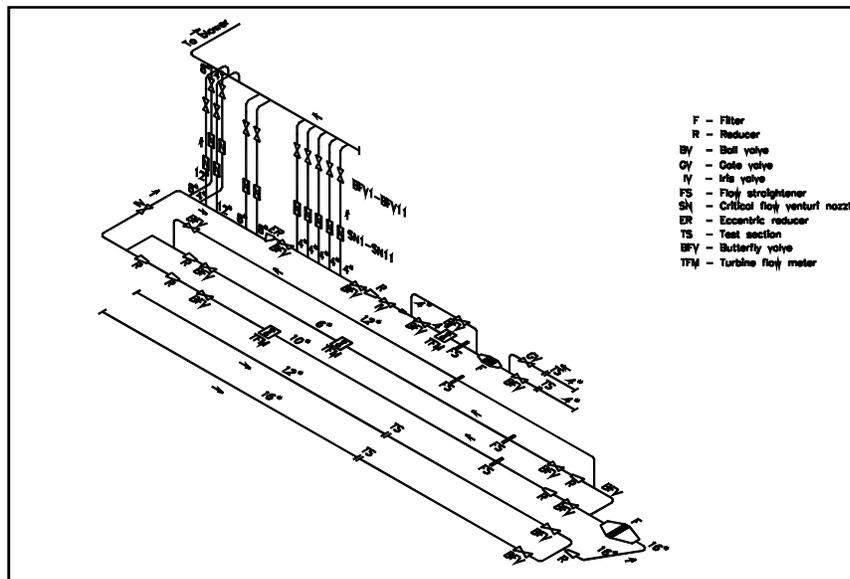


Fig1. Schematic of Secondary Air Flow Laboratory

2. Description of PVTt Facility

The ‘heart’ of the facility is the cylindrical stainless steel volume vessel with two spherical dish ends having an approximate internal volume of 2 m³. It is fitted with necks both at top and bottom.

The schematic arrangement of the facility is shown in Fig. 2. The nozzle is connected to the vessel with a quick acting electro-pneumatically operated high vacuum butterfly valve using ISO KDN100 flanged fittings. The valve operations are controlled manually. Distribution of air temperature inside the vessel is measured using 12 Resistance Temperature Detectors inserted using thermo wells at desired locations spanning the height of the volume vessel. High vacuum couplings (ISO KF, ISO-K) and vacuum valves are provided to ensure sufficient leak tightness in the vessel. A vacuum pump evacuates the vessel to the required initial pressure (<10 Pa) in the vessel. The vacuum inside the vessel is monitored by means of two compact capacitance gauges with digital indicator. The final pressure inside the vessel is measured by means of a high accuracy multifunction digital pressure indicator with resonant sensors. Compact capacitance gauges and RTDs are installed permanently in the vessel

This unique primary calibration facility works on the principle of measurement of pressure (P), volume (V), temperature (T) and time (t). It has been established to achieve the following prime objectives:

- i) Primary calibration of critical flow venturi nozzles having nominal flow capacities less than 90 m³/h with uncertainties better than $\pm 0.1\%$ using ambient air.
- ii) Establishment of traceability to National standards.

The following are the salient features of the facility.

Method	: $PVTt$ method
Primary parameter	: Volume
Medium	: Conditioned Air.
Temperature	: 25 ± 1 °C.
Pressure of air in vessel	: <10 Pa (a) (Initial) : <75000Pa (a) (Final)
Volume of vessel	: 2 m ³ (Nominal)
Collection time	: 60 to 250 s
Valve opening /closing time	: Better than 60 ms
Flow rate	: 90 m ³ /h (maximum)
Uncertainty	: Better than $\pm 0.1\%$

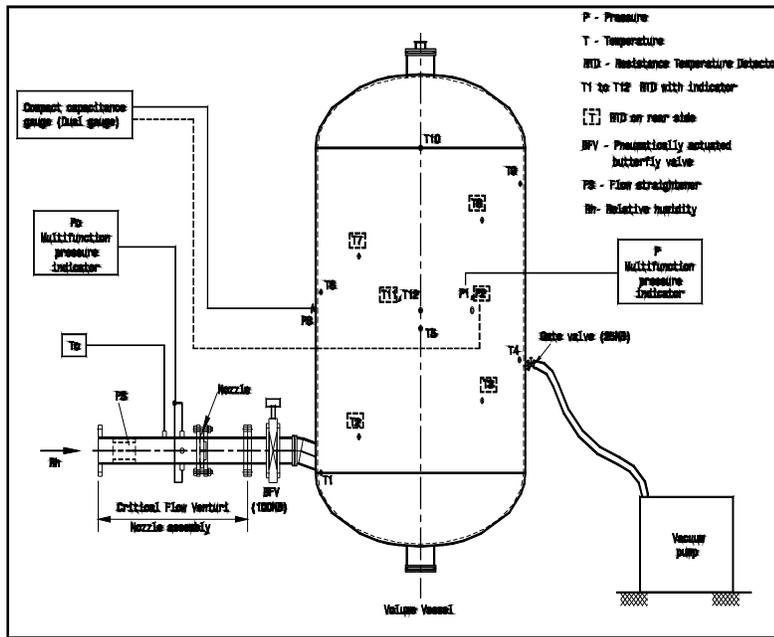


Fig 2. PVT facility at FCRI

3. Technical Specification of Critical flow venturi nozzle (CFVN) package

Nominal flow capacity : 25m³/h

Type : Toroidal throat Venturi nozzle

Design standard : ISO 9300: 2005

Throat diameter : 6.64mm

Pipe size : 2" NB

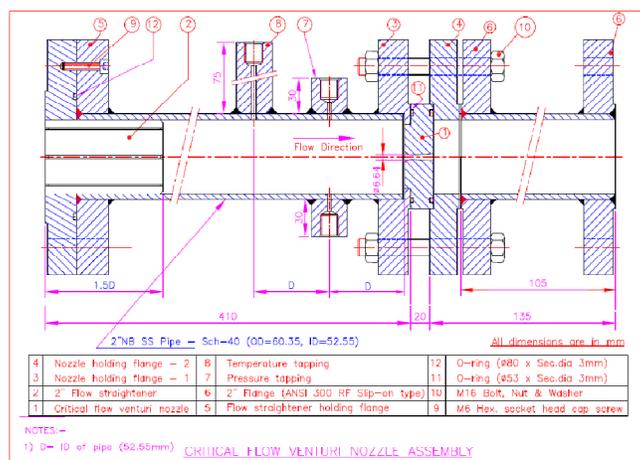


Fig. 3 CFVN assembly

Schematic of nozzle assembly is shown in Fig.3 The above Critical flow venturi nozzle was calibrated using PVTt facility in suction method and was further calibrated using the 500 lit capacity Bell prover both in the Discharge & filling mode of operation of the prover.

4. Calibration of Critical Flow Venturi Nozzle with PVTt facility

Critical Flow Venturi Nozzles are secondary flow measuring devices that operate at the maximum possible flow rate for the existing upstream conditions. The air flow accelerates to the critical velocity at the throat, which is equivalent to the local sound velocity. The nozzle has a throat diameter of 6.64 mm and is assembled in 50 mm NB pipe with a flow straightener at upstream. For this nozzle, to ensure critical flow, a maximum back pressure ratio less than 0.8 must be maintained across the nozzle. The nozzle under calibration is mounted at upstream of the quick acting butterfly valve. With the valve in closed condition, an initial pressure less than 10 Pa (a) is created in the vessel using a vacuum pump. Subsequently the pump is isolated and pressure inside the vessel is monitored to detect leakage if any. Sufficient time is allowed for temperature and pressure stabilization inside the vessel. By opening the quick acting butterfly valve, the ambient conditioned air is drawn into the vessel through the nozzle and simultaneously triggers a time counter. When the pressure of air in vessel reaches about 75 kPa (a), the valve is closed and the signal from proximity sensor stops the timer at the same time. Thus the timer measures the duration of valve opening or time of collection of air in the vessel. More than 2 hours is allowed for stabilization of vessel conditions. The final pressure and temperature of air in the vessel are recorded after stabilization. The actual mass of air is calculated from the difference between the initial and final density of air in the vessel and established volume of PVTt vessel. Coefficient of Discharge (C_d) of the Critical flow venturi nozzle was established by the ratio of actual mass flow rate and theoretical mass flow rate estimated using ISO 9300 specified equations. The entire calibration is repeated a number of times to establish the mean C_d and to assess the random uncertainty associated with calibration.

5. Calibration of Critical Flow Venturi Nozzle with 500 lit Bell prover

The bell prover consists of a cylindrical tank open at the top and a central "dry well", which together form an annulus that is nearly filled with sealing oil. Into this annulus is placed an inverted cylindrical tank, i.e., the bell, open at the bottom and closed at the top. Its weight is nearly balanced by counterweights so that it can be raised or lowered by a small differential pressure (0.3 kPa) to collect and measure a volume of gas. Smaller counterweight is mounted on a cam so that it provides a correction for buoyancy effects as the bell immersion in the sealing liquid changes. A pipe that passing above the liquid communicates with the trapped volume. As the bell is lowered gas is displaced from the cylinder to the meter under test. By knowing the volume/length relationship for the bell the volume of gas displaced through the meter may be determined. The prover at FCRI consists of a 500 lit capacity Bell and it can be used in both Filling and discharge mode of operation. The digiruler mechanism attached to the prover indicates the Bell movement and volume discharged from the prover is estimated using the calibration factor of the prover. Schematic of Bell prover facility at FCRI is indicated in the Fig 4 given below.

6. ISO equation for Cd of Critical flow venturi nozzle

As per ISO 9300: 2005 the equation for Cd of Toroidal throat CFVN is

$$C_{d'} = a - bRe_{nt}^{-n} \quad \dots(1)$$

Where a= 0.9959, b= 2.72, n= +0.5 for Throat Reynolds number range of 2.1 E+04 to 3.2E+07.

The coefficient of discharge Cd estimated using the above equation for the 3 methods of calibration at different Reynolds numbers are detailed in Table 2 given below and their deviations from the experimental values are also indicated in the same table

Table2. Comparison of Experimental Cd values & ISO values

Sl. No.	Experimental Coefficient of discharge (Mean) Cd	ISO value Coefficient of discharge Cd	Deviation from ISO Vaule
[1]	[2]	[3]	[4]
1	0.98259	0.98645	-0.39
2	0.98242	0.98663	-0.43
3	0.98672	0.98818	-0.15

Graphical variation of ISO values and Experimental Cd values are indicated in the Fig 5. Below

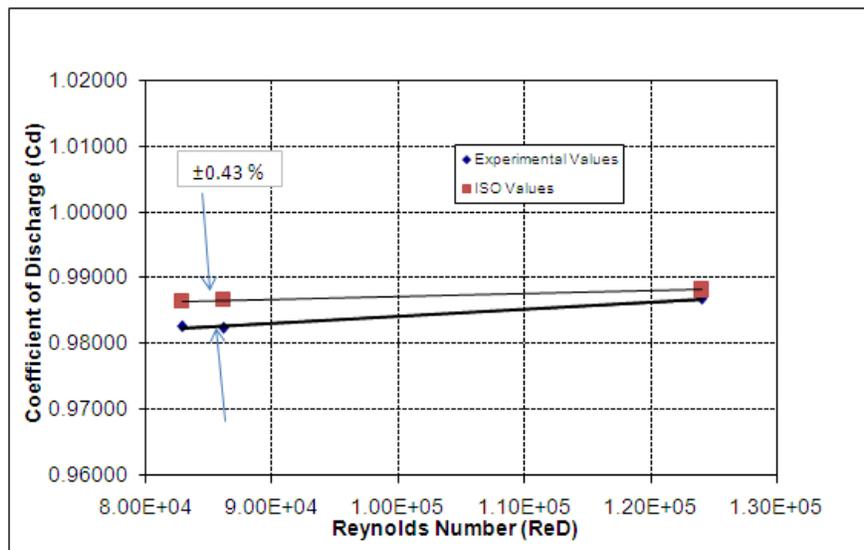


Fig 5. ReD vs Cd chart

7. Estimation of Uncertainty in PVTt & Bell prover method of Calibration.

The overall uncertainty in the calibration of critical flow venturi nozzle using *PVTt* and Bell prover methods are estimated by combining the uncertainties of actual mass flow measurement and the theoretical flow rate from the nozzle. The equation for theoretical flow rate is:

$$2. \quad m_t = \pi \times d^2 / 4 \times C^* \times P_o \times \sqrt{M_e / (R \times T_o)}$$

Where P_o and T_o are the pressure and temperature measured at the upstream of the nozzle, d is the throat diameter and C^* is critical flow factor. The coefficient of discharge of the nozzle defined as the ratio of actual mass flow rate to theoretical flow rate is calculated as:

$$3. \quad C_d = m_a / m_t$$

The systematic uncertainty in the coefficient of discharge $E_s(C_d)$ is given as the combination of individual component uncertainties of the above equations. For PVTt method and Bell prover uncertainty in actual flow measurement is estimated and it is combined with uncertainty in theoretical flow rate to estimate the total uncertainty in determination of Cd.

Uncertainty in the Variables of PVTt method and Bell prover are given in Tables 3 & 4

Table 3. (*PVTt Method*)

$E_s(P)$	±0.06 %
$E_s(V)$	±0.05 %
$E_s(T)$	±0.1 %
$E_s(t)$	±4.5E-05%
$E_s(P_o)$	±0.03 %
$E_s(M_e)$	±0.0013 %
$E_s(R)$	±0.01 %
$E_s(T_o)$	±0.5 %

Table 4 (*Bell prover*)

$E_s(P)$	±0.002 %
$E_s(V)$	±0.1 %
$E_s(T)$	±0.03 %
$E_s(t)$	±4E-04%
$E_s(P_o)$	±0.03 %
$E_s(M_e)$	±0.03 %
$E_s(R)$	±0.01 %
$E_s(T_o)$	±0.5 %

Expanded uncertainties in the Primary standard facilities of FCRI, PVTt and Bell prover are estimated as 0.05 and 0.1% as per NABL 141 guidelines.

8. Conclusion

The analysis of the results indicated that the performance of the CFVN is in line with ISO established Cd trend curve for Toroidal throat venturi nozzle and is within $\pm 0.15\%$ for Higher operating throat Reynolds number and for lower Reynolds number the maximum deviation was nearly $\pm 0.43\%$. Also the Cd values established for the CFVN with PVTt and Bell prover resulted in the same Mean value with a deviation of only 0.02%, and this established the dynamic traceability in measurements for the two Primary standard facilities at FCRI.

References

- [1] ISO 9300:2005 (E) "Measurement of gas flow by means of critical flow venturi nozzles"
- [2] AGA 12 "Meter Proving"
- [3] ISO 5168 : 2005 "Procedures for Evaluation of Uncertainties"
- [4] NABL 141 "Guidelines for Estimation of Uncertainty"