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Influence of Reynolds number on Cd of Critical flow venturi nozzle and validation with ISO standards

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ABSTRACT

Critical Flow Venturi Nozzles (CFVN) of throat diameter 3.32mm,4.698mm & 6.64mm having Nominal Flow capacities 6.3m^3/h, 12.5m^3/h & 25m^3/h designed at Fluid Control Research Institute (FCRI), India as a transfer standard for undertaking calibration of master air/gas flow meters was tested at different operating pressures using the PVTt (Pressure, Volume,Temperature & time) & Primary standard Gravimetric system (PSGS) facilities of the Institute. The Nozzles 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 PVTt facility of 2m^3 Nominal volume and 90 m^3/h maximum flow capacity and a Gravimetric system of 1500 ltr volume and with a maximum flow capacity of 50m^3/h. The Coefficient of Discharge (Cd) of the Critical Flow Venturi Nozzle assemblies were established with both PVTt facility and PSGS at different operating pressures so as to achieve a wide range of Reynolds numbers as per the limits specified in ISO 9300 standard for toroidal throat venturi nozzles.

Throat Reynolds number range of the nozzles tested were between 4.1E+04 to 1.3E+06. Cd of the nozzles established from Primary Calibration facilities were compared with the values determined using the ISO equation which is a function of Throat Reynolds number and Coefficients as specified in the standard. The uncertainty of ISO specified equation for toroidal throat Venturi nozzle is 0.3% at 95% confidence level and the Uncertainties of Primary Calibration facilities of FCRI are better than 0.1% and hence are at par for validation of experimental results with ISO values.

Keywords: Critical Critical flow venturi nozzle, PVTt facility, Primary Gravimetric systam, Coefficent of discharge, Reynolds Number, Validation, 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 KRISS, 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 m^3/h. This facility is used for model studies, calibration/testing of flow products upto 10,000 m^3/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.

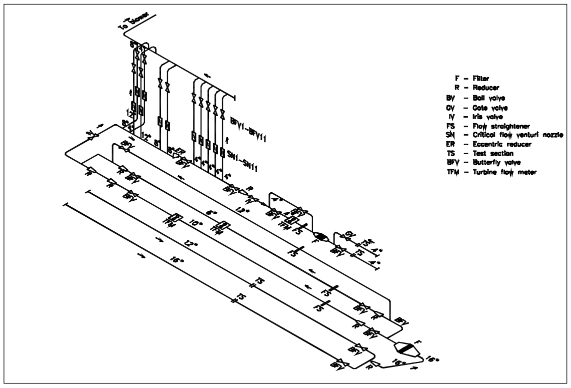


Fig 1- Schematic of secondary air flow laboratory

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 m^3. 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 m^3/h with uncertainties better than ±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 ^{o}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 ± 0.1%

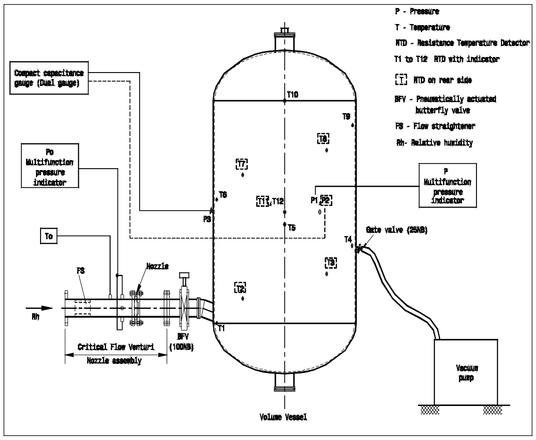


Fig 2- PVTt facility at fcri

3. DESCRIPTION OF PRIMARY STANDARD GRAVIMTERIC SYSTEM(PSGS) FACILITY AT FCRI

The loop consists of a spherical vessel on a mass comparator, test meter mounted at upstream of a critical flow venturi nozzle and a bypass line opened to atmosphere interconnected with a ‘’Tee’. The a pilot operated air regulator maintains a preset pressure at upstream of the Critical flow Venturi nozzle. The three pneumatically operated ball valves in the ‘Tee’ stop or divert the flow from the test meter line to atmosphere or to the spherical vessel. The air passed through the critical flow venturi nozzle and the test meter is collected in a spherical air vessel. The mass of air collected is measured using a mass comparator. The time of collection of air is measured using a universal counter. The pressures are measured using multifunction pressure indicators. The temperatures are measured using digital temperature indicators with RTD. The pulse for a preset time period is measured using universal counters. The relative humidity is measured using pressure dew point measuring instrument.

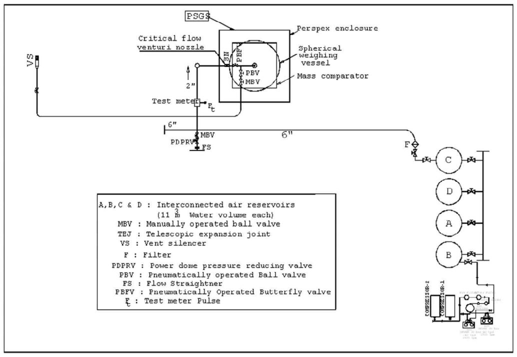
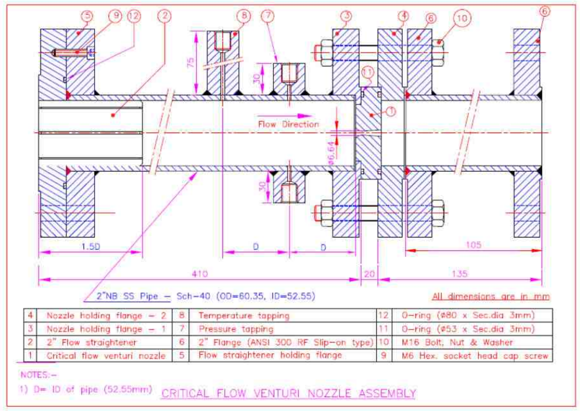


Fig 3 - PSGS facility at FCRI

4. TECHNICAL SPECIFICATION OF CRITICAL FLOW VENTURI NOZZLE (CFVN) PACKAGE

Nominal flow capacity	: 6.3/12.5/25m^3/h
Type	: Toroidal throat Venturi nozzle
Design standard	: ISO 9300: 2005
Throat diameter	: 3.32/4.698/6.64mm
Pipe size	: 2" NB



4	Nozzle holding flange – 2	8	Temperature tapping	12	O-ring (ø80 x Sec.dia 3mm)
3	Nozzle holding flange – 1	7	Pressure tapping	11	O-ring (ø53 x Sec.dia 3mm)
2	2" Flow straightener	6	2" Flange (ANSI 300 RF Slip-on type)	10	M16 Bolt, Nut & Washer
1	Critical flow venturi nozzle	5	Flow straightener holding flange	9	M6 Hex. socket head cap screw

Fig. 4- Typical assembly of a CFVN

Schematic of typical CFVN assembly is shown in Fig.4. Three numbers of CFVN's of throat diameters 3.32, 4.698 and 6.64mm were used in the experimental program. The above Critical flow venturi nozzles were calibrated using PVTt facility in suction method and was further calibrated using the PSGS facility at different operating pressures from 2 to 20 bar abs so as to achieve different Reynolds number range as specified in the ISO standard 9300 for Toroidal throat venture nozzle.

5. 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 3.32 mm and was 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 (Cd) 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 Cd and to assess the random uncertainty associated with calibration. The tests were repeated with CFVN's of throat diameters 4.698 & 6.64 mm.

6. CALIBRATION OF CRITICAL FLOW VENTURI NOZZLE WITH PSGS FACILITY

Required operating pressure was maintained at the upstream side of the CFVN using the dome loaded pressure regulator and the actual mass flow rate was determined using the 1.5m^3 volume tank and the Mass comparator weighing system. The mass of air collected in the weighing system varied from 0.5 to 16 kg approximately depending on the operating pressure and nominal flow capacity of the CFVN. Collection time in the vessel was in the range of 60 to 360 seconds depending on flow rate. Cd values were determined for different operating Reynolds number range by this method.

7. ISO EQUATION FOR CD OF CRITICAL FLOW VENTURI NOZZLE

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

$$Cd = a - bRe_{nt}^{-n}$$

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

Constants a, b & n depends upon the type of Critical flow venturi nozzle and the corresponding values are given in the ISO 9300 standard and the specified uncertainty of Cd values by the above equation is 0.3% for Toridal throat CFVN.

8. EXPERIMENTAL CD VALUES AND ISO VALUES

Cd values, Reynolds number range and the deviations from ISO values for the three tested CFVN's are given in Tables 1 to 3 and Figs 5 to 7.

Table 1- Cd values for 6.3m3/h flow capacity CFVN

Sl. No.	Nominal pressure bar a	Method adpted	Throat Reynolds number Red -	Actual flow rate m_a kg/h	Experimental values Coefficient of discharge Cd -	Coefficient of discharge using ISO equation Cd_{ISO} -	Deviation from ISO 9300 values %
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
1	20	PSGS	8.32E+05	147.80	0.9969	0.9929	0.40
2	18		7.52E+05	133.49	0.9972	0.9928	0.44
3	16		6.67E+05	118.18	0.9977	0.9926	0.52
4	14		5.88E+05	103.96	0.9984	0.9924	0.61
5	12		5.01E+05	88.51	0.9979	0.9921	0.59
6	10		4.22E+05	74.44	0.9976	0.9917	0.60
7	8		3.43E+05	60.17	0.9974	0.9913	0.62
8	6		2.61E+05	45.79	0.9977	0.9906	0.71
9	4		1.75E+05	30.56	0.9966	0.9894	0.73
10	2		9.39E+04	16.45	0.9943	0.9870	0.74
11	1	PVTt	4.16E+04	7.17	0.9900	0.9826	0.76

Fig 5- Variation of Cd with Reynolds number for 6.3 m3/h CFVN

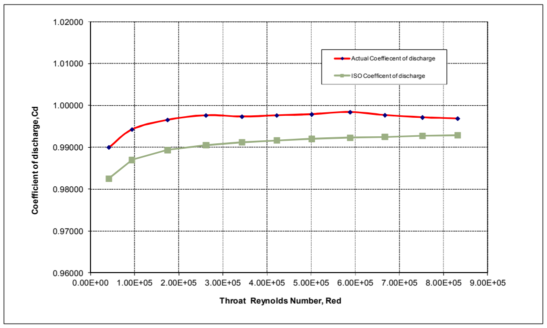


Table 2 - Cd values for 12.5m3/h flow capacity CFVN

Sl. No.	Nominal pressure bar a	Method adopted	Throat Reynolds number Red -	Actual flow rate m_a kg/h	Coefficient of discharge Cd -	Coefficient of discharge using ISO equation Cd_{ISO} -	Deviation from ISO 9300 values %
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
1	20	PSGS	1.13E+06	288.5	0.9966	0.9933	0.33
2	18		1.04E+06	266.1	0.9971	0.9932	0.39
3	16		9.25E+05	235.7	0.9976	0.9931	0.46
4	14		8.00E+05	203	0.9982	0.9929	0.54
5	12		6.98E+05	176.3	0.9982	0.9926	0.56
6	10		5.92E+05	149.3	0.999	0.9924	0.67
7	8		4.66E+05	117.5	0.9993	0.9919	0.75
8	6		3.56E+05	89.53	0.9986	0.9913	0.74
9	4		2.43E+05	61.1	0.9959	0.9904	0.56
10	2		1.28E+05	32.01	0.9964	0.9883	0.81
11	1	PVTt	5.89E+04	14.37	0.9876	0.9847	0.30

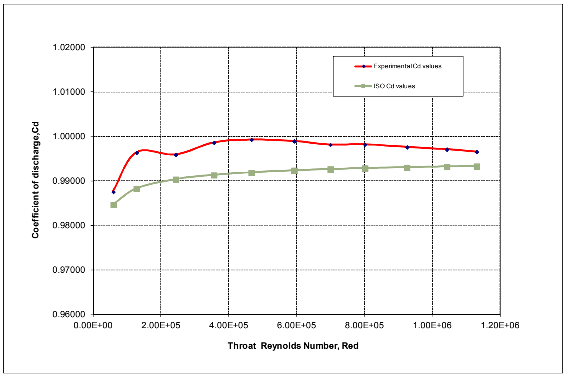


Fig 6 - Variation of Cd with Reynolds number for 12.5m3/h CFVN

Sl. No.	Nominal pressure bar a	Method adpted	Throat Reynolds number Red -	Coefficient of discharge Cd -	Coefficient of discharge using ISO equation Cd_{ISO} -	Deviation from ISO 9300 values %
[1]	[2]	[3]	[4]	[5]	[6]	[7]
1	16	PSGS	1.30E+06	0.9924	0.9935	-0.11
2	10		8.40E+05	0.9929	0.9929	0.00
3	6		5.00E+05	0.9923	0.9921	0.02
4	5		4.20E+05	0.9904	0.9917	-0.13
5	1.5	BELL PROVER	1.24E+05	0.9867	0.9882	-0.15
11	1	PVTt	8.28E+04	0.9826	0.9864	-0.39

Table 3- Cd values for 25m3/h flow capacity CFVN

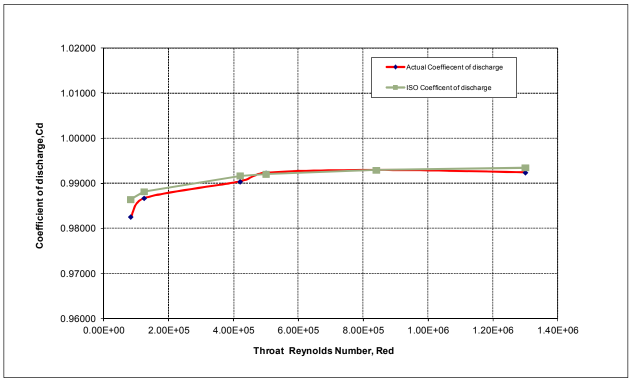


Fig 7- Variation of Cd with Reynolds number for 25m3/h CFVN

9. ESTIMATION OF UNCERTAINTY IN PVTT & PSGS METHODS OF CALIBRATION.

The overall uncertainty in the calibration of critical flow venturi nozzle using $PVTt$ and PSGS 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:

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

Where P_0 and T_0 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:

$$2. \quad C_d = m_a / m_t$$

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 PSGS 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 PSGS method and PVTt are given in Tables 4 & 5

$E_s(P)$	±0.03%
$E_s(V)$	±0.1%
$E_s(T)$	±0.28%
$E_s(t)$	±0.007%
$E_s(P_o)$	±0.03 %
$E_s(M_e)$	±0.0013 %
$E_s(R)$	±0.01 %
$E_s(T_o)$	±0.28%

Table 4- (PSGS Method)

$E_s(M)$	±0.04%
$E_s(P)$	±0.02%
$E_s(T)$	±0.28%
$E_s(t)$	±0.002%
$E_s(P_o)$	±0.02%
$E_s(M_e)$	±0.0013%
$E_s(R)$	±0.01%
$E_s(T_o)$	±0.28%

Table 5- (PVTt method)

Expanded uncertainties in the Primary standard facilities of FCRI, PVTt and PSGS methods are estimated as better than 0.1% as per NABL 141 guidelines.

10. OBSERVATIONS BASED ON EXPERIMENTAL DATA

- Deviation between ISO Cd values and Cd values obtained by PVTt method and PSGS method at 1bar abs & 2bar abs results are matching and magnitude of deviation (0.75%) is same as indicated in the previous table for SN5.
- Generally increasing trend in Cd values is seen with increase of Reynolds number.
- Same trend is reported in ISO 9300 equation also.
- Variation of 1% is reported in ISO equation with variations in operating pressures from 1 to 20 bar abs.
- Maximum variation of 0.9 % is observed in Cd values obtained by experimental method in the operating pressures from 1 to 20 bar abs.
- At higher operating pressures deviation of Cd from ISO values is only 0.4%.
- Deviation up to 0.9% is observed for lower operating pressures (From ISO values).
- There could be an uncertainty component of the order of ±0.3 to 0.4% in Cd values due to variations in pressure from 2 to 20bar and the same has to be accounted in uncertainty estimates.
- At Higher Reynolds number the experimental Cd values are more closer to ISO values.
- Closeness to ISO Cd values is more dependent on operating density and hence the Reynolds number rather than the throat diameter of the nozzle.

11. CONCLUSION

- Experimental Cd values can vary up to 0.9 % from ISO values depending on operating pressures from 1 bar abs to 20bar abs.
- For 25m3/h CFVN also for higher Reynolds number deviation of Cd from ISO values is lesser when compared to lower Reynolds number values.
- With increase in Reynolds number Cd values are closer to ISO values.
- Instead of assuming constant values of Cd, for the operating pressure range from 1 to 20bar abs,

interpolated Cd values based on Reynolds number is to be used for flow estimation in precision flow calibration application.

- Possible causes for Cd variations from ISO values may be due to Machining inaccuracies, surface finish variations, straight length requirement variations, disturbances in flow due to upstream fittings etc of CFVN from ISO recommendations.
- Recommended Surface roughness for throat and inlet profile of CFVN has to be better than 15×10^{-6} d as per ISO recommendations. Roughness values of in-service CFVN's at FCRI facilities are on the higher side by 10 to 20 %.

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