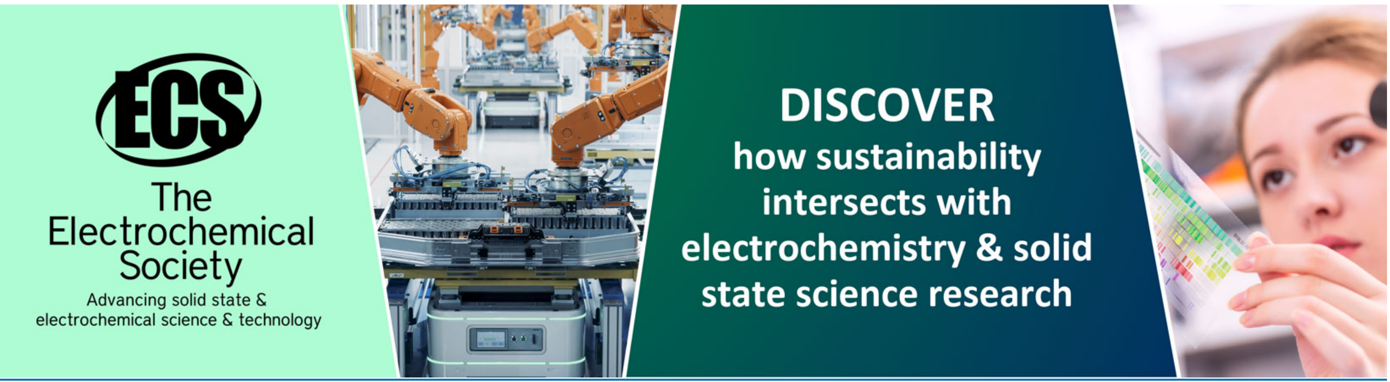
Characterization of the Venturi flowmeters for the control of ITER magnets



IOP Conf. Series: Materials Science and Engineering **502** (2019) 012166 doi:10.1088/1757-899X/502/1/012166

Characterization of the Venturi flowmeters for the control of ITER magnets

S Varin[1], J–M Poncet[*1], J André[1], E Ercolani[1], N Luchier[1], C Mariette[1], N Clayton[2], J-Y Journeaux[2]

[1] Univ. Grenoble Alpes, CEA, INAC-SBT, 38000 Grenoble, France
[2] ITER Organization, Route de Vinon-sur-Verdon, 13115 Saint Paul-lez-Durance, France

E-mail: sandra.varin@cea.fr or jean-marc.poncet@cea.fr

Abstract. Within the framework of the ITER project, CEA/SBT is in charge of the design, manufacturing and delivery of 277 Venturi flowmeters. The latter were developed for either the control of the supercritical helium flow in the magnets at cryogenic temperature (4.5 K) or the operation of the current leads at room temperature. Depending on the temperature, the values of the Reynolds number in the Venturi tubes are significantly higher or lower than those specified in the standard NF EN ISO 5167-4 regarding the design of Venturi flowmeters. An experimental determination of the flowmeter coefficient was therefore required. Due to the large number of flowmeters, a manufacturing strategy was developed in order to obtain a reproducible behaviour. This strategy was validated by the experimental results obtained at room and cryogenic temperature.

1. Introduction

Since June 2014, CEA-SBT has been contracted to supply 277 Venturi tube flowmeters to the Magnet Division of the ITER Organization. In June 2018, the last Venturi tubes were delivered.

The characteristics and operating conditions of each type of Venturi tubes are listed in Table 1. These flowmeters will be used to operate the superconducting magnet system of the ITER tokamak. Two types (*i.e.* DN8 and DN10) are dedicated to the operation of the current leads at room temperature while the other types will be used for the control of the supercritical helium flow in the magnets at cryogenic temperature. The former are referred to as warm flowmeters while the latter are referred to as cold flowmeters. DN25 flowmeters were also manufactured in a three-pressure-tap configuration allowing secondary quench detection [1].

Table 1. List and characteristics of the Venturi tubes.

Size	Mass flowrate	Temperature	Pressure	Reynolds number	Number
DN8	0.1 to 1 g/s	Near 300 K	3.8 to 4 bar	6×10^2 to 6×10^3	18
DN10	1 to 7 g/s	Near 300 K	3 to 4 bar	3×10^3 to 3×10^4	42
DN15.20	2 to 20 g/s	4.2 to 6 K	4 to 10 bar	4×10^4 to 5×10^5	89
DN15.30	3 to 30 g/s	4.2 to 6 K	4 to 10 bar	6×10^4 to 8×10^5	28
DN20	13 to 130 g/s	4.2 to 6 K	4 to 10 bar	2×10^5 to 3×10^6	40
DN25	40 to 400 g/s	4.2 to 6 K	4 to 10 bar	4×10^5 to 6×10^6	60

[*] To whom any correspondence should be addressed

As the values of the Reynolds number in the Venturi tubes were not included in the range specified in the standard NF EN ISO 5167-4 regarding the design of Venturi flowmeters, an experimental characterization of the flowmeter was necessary. A manufacturing strategy was developed in order to reduce the uncertainty of measurement and obtain a reproducible behaviour. An experimental determination of the flow coefficient of the Venturi tubes was performed at room and cryogenic temperature. The strategy and the experimental results are presented in this paper.

2. Sizing and manufacturing strategy

2.1. Sizing

The Venturi tubes were designed following the French and European standard NF EN ISO 5167-4 [3], even though this standard was not strictly applicable for the ranges of Reynolds number defined in Table 1 [1]. In the experience of CEA-SBT, this method of design can allow high-accuracy measurement, provided that the flow coefficient, which takes into account the fluid compressibility and the pressure losses in the Venturi tube, is measured.

The mass flowrate in a Venturi tube is derived from the Bernoulli's equation as follows (1):

$$\dot{m} = \theta.\frac{\pi.}{2\sqrt{2}}.(d^{-4} - D^{-4})^{-0.5}.\sqrt{\rho(P_D, T_D).(P_D - P_d)} \quad (1)$$

where:

$\dot{m}$:	mass flowrate	D, d:	upstream and neck diameters, respectively
θ:	flow coefficient	P_D, T_D:	pressure and temperature in the upstream pipe
ρ:	density of the fluid	P_d:	pressure at the neck diameter

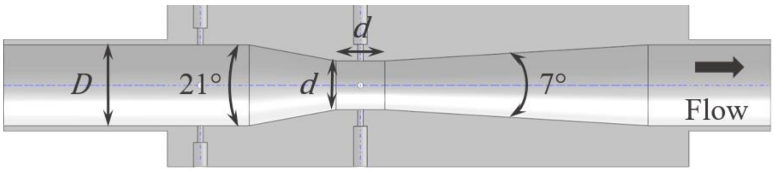


Figure 1. Geometry of the Venturi gas stream.

2.2. Measurement accuracy

The measurement accuracy of the flowmeters results from the parameters that were determined during the test phase at CEA-SBT and those that will be determined during the operation of the ITER machine. The measurement accuracy can be calculated using the following formula, which was established in [1].

$$\frac{\mathrm{d}\dot{m}}{m} = \sqrt{\begin{array}{l}\left(\frac{\mathrm{d}\dot{m}_m}{\dot{m}_m}\right)^2 + 2.\left(\frac{2.d^4}{(D^4-d^4)}.\frac{\mathrm{d}D}{D}\right)^2 + 2.\left(\frac{2.D^4}{(D^4-d^4)}.\frac{\mathrm{d}d}{d}\right)^2 + \left(\frac{\mathrm{d}(\Delta P_m)}{2.\Delta P_m}\right)^2 + \left(\frac{\mathrm{d}(\Delta P)}{2.\Delta P}\right)^2 \\ +\left(\frac{1}{2.\rho_m}.\left(\left(\frac{\partial\rho}{\partial T}\right)_P \mathrm{d}T_m + \left(\frac{\partial\rho}{\partial P}\right)_T \mathrm{d}P_m\right)\right)^2 + \left(\frac{1}{2.\rho}.\left(\left(\frac{\partial\rho}{\partial T}\right)_P \mathrm{d}T + \left(\frac{\partial\rho}{\partial P}\right)_T \mathrm{d}P\right)\right)^2\end{array}} \quad (2)$$

Where the subscript m refers to the measurement performed at CEA/SBT.

The geometry of the flowmeters as well as the determination of the flow coefficient have an impact on the overall uncertainty, hence the manufacturing strategy detailed in the following section.

2.3. Manufacturing strategy

Prior to this project, the Venturi tubes designed by CEA-SBT were tested individually after being manufactured in order to determine their respective flow coefficient. An individual characterization of the flowmeters was needed as the behaviour was likely to vary from one flowmeter to another. This manufacturing strategy was perfectly adequate for a small number of flowmeters.

For this project, the individual characterization of each flowmeter would have been too costly and time-consuming, due to the large number of Venturi tubes, *i.e.* 277. A new approach consisting in setting tight dimensional tolerances (*e.g.*: between ±0.02 and ±0.05 mm on diameters, ⌀0.02 on concentricity) was therefore adopted in order to obtain a reproducible behaviour. All flowmeters underwent a dimensional control in order to ensure the tolerances were met and reduce the uncertainty of measurement of the flowmeters (*e.g.*: the uncertainty on diameters became lower than ±0.002 mm after measurement). The latter depends on the geometry, as detailed in (2). The flow coefficient was determined for each type of flowmeters by testing a few flowmeters in operating conditions. 7 DN8 and 10 DN10 flowmeters were tested while 3 flowmeters were tested for each type of cold flowmeters, *i.e.* DN15, DN20 and DN25 flowmeters.

3. Apparatus and method for the characterisation of flowmeters

Warm flowmeters and cold flowmeters were tested on two different test benches. Warm flowmeters were tested on the test bench shown in Figure 2. The test bench was fed with helium at 16 bar and ambient temperature provided by a compressor. The pressure and mass flowrate were adjusted in the circuit via manual valves. The flow coefficient of the tested Venturi tube was determined by comparison with a Coriolis flowmeter. The temperature and pressure at the upstream of the Venturi tube as well as the differential pressure, *i.e.* the difference between the upstream pressure and the pressure at the restriction, were measured for this purpose.

Cold flowmeters were tested on the Helios loop (HElium Loop for hIgh lOads Smoothing), as shown in Figure 3. This loop was cooled by a helium refrigerator producing 800 W @ 4.5 K. A circulating pump allowed supercritical helium to flow through the Helios loop, which included two heat exchangers that were immersed in a liquid helium bath and the three branches where the Venturi tubes were installed. Each branch included three Venturi tubes, one Coriolis flowmeter and thermometers at the upstream of each Venturi tube. Manual valves at room temperature allowed the measurement of the upstream pressure and differential pressure of the three Venturi tubes of any given branch. For both cold and warm flowmeters, the flow coefficient of each Venturi tube was determined by comparison with a Coriolis flowmeter and averaged over a duration greater than 5 minutes. This measurement was repeated for different conditions of pressure, temperature and mass flowrate

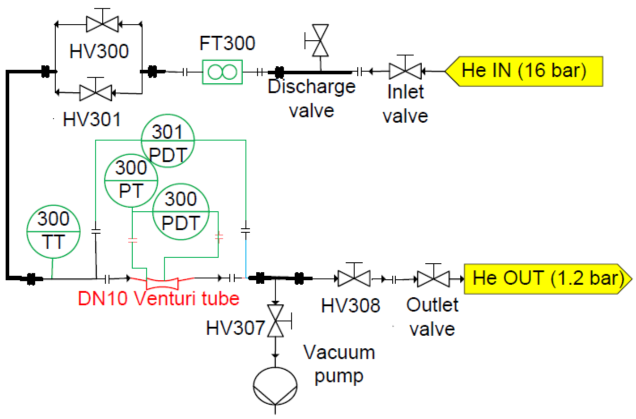


Figure 2. Process Flow Diagram of the warm bench.

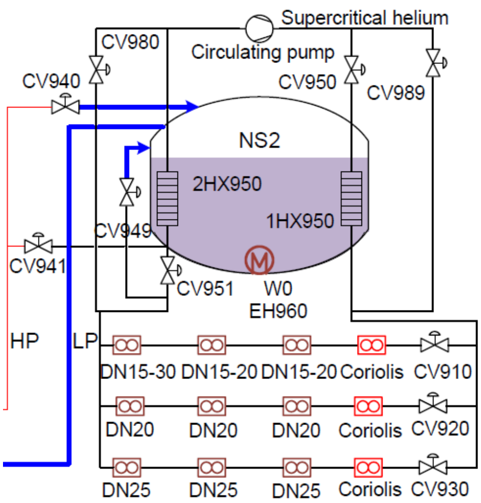


Figure 3. Simplified process Flow Diagram of the Helios loop.

4. Results

4.1. Warm flow test

The test of warm flowmeters were performed at ambient temperature for the different ranges of pressure and mass flowrate specified in Table 1 and, consequently, for pressures up to 4 bar and mass flowrates up to 7 g/s.

The flow coefficient of warm flowmeters was found to be dependent of the pressure as well as the differential pressure (and by extension the mass flowrate), as shown in Figure 4. The flow coefficient increased as the mass flowrate rose at low mass flowrates. At higher mass flowrates, the flow coefficient was stable, except for DN10 flowmeters for which a slight decrease in flow coefficient was observed at full-range at 3 bar. For each type of warm flowmeters, similar results were obtained for the different tested flowmeters with a relative difference between flow coefficients lower than 2% at full-range. The mean value of the flow coefficient and its uncertainty is shown in Figure 4. The values of the flow coefficient were all included in the interval [mean – uncertainty, mean + uncertainty].

4.2. Cold flow test

Cold flowmeters were tested for 7 couples of pressure and temperature, *i.e.* (4.5 K, 4 bar), (4.5 K, 5 bar), (4.5 K, 8.5 bar), (5 K, 5 bar), (5.9 K, 4 bar), (5.9 K, 5 bar) and (5.9 K, 8.5 bar) for different ranges of mass flowrates. The latter are specified in Table 1, except for DN25 flowmeters. The DN25 flowmeters were not tested up to their full range of mass flowrate due to the available power of the CEA-SBT refrigerator. The maximum achievable mass flowrate on the Helios loop ranged from about 250 to 330 g/s depending on the conditions of pressure and temperature. As shown in Figure 5, the flow coefficients were found to remain constant when the operating conditions changed (pressure, temperature or mass flowrate). This behaviour differed from that obtained for warm flowmeters. This difference might result from the high values of the Reynolds number that were observed for cold flowmeters (see Table 1). The uncertainty on the flow coefficient is shown for two couples of pressure and temperature, *i.e.* (5 K, 5 bar) and (5.9 K, 4 bar), in Figure 5. The flow coefficients fell within the interval [mean – uncertainty, mean + uncertainty]. Similar results were obtained for flowmeters of a given type with a relative difference between flow coefficients lower than 3% at full-range.

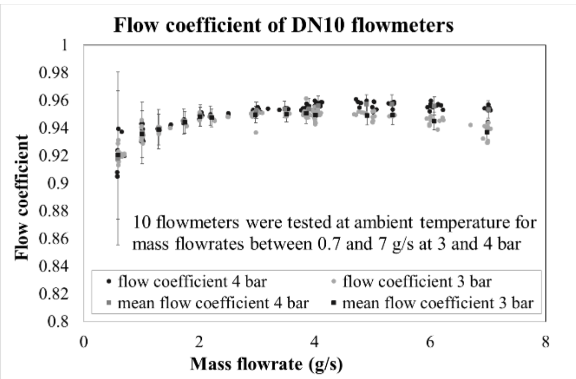


Figure 4. Flow coefficient of DN10 flowmeters.

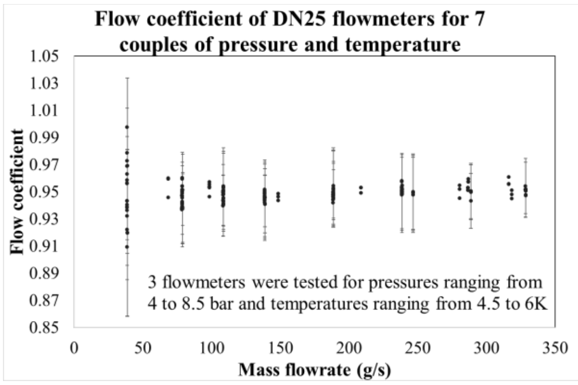


Figure 5. Flow coefficient of DN25 flowmeters.

5. Validation of the manufacturing strategy

The purpose of these tests was to determine the flow coefficient of each type of flowmeters, validate the design of the flowmeters and validate the manufacturing strategy.

For cold flowmeters, the value of the flow coefficient was found to be constant and could be simply implemented on the ITER machine. On the contrary, the flow coefficient of warm flowmeters was found to be dependent of the differential pressure. As the latter will be measured on the ITER machine, flow coefficient were fitted as a function of the differential pressure. This would allow the generation of data tables that could be implemented on the ITER machine.

Figure 6 and Figure 7 shows the probable error on the measurement of the mass flowrate after considering the uncertainty due to the determination of the flow coefficient. The measurement accuracy of the flowmeter decreases as the mass flowrate decreases. The effect of pressure and temperature on the measurement accuracy was previously discussed in [1].

The experimental flow coefficients were similar to those established during design calculation with a maximum difference at full-range of about 4% for DN25 flowmeters and about 2% for the others. A reproducible behaviour was obtained for all tested flowmeters of a given type, with a difference in flow coefficient lower than 3% at full-range. This validated the approach consisting in setting tight dimensional tolerances and testing a few flowmeters in operating conditions.

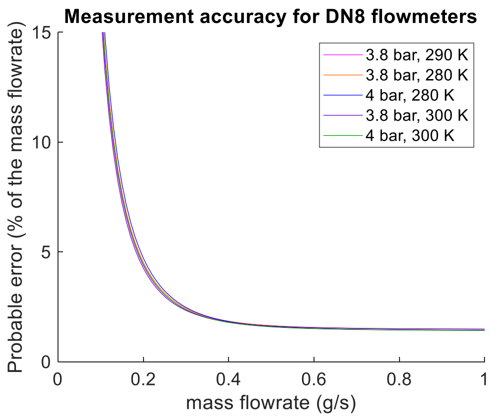


Figure 6. Measurement accuracy for DN8 flowmeters.

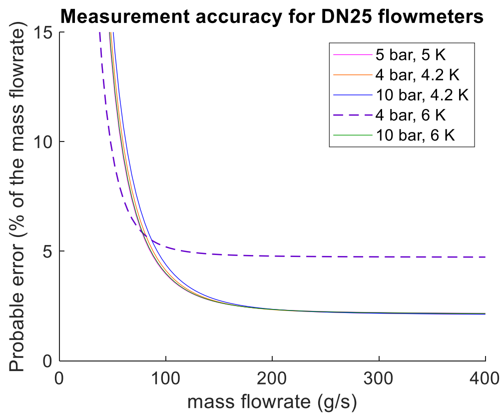


Figure 7. Measurement accuracy for DN25 flowmeters.

6. Conclusion

17 warm flowmeters and 9 cold flowmeters were tested at various conditions of pressure, temperature and mass flowrate in order to determine their flow coefficient. Reproducible results were obtained between the flowmeters of a given type. This shows the relevance of the approach consisting in setting tight dimensional tolerances and testing a few flowmeters in operating conditions. For cold flowmeters; the flow coefficients were found to remain constant when the operating conditions changed (pressure, temperature or mass flowrate), as expected. As for warm flowmeters, flow coefficient fits as a function of the differential pressure were established. The flow coefficients that were determined and the measurement of the geometry that had been previously performed will allow the measurement of the mass flowrate on the ITER machine.

Acknowledgements

The authors would like to thank N. Besson, P. Nivelon, M. Bon-Mardion, A. Delattre, A. Attard, P. Bonnay, J. Ceszkowski, F. Bancel, B. Rollet and J. Manzagol for their technical support and fruitful discussions.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organisation.

References

[1] André J, Poncet J-M, Ercolani E, Clayton N and Journeaux J-Y 2015 Series Supply of Cryogenic Venturi Flowmeters for the ITER Project *IOP Conf. Ser.: Mater. Sci. Eng.* **101** 012155

[2] Poncet J-M, Manzagol J, Attard A, André J, Bizel-Bizellot L, Bonnay P, Ercolani E, Luchier N, Girard A, Clayton N, Devred A, Huygen S, Journeaux J-Y 2017 Cryogenic instrumentation for ITER magnets *IOP Conf. Ser.: Mater. Sci. Eng.* **171** 012130

[3] NF EN ISO 5167-4 2003 Mesure de débit des fluides au moyen d'appareils déprimogènes insérés dans des conduites en charge de section circulaire *AFNOR* pp.1-6.

[4] Serio L 2007 A cryogenic helium mass flowmeter for the Large Hadron Collider *PhD thesis (Cranfield University)* pp 110-114.