Series Supply of Cryogenic Venturi Flowmeters for the ITER Project

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Abstract. In the framework of the ITER project, the CEA-SBT has been contracted to supply 277 venturi tube flowmeters to measure the distribution of helium in the superconducting magnets of the ITER tokamak. Six sizes of venturi tube have been designed so as to span a measurable helium flowrate range from 0.1 g/s to 400g/s. They operate, in nominal conditions, either at 4K or at 300K, and in a nuclear and magnetic environment. Due to the cryogenic conditions and the large number of venturi tubes to be supplied, an individual calibration of each venturi tube would be too expensive and time consuming. Studies have been performed to produce a design which will offer high repeatability in manufacture, reduce the geometrical uncertainties and improve the final helium flowrate measurement accuracy. On the instrumentation side, technologies for differential and absolute pressure transducers able to operate in applied magnetic fields need to be identified and validated. The complete helium mass flow measurement chain will be qualified in four test benches: - A helium loop at room temperature to insure the qualification of a statistically relevant number of venturi tubes operating at 300K.- A supercritical helium loop for the qualification of venturi tubes operating at cryogenic temperature (a modification to the HELIOS test bench). – A dedicated vacuum vessel to check the helium leak tightness of all the venturi tubes.- A magnetic test bench to qualify different technologies of pressure transducer in applied magnetic fields up to 100mT.

1. Introduction
Since June 2014, CEA-SBT has been contracted to supply 277 venturi tube flowmeters to measure the distribution of helium in the superconducting magnets of the ITER tokamak. Six sizes have been designed to cover the full range (table 1). Furthermore, the largest size is supplied in two configurations: a two-pressure-tap configuration (classical configuration to measure helium mass flowrate) and a three-pressure-tap configuration, to measure flowrate and to be used as secondary quench detection (measurement of back flow).

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Table 1. List & characteristics of series of the venturi tubes.

| Size    | Mass flowrate | Temperature | Pressure | number |
|---------|---------------|-------------|----------|--------|
| DN8     | 0.1 to 1 g/s  | Near 300 K  | 3 to 4 bars | 18     |
| DN10    | 1 to 7 g/s    | Near 300 K  | 3 to 4 bars | 42     |
| DN15.20 | 2 to 20 g/s   | 4.2 to 6 K  | 4 to 6 bars | 89     |
| DN15.30 | 3 to 30 g/s   | 4.2 to 6 K  | 4 to 6 bars | 28     |
| DN20    | 13 to 130 g/s | 4.2 to 6 K  | 4 to 6 bars | 40     |
| DN25    | 40 to 400 g/s | 4.2 to 6 K  | 4 to 6 bars | 42     |
| DN25.3TAP | 40 to 400 g/s | 4.2 to 6 K  | 4 to 6 bars | 18     |

In addition to the supply, different tests will be performed in order to guarantee the correct operation of the entire acquisition chain:
- The qualification of 16 venturi tubes at room temperature; this test is a qualification of a statically relevant number of “warm venturi tubes”
- The qualification of 9 venturi tubes in cryogenic conditions
- The leak check of all the venturi tubes
- The identification and the test of 8 pressure transducers (4 absolute and 4 differential) in magnetic fields of 100mT.

Due to the number of venturis to be supplied, the required measurement accuracy and the specific conditions of use, a dedicated production process has been developed. This comprises the detailed design of the venturis, the development of specific tests benches and the organization of the manufacturing activities.

The first part of this article explains the drivers for the design, reports the measurement accuracy estimations and presents the specific process developed for the manufacturing control of these venturi tubes. The second part details the four test benches manufactured to perform all the qualification tests. The test bench design took into account criteria such as: repeatability of manufacturing, reduction of cost and manpower needs.

2. Sizing and measurement accuracy estimation

2.1. Sizing of venturi flowmeters

The venturi Flowmeters for ITER have been designed following the standard NF EN ISO 5167-4 [1] even if this standard is not strictly applicable in our case:
- The diameter of the upstream (D) pipe is smaller than 50 mm
- The Reynolds number in the upstream pipe is less than $2 \times 10^5$ for flowmeters operating at room temperature
- The Reynolds number in the upstream pipe is greater than $2 \times 10^6$ for flowmeters operating at around 4 K with supercritical helium
- The general design of the helium stream is given in the following figure (figure 1).
Nevertheless the CEA/SBT experience is that such a design can give good results in cryogenic conditions. A key point is that the flowrate coefficient, which takes into account the fluid compressibility and the pressure losses in the venturi, must be measured in order to achieve high accuracy flowrate measurements.

The mass flow rate in a venturi can be derived from the Bernoulli relation, adapted for venturi flowmeters (1):

$$m = \alpha \frac{\pi}{2 \sqrt{2}} (d^{-4} - D^{-4})^{-0.5} \sqrt{\rho (P_D, T_D)} (P_D - P_d)$$

where:

- \(m\): mass flow rate
- \(\alpha\): flowrate coefficient
- \(D\) and \(d\): upstream and neck diameters respectively
- \(P_d\) and \(T_d\): pressure and temperature in the upstream pipe
- \(\rho\): density of the fluid
- \(P_d\): pressure at the neck diameter

All sizes of venturi flowmeter have been designed to have the same differential pressure \((\Delta P = P_D - P_d = 200 \text{ mbar})\), so as to use only one kind of differential pressure transducer.

### 2.2. Measurement accuracy

As for all measuring tools, the results obtained include some uncertainties. For the venturi flowmeters installed at ITER, two sources can be identified: uncertainties that come from parameters measured during the operation of the ITER machine \((P_D, T_D, \Delta P)\) and those measured during the manufacturing and tests of the flowmeters \((\alpha, D, d)\). \(D\) and \(d\) will be measured for each flowmeter in order to minimize the geometrical error, and \(\alpha\) will be statistically estimated at the CEA/SBT laboratory in two dedicated test benches in order to minimize the cost of this part of the work.

To estimate the flowrate coefficient, all the physical values have to be measured and this includes the mass flow rate. CEA/SBT has proposed to use a Coriolis flowmeter as CERN has demonstrated the capability of this technology to operate at cryogenic temperature [2]. It turns out that some uncertainties appear twice (on \(P_D, T_D, \Delta P\)): the first time during the measurement in the lab and the second time during the operation in the ITER machine. To distinguish the two cases, an index \(m\) is added for the measurements performed in the laboratory. By differentiation of formula (1), the relation which links the uncertainties can be calculated.

$$\frac{da}{\alpha} = \frac{dm_m}{m_m} + \frac{2d^4}{(D^4-d^4)} \frac{db}{b} - \frac{2D^4}{(D^4-d^4)} \frac{dd}{d} - \frac{1}{2 \rho_m} \left( \left( \frac{\partial \rho}{\partial P} \right)_T dT_m + \left( \frac{\partial \rho}{\partial T} \right)_P dP_m \right) - \frac{d(\Delta P_m)}{2\Delta P_m}$$

$$\frac{dm}{m} = \frac{da}{\alpha} - \frac{2d^4}{(D^4-d^4)} \frac{db}{b} + \frac{2D^4}{(D^4-d^4)} \frac{dd}{d} + \frac{1}{2 \rho} \left( \left( \frac{\partial \rho}{\partial T} \right)_P dT + \left( \frac{\partial \rho}{\partial P} \right)_T dP \right) + \frac{2(\Delta P)}{2\Delta P}$$

The flowrate coefficient will be measured on several venturi flowmeters (of a given size) and will then be applied to all venturis of that size. This results in the geometrical uncertainties being taken into account twice. If a quadratic error is calculated, the uncertainties follow the formula (4):

$$\frac{dm}{m} = \sqrt{\left( \frac{dm_m}{m_m} \right)^2 + 2 \left( \frac{2d^4}{(D^4-d^4)} \frac{db}{b} \right)^2 + 2 \left( \frac{2D^4}{(D^4-d^4)} \frac{dd}{d} \right)^2 + \left( \frac{d(\Delta P_m)}{2\Delta P_m} \right)^2 + \left( \frac{2(\Delta P)}{2\Delta P} \right)^2}$$
During ITER magnet operation, cold flowmeters will operate at temperatures between 4.2 K and 6 K and at pressures between 4 bars to 10 bars. In these conditions, the flowmeters will work near the helium critical point (2.27 bars, 5.2K) where there is a strong dependence of the helium density with the temperature. The consequence is a significant variation of the uncertainty on the mass flow measurement depending on the operating point. Figure 2 shows the uncertainty obtained in the estimation of the density of the helium depending on the pressure and the temperature. This result is obtained with an assumed uncertainty of 2.5 % for the temperature measurement and 0.2 % (full scale) for the pressure measurement.

An absolute error of 2 µm is assumed for the geometrical measurements. The measurement error on the mass flow rate as measured by the Coriolis flowmeter is estimated to be 2 %. Figure 3 shows the estimated error on the mass flow rate measured by a DN25 venturi flowmeter, once all the uncertainties are taken into account. A significant variation is observed (up to a factor 5) depending on the operating point of the venturi tube.

3. Implementation

3.1. Manufacturing organization

Figure 3 shows the manufacturing workflow which has been implemented in order to simplify the required tests and to ensure the quality of all the venturi tubes. The pressure transducer test is independent of the venturi tube manufacturing so it does not appear in this scheme. A metrology step has been implemented immediately after the venturi has been machined, but before any welding operations take place. This measurement of the geometry of the gas stream is made on all venturis, and results in a reduction of the geometrical uncertainties. Moreover, this allows CEA-SBT to perform a statistical estimation of the flowrate coefficient $\alpha$. After the metrology step, the venturi undergoes welding operations before being subjected to a thermal shock, and then helium leak test under pressure. The venturis are prepared in one of two intermediate configurations, see figure 4a and 4b.
In the “closed” configuration (figure 4a) three of the four open ports are welded closed with a plug. A VCR fitting is welded to the remaining port (the upstream pressure tap). It is through this port that the venturi is pressurised with helium gas up to the test pressure of 43 bar. The venturi is placed inside a dedicated vacuum vessel (figure 5a) for the leak test. The “connected” configuration (figure 4b) is adapted to the mass flowrate qualification of the venturi. Dedicated fittings are welded onto all four open ports to facilitate connection to the warm or cold helium flowrate measurement benches. (Figure 5b and 5d). In order to perform a leak test of a venturi in the “connected” configuration, all the openings (except the upstream pressure tap) are closed using plugs and metal seals.

In the final step, the venturis are returned to the manufacturer for removal of all fittings by spark machining before delivery to ITER (figure 4c).
3.2. Test bench description

3.2.1. Leak test bench (figure 5a)
This test bench has two purposes: firstly to measure the leak tightness of the venturi tube by connecting the vacuum chamber of the bench to a helium spectrometer and by injecting helium inside the venturi. The second is a test under pressure which is required for pressure equipment. For these tests, only one connection (the upstream pressure tap) on the venturi is used, and this is the case for all sizes of venturi tube. Five venturi tubes are tested during each run to reduce the manpower required and the vacuum pumping time. In the distribution piping, the number of pressure transducer had been reduced to only 1 thanks to a system of valves. Each time a valve is opened (to connect to one venturi under test), the increase of volume entails a decrease of pressure in the line. The recovery to the initial pressure demonstrates that the venturi under test has indeed been pressurized with helium. The pressure in the venturi as well as the measured leak rate is recorded. If a leak is detected, the venturi tube which has failed can be identified and isolated from the other venturis under test.

3.2.2. Magnetic bench (figure 5b)
The aim of this test is to identify pressure transducers which are able to accurately measure the pressure when subjected to a magnetic field of 100 mT. The pressure transducers in the ITER machine will be subjected to such a magnetic field. The behaviour of 8 sensors will be characterised in a constant magnetic field applied in three directions. Four different technologies of pressure transducer will be tested: piezoelectric, capacitive, resistive and optical. These tests will be performed in a superconducting coil available in CNRS-CRETA (France). A dedicated test bench has been designed to react the magnetic forces and to guarantee the position of the pressure transducers.

During the tests, the pressure transducers will be mounted in a cubic stainless steel frame. The frame is inserted in a cubic support which allows orientation in three directions in the applied magnetic field. This cubic support has two functions: to maintain the sensor mechanically and to connect the sensor to the gas piping. This piping is also connect to a valve panel with two pressure transducers, located far from the magnetic field, which are used as reference sensors.

3.2.3. Warm flowrate measurement bench (figure 5c)
The warm (300 K) flowrate measurement bench will be used to qualify sixteen “warm” venturi tubes, one at a time. The principle is to determinate the flowrate coefficient $\alpha$ by using a coriolis flowmeter as a reference sensor. This estimation could be made with helium gas (supplied from the warm station kof the \textit{400 W @1.8K} cryorefrigerator) or with nitrogen gas.
As advocated in [1], the absolute pressure and temperature are measured at the upstream pressure tap of the venturi tube. The differential pressure is measured between the two pressure taps. In order to estimate the pressure drop across the whole of venturi tubes, a differential pressure transducer is also installed between the upstream and the downstream ports of the venturi.

![Figure 6. Simplified process flow diagram of the cold bench.](image)

3.2.4. Cold flowrate measurement bench (figure 5d)

This bench is a modification of our supercritical and cryogenic loop, called “HELIOS” (HElium Loop for high LOaded Smoothing). This bench will be used to qualify the performance of the three sizes of cryogenic venturi. Three examples of each venturi size will be tested in series (figure 6). The principle of this bench is similar to that of the warm bench:

- The flowrate coefficient $\alpha$ is estimated by comparison with a reference flowmeter at cryogenic temperatures.
- The pressure losses in the venturi tube are also measured.

The reference measurement of the mass flowrate will be performed in two ways: by thermal estimations and/or by coriolis flowmeter (as describe in [2]). For the largest mass flow rates, only the comparison with coriolis flowmeter can be performed due to the limited power of our refrigerator.

Each series of venturi will be tested in stable conditions. A set of switching valves is used to reduce the number of pressure sensors. As shown by the measurement accuracy calculations, the thermometry needs to be particularly well implemented in order to obtain good overall flowrate measurement accuracy. Dedicated thermometric supports (with copper “fingers” inserted into the fluid stream) will be used.

4. Conclusion

At the date of the conference, the project is still in the pre-production phase. The warm flowrate bench and the leak test bench have already been manufactured. The magnetic test bench is currently being
manufactured, and the technical specifications for the modification to the cold flowrate test bench are being finalised. The supply contract for the manufacture of the venturi tubes is due to be signed imminently with a subcontractor and we are confident to our manufacturing process. In addition to the manufacturing know-how, the critical points of the project are the measurement of temperature and mass flowrate in cryogenic conditions. For the former, CEA-SBT will use its skills to perform the measurement with good accuracy (CEA-SBT is also in charge of the supply of 2200 thermometric chain for the ITER Magnets). For the latter, we have already used a coriolis flowmeter [2] in previous applications with good results. Furthermore, two new coriolis flowmeters have been procured and benchmarked against older coriolis flowmeters; the initial analysis indicates very good correlation between these measurements.

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Disclaimer
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization

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