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**RECENT DEVELOPMENTS AND QUALIFICATION
OF CRYOGENIC HELIUM FLOW METERS**

A. Bézaguet¹, A. Rivetti² and L. Serio¹

Flow measurement of cryogenic fluids is a useful diagnostic tool not only to assess thermal performance of superconducting devices and related components but also for early diagnosis of faulty components/systems and to assure the correct sharing of cryogenic power. It is mainly performed on the recovery at room temperature of vapor from liquid boil-off due to lack of commercially available robust and precise cryogenic mass flow meters. When high-accuracy or fast-time response is needed, or individual gas recovery at room temperature is not available, it is necessary to measure directly the fluid feed at cryogenic temperature. The results of extensive testing of industrially available and in-house developed flowmeters outlining characteristics and advantages of each measuring method are presented.

1 LHC Division, CERN, Geneva, Switzerland

2 IMGC, Istituto di Metrologia "G. Colonnetti", Torino, Italy

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A. Bézaguet¹, A. Rivetti² and L. Serio¹

¹LHC Division, CERN, 1211 Geneva 23, Switzerland

² IMGC, Istituto di Metrologia “G. Colonnetti”, Strada delle Cacce 73, I-10135 Torino

ABSTRACT

Flow measurement of cryogenic fluids is a useful diagnostic tool not only to assess thermal performance of superconducting devices and related components but also for early diagnosis of faulty components/systems and to assure the correct sharing of cryogenic power. It is mainly performed on the recovery at room temperature of vapor from liquid boil-off due to lack of commercially available robust and precise cryogenic mass flow meters. When high-accuracy or fast-time response is needed, or individual gas recovery at room temperature is not available, it is necessary to measure directly the fluid feed at cryogenic temperature. The results of extensive testing of industrially available and in-house developed flowmeters outlining characteristics and advantages of each measuring method are presented.

INTRODUCTION

It has been reported in a previous paper (Casas and Serio 1998) that flow metering of cryogenics at room temperature is well defined and instruments of various types are industrially available; the same is not valid for flow measurements at low temperature. A rather scarce literature and the unavailability of commercial devices makes it difficult to identify and correctly operate a flow meter with helium at cryogenic temperature. Furthermore, the lack of tests and calibration facilities reduces the chance to measure a cryogenic helium flow with accuracy better than 10 %. A comprehensive list and description of cryogenic helium flow measuring devices was established several years ago by Rivetti *et al.* (1996). The paper describes devices available at the time (mainly Venturi and turbine flow meters) together with their intrinsic limitations and needs for calibration, but also remarkably foresees new possible methods of flow measurements at cryogenic temperature that have been finally tested and proven reliable and accurate in the present paper despite technological difficulties.

1. TEST FACILITIES

In order to assess performances and characteristics of various types and makes of flow measuring devices, several test facilities were employed. Methods and devices that were developed in-house or commercially available were at first designed or adapted for cryogenic use, based on the analysis of the dynamic range of the measurement, the requirements of the cryogenic system and the fluid properties. Their possible performance and limitations were then theoretically analyzed before assembly. Once assembled and eventually tested in industry, the investigated instruments underwent an extensive test program comprising warm pressure and leak testing, cryogenic testing at CERN (performance and accuracy within ± 1.5 %), thermal cycling, cryogenic testing at an independent metrological laboratory (IMGC – Italy) with a calibration module of the

absolute type (Rivetti *et al.* 1994) accurate within $\pm 0.5\%$, radiation tests (Rausch and Tavlet 1999), long term reliability studies and zero stability/drift measurements at CERN superconducting magnets test facilities. The flow meters were tested at various flowrates between 0.5 g/s and 30 g/s, temperatures between 1.7 K and 10 K and pressures between 1 kPa and 0.5 MPa, using boiling as well as sub-cooled, supercritical and superfluid helium.

2. DEVELOPMENT AND INVESTIGATION OF CRYOGENIC VOLUMETRIC FLOW METERS

Volumetric flow meters are the most commonly used and developed type of cryogenic flow meters because of historical reasons mainly driven from the development for the oil industry where volumetric flow is still used as a standard for billing purposes. They are, however, not necessarily the best instruments for cryogenic use if the main goal is the measurement of the thermal performance of a superconducting device or the diagnostic of cryogenic cooling power distribution. If a mass flowrate needs to be ultimately measured it is necessary to take into consideration the cost, accuracy and increase in the measuring system complexity of temperature and pressure sensors devoted to determine helium density.

2.1 Turbines

Turbine meters working in liquids at room temperature are considered within the most accurate flowmeters if individually calibrated. The use of an additional turbine meter in series to detect possible variations of the calibration factor is also recommended. The cost of a turbine flow meter, if accuracy is required, is therefore relatively high. The flow meter tested was a standard turbine used also at room temperature. It is calibrated in water and then a scaling factor is used. It showed large errors (about $\pm 17\%$ accuracy) in the calibration factor and after few thermal cycles a variation of the calibration factor was detected and the turbine behaved as if the friction between rotor and stator had increased. An alternative turbine meter, characterised by a magnetic passive suspension of the rotor was also considered. This turbine, developed by IMGC on the basis of a previous prototype (Rivetti *et al.*, 1987), has a rotor magnetically levitated through the interaction between a magnet situated on the rotor and melted YBCO superconductors on the body. Its design is characterised by an electro-magnetic system used to maintain the rotor in the correct position during the superconducting transition and to release it as soon as the magnetic interaction is established. According to first tests made on the IMGC calibrator with the meter body immersed in cryogenic helium, the turbine measures flowrates in a range 1:10 up to 30 g/s to accuracy around $\pm 2\%$ of the full scale.

2.2 Time of flight

This flow meter, developed at CERN, is based on the measurement of the time-of-flight of an injected heat pulse. Two thermal sensors at a known distance detect the heat pulse injected by an upstream heater. The velocity of the fluid stream can be worked out by measuring the time interval between the temperature peaks detected by the two sensors, and by dividing it by the distance in between. The heater is made of a copper-Constantan non-coated wire and the thermometers are made of superconducting Nb-Ti wire, the same used in commercially available liquid level gauges. The heater and superconducting wires are glued, with a thermal conductive but electrically insulated medium (epoxy with 45 % Allumina and Boron Nitride from Epotecny), to sections made of a thin copper tube with grooves to accommodate the wire and reduce the local thickness. These copper sections are

spaced with 5 cm long sections made of stainless steel to reduce the conduction via the tube. A power of 20 and 50 W is injected with a pulse duration of a few hundred ms, which increases the flowing helium temperature at nominal working conditions (0.3 MPa, 5 K) above the quenching temperature of the superconductors (i.e. 9 K). The sudden resistive transition of the superconductor permits to clearly detect the passage of the warm front. Experimental results at CERN test station have shown that accuracy of the order of $\pm 10\%$ can be obtained but the main limitations are the difficulty in controlling the heating current of the superconductors and to discriminate the superimposed local velocity coming from the resistive transition of the first superconductor.

3. DEVELOPMENT AND INVESTIGATION OF CRYOGENIC MASS FLOW METERS

3.1 Hot wire

The flowmeter, developed in industry, is comparable to a hot wire anemometer but with a pulsed power injection and a measurement of the speed of cooling. The tests have shown that this mode of operation is unpractical and not accurate and the final prototype tested is a pure hot wire anemometer. The sensor used is a cable with mineral insulator and the sensing part is made of a Rh-Fe wire. The electrical insulation is made with magnesium and compacted alumina. It traverse the conduit from one side to the other and has double leak tight connections. Especially under supercritical helium conditions, where significant variations of the fluid properties exist, this measuring method shows its limitations and the need for other sensors to better compute the flowrate. Final accuracy of $\pm 10\%$ can be obtained with individual calibration or proven reproducibility in the production.

3.2 Heated temperature sensor

This type of flowmeter developed at CERN, measures the rate of heat loss to the flow stream from a heated element such as a thermistor or a film sensor. The sensor is maintained at a constant temperature (i.e. resistance) and measure the flow as a function of the required power. The advantage is that the sensors are very small, require little power and have a fast response time. The disadvantage is the non-linear response, sensitivity to thermal conductivity and dependency on the velocity profile. Individual calibration is necessary. Correlations are available in the literature to infer the mass flowrate from the required power to maintain a constant temperature difference between the fluid and the sensor. In order to measure resistance changes at 5 K, without having to supply high power to increase the sensor temperature, the choice of the heated element is restricted to material used to measure cryogenic temperatures as CERNOX™ semiconductor type calibrated temperature sensors. The sensor operation temperature is chosen to be between 10 K and 15 K in order to have a sufficient ΔT to transfer heat, minimise the heat transfer to the helium and operate in a region of good sensitivity to temperature variations. The accuracy of this type of flow meter is dependent on the standard deviation of the law of heat transfer and is therefore difficult to obtain better than $\pm 10\%$. Furthermore, the use in industrial or large size applications should be avoided because of the presence of a feedthrough to the process fluid and complex operation (at least at this stage of development).

3.3 Coriolis

Coriolis meters, developed in industry, have been used for more than 15 years in a wide range of application at room temperature, e.g. for the oil, pharmaceutical, food and beverage, chemical industry, etc., and proven to be particularly reliable and accurate. Their

main advantage are the absence of moving parts, high accuracy and repeatability, and no need of individual calibration at cryogenic temperatures. Their main disadvantages are the dimensions and a high pressure drop. The relatively high purchase price are purely capital costs as the engineering, installation and maintenance costs are negligible, when compared to most of the other products (Baker, 2000). Different sizes of meters were tested from two main manufacturers at various temperatures and helium fluid state (liquid, supercritical, superfluid). Industrial Coriolis meters can be successfully used at cryogenic temperatures by applying a correction to the Young's module of the material used for low temperature operation. The values of the Young's module down to 5 K can be found in the literature (Ledbetter, 1981) or can be calculated by calibrating a meter of a known metallurgical composition at working temperature. All flow meters made of the same material will have the same accuracy within the precision of the measuring methods applied (i.e. $\pm 0.5\%$ in our case) that is actually better than the precision of the Young's module data available in the literature.

TABLE 1. Qualitative comparison of various cryogenic flow meters

Type of meter	Recommended application	Accuracy [ultimate]	Repeatability	Rangeability Press. Drop	Cost capital/ operation
Coriolis	Mass flow, industrial, high accuracy	$\pm 0.25\%$ [$\pm 0.25\%$]	$\pm 0.1\%$	Very good Medium	Med/high Low
Heated temp. sensor	Mass flow, laboratory, low cost flow monitor	$\pm 10\%$ [$\pm 5\%$]	$\pm 5\%$	Low Very good	Low Medium
Hot wire	Mass flow, laboratory, flow monitor	$\pm 10\%$ [$\pm 5\%$]	$\pm 5\%$	Low Very good	Med/low Medium
Time-of-Flight	Volumetric, laboratory, flow monitor	$\pm 10\%$ [$\pm 10\%$]	$\pm 10\%$	Medium Very good	Medium High
Turbine Classical	Volumetric, laboratory, or industrial	$\pm 17\%$ [$\pm 2\%$]	$\pm 2\%$	Medium Good	Medium High
Turbine Levitated	Volumetric, laboratory	N/A [$\pm 2\%$]	$\pm 2\%$	Medium Good	High Medium
Venturi	Volumetric, laboratory	N/A [$\pm 2\%$]	$\pm 2\%$	Medium Good	Medium High

CONCLUSIONS

Table 1 summarises, advantages and disadvantages of different methods of flow measurement for cryogenic helium applications. Accuracy supposes only a room temperature calibration and is in % of the full-scale of the instrument. Ultimate accuracy can only be reached with calibration at working conditions.

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