Test stand for determination of the heat flux to the cold elements of cryogenic systems in case of the vacuum vessel failure

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Abstract. The design process of cryogenic equipment requires sizing of the safety accessories for all enclosures containing cryogenic gas or liquid. The size of the accessories depends on the heat load to the cryogen. Vacuum failure following the ventilation of the insulating vacuum with atmospheric air is often considered as a maximum credible incident. For such case the heat inputs to blank liquid nitrogen and to liquid helium vessels have been experimentally determined by other researchers. Nevertheless, for helium systems elements as an actively cooled thermal shield, with a MLI covered external side and bare internal side, experimental data does not exist. WUST has designed a test stand that allows the experimental determination of the heat flux to the helium vessel, nitrogen vessel and to the thermal shield in case of the accidental break of the vacuum. The paper describes the test stand design and test methodology.

1. Introduction

All parts of cryogenic system containing liquified gases must be equipped with safety systems devices, to protect them against overpressure in case of system failure. Applicability of this equipment depends on design process which has to predict possible hazardous scenarios during the cryogenic system operation. Typical risks may be: quench of superconducting magnets, loss of insulation vacuum and equipment or operation failure [1].

A helium cryogenic system generally consists of cold elements (vessels, process lines) containing helium. The elements are kept in vacuum vessels for thermal insulation purpose. The tank is wrapped usually with 10 – 20 layers of multilayer insulation (MLI) and is often surrounded by actively cooled radiation shields at 35 – 90 K temperature level [2]. In the case of a failure resulting in vacuum insulation degradation with atmospheric air, the heat inputs to blank helium vessels have been measured to 3.7- 5.0 kW/m² [3, 4, 5]. The heat inputs to the external side of the liquid nitrogen cooled radiation shield wrapped with 30 layers of MLI can reach as much as 0.25 kW/m², after 100 min of exposure [6]. There is no experimental data showing heat loads to the internal side of the radiation shields. The available currently standards for the sizing of the safety equipment are based on the maximum heat fluxes what may lead to the apparatus oversizing [7]. Currently there is ongoing research regarding the heat transfer to the helium vessel in case of vacuum degradation [7, 8], however it does not take into...
consideration other cold components. Therefore, in order to allow experimental study on the heat flux to all type of the cold surfaces of the typical cryogenic system in case of different scenario of the sudden insulation vacuum degradation, the dedicated test stand has been designed and built on Wroclaw University of Science and Technology.

2. Problem description

The venting fluid increasing the pressure in the vacuum space may come from two directions: internal and external. The internally coming gas is a result of a leak of the cryogen. The external gas, usually air, comes from the surroundings after a break of the vacuum vessel. During the vacuum degradation, depending on the temperature of the system’s elements and physical parameters of the venting fluid, the following mechanisms may drive the heat transfer:

- if the temperature of an element is higher than the boiling temperature of the venting gas, only convection occurs
- if temperature of the element is between the boiling and the triple points of the ventilating gas then condensation of the gas starts
- if temperature is of the element is equal or lower than the triple point of the ventilating gas then the gas solidifies

The heat inlet to the considered element during one of the possible scenarios is described by equation 1, where \( T_{\text{chamber}} \) is the temperature in the vacuum chamber, \( T_{\text{cryo}} \) is the temperature of the cryogen and \( R_{\text{tot}} \) is the total thermal resistance. The total resistance is a sum of resistances associated with: convection in liquid cryogen; conduction through the vessel’s wall; conduction through the solid deposit; convection in the liquid deposit; convection in the degraded vacuum. Depending on the conditions, not all of the features may occur, however, during the preparation of an experiment one should aim in covering all of the possible scenarios.

\[
\dot{Q} = \frac{(T_{\text{chamber}} - T_{\text{cryo}})}{R_{\text{tot}}} \quad (1)
\]

3. Laboratory stand

The scheme of the stand is shown in figure 1. The cryostat consists of a vacuum chamber, (1), in which is located a vessel designed for helium storage (3). The tank is surrounded with the nitrogen cooled thermal shield (2) fed from a bottom placed vessel (5). The cold container is protected by a safety valve (4). The gas used for the degradation of the vacuum is brought from a gas cylinder (6). To ensure the working fluid’s pressure is at desired level, close to 1 bar, a buffer volume is introduced (7).
Figure 1 Schematic drawing of the laboratory stand.

The flow of inlet and outlet evaporated gas is measured by three mass flowmeters (M). Additionally, the temperature of the evaporated nitrogen is evaluated by a Pt100 temperature sensor mounted on the outlet from the thermal shield (T\(_{\text{N2}}\)). The temperature of the helium inside the vessel is measured with a CERNOX temperature sensors (T\(_{\text{He}}\)). The pressure inside the helium tank is measured in range up to 4 bar (p\(_{\text{He}}\)), what corresponds to the safety valve set pressure. The shield is equipped with a collection of PT1000 temperature sensors (T\(_{s}\)). The pressure inside the vacuum vessel is measured with another pressure transmitter (P\(_{v}\)). The pressure inside the buffer volume is measured with a pressure transmitter (p) and controlled by the set of valves.

| Table 1 Dimensions of chosen stand’s elements. |
|-----------------------------------------------|
| **Element**            | **Dimension** | **Value**  |
|---|---|---|
| Vacuum vessel          |             |           |
| Horizontal length      | 3600 mm     |           |
| Horizontal diameter    | 320 mm      |           |
| Vertical length        | 1900 mm     |           |
| Vertical diameter      | 506 mm      |           |
| Volume                 | 530 l       |           |
| Thermal shield         |             |           |
| Horizontal length      | 3500 mm     |           |
| Horizontal diameter    | 196 mm      |           |
| Vertical length        | 980 mm      |           |
| Vertical diameter      | 250 mm      |           |
| Internal heat transfer area | 2.94 m\(^2\) |     |
| External heat transfer area | 3.02 m\(^2\) |     |
3.1. Measurement methodology

The test stand allows a separate evaluation of the heat input to the three elements: helium vessel, nitrogen vessel and the thermal shield.

The helium vessel is protected by a safety valve. During the experiment, the pressure inside the tank is expected to rise up to the valve set pressure. The measurement of the heat transferred to the helium may be divided into phases before after the safety valve opening respectively. The heat transferred in the first phase, $\dot{Q}$, is assumed to be fully used for the change of the internal energy, $U$, equation 2. It is evaluated by the measurement of the temperature and pressure change inside the vessel.

$$\dot{Q} = \frac{dU}{dt}$$

(2)

When the valve opens, besides the internal energy change one needs to consider the outflowing gaseous helium stream, its enthalpy, $\dot{H}_{\text{out}}$, and kinetic energy, $\dot{E}_k$, equation 3. It is evaluated with the usage of mass flowmeter mounted on the valve outlet.

$$\dot{Q} = \frac{dU}{dt} + \dot{H}_{\text{out}} + \dot{E}_k$$

(3)

The thermal shield nitrogen supply tank is not equipped with a safety valve, therefore all of the heat delivered there is assumed to be used for the evaporation of the medium. The evaporating mass flow is measured with a mass flowmeter. The amount of heat obtained by the thermal shield is calculated taking into account the temperature change of the shield.

Depending on what heat transfer mechanism is emphasized during the measurement another venting fluid should be chosen. The properties of possible gases are shown in the table 2. When the internal accident is simulated helium may be used. For the vacuum vessel damage simulation normally air is used, as the air vents the vacuum vessel during the real systems failure. Nevertheless, as WUST’s test stand has nitrogen cooled thermal shield, vacuum vessel ventilation with air will not provide the effect of the venting gas solidification at cold thermal shield surface, what would exist in the real systems with the thermal shield’s temperature below the air triple point temperature, i.e. below 59.8 K. Therefore, in WUST’s experiment argon is preferred to air, since its freezing temperature (83.8 K) is higher than nitrogen normal boiling temperature (77.3 K), what covers all the possible heat transfer mechanisms both for helium- and nitrogen-temperature elements.
### Table 2 Chosen physical properties of working fluids at 1 bar pressure [9].

| Fluid   | Boiling temperature, K | Freezing temperature, K | Heat of evaporation, kJ/kg | Heat of melting, kJ/kg |
|---------|------------------------|-------------------------|-----------------------------|------------------------|
| Helium  | 4.23                   | -                       | 20.8                        | -                      |
| Air     | 78.9                   | 59.8                    | 205.5                       | -                      |
| Nitrogen| 77.3                   | 63.3                    | 199                         | 25.8                   |
| Argon   | 87.3                   | 83.8                    | 163                         | 29.6                   |

### 4. Final remarks

Due to the need of proper selection of the cryogenic safety valves, all the heat fluxes to cryogenic cold elements during the system failure should be evaluated. One of the possible dangerous failures is a degradation of an insulation vacuum with gas. Wroclaw University of Science and Technology has designed and built a laboratory test stand for measurement of the heat inputs to the element of cryogenic installation such as the helium vessel and the actively cooled thermal shield. Such setup may allow for estimation of thermal shield influence on the heat transfer to the helium vessel during such failure. Argon has been chosen as the insulation vacuum degrading medium since its triple point temperature is higher than the temperature of the thermal shield. Currently the measurement methodology and the sensor placement has been planned. The current works, before the experiment in helium temperature, are focused on the nitrogen temperature experiment campaign what allow cold commissioning of the test stand and its instrumentation as well as designation of a temperature profile along the thermal shield geometry and modification of the sensor location.

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### Acknowledgments

The work has been partly supported by statutory funds from Polish Ministry for Science and Higher Education for the year of 2018.