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Abstract

The presently constructed cryostats, especially using superfluid helium require careful engineering design to minimize the operation cost of the system. The technical optimization of cryogenic devices can be successfully achieved by means of entropy minimization method. The paper gives an example of the entropy minimization based optimization of thermal shielding in a superfluid helium NED cryostat. The cryostat design is based on the Claudet bath principle. The cryostat thermal shields have been optimized by means of entropy generation method. The papers presents thermodynamic background of the method, gives the main design features of the NED cryostat and the optimization results.

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The presently constructed cryostats, especially using superfluid helium require careful engineering design to minimize the operation cost of the system. The technical optimization of cryogenic devices can be successfully achieved by means of entropy minimization method. The paper gives an example of the entropy minimization based optimization of thermal shielding in a superfluid helium NED cryostat. The cryostat design is based on the Claudet bath principle. The cryostat thermal shields have been optimized by means of entropy generation method. The papers presents thermodynamic background of the method, gives the main design features of the NED cryostat and the optimization results.

INTRODUCTION

Optimization by entropy generation minimization is based on the Gouy-Stodola theorem, stating that each irreversible process causes losses in available work that are directly proportional to the entropy production:

$$W_{lost} = T_o \sum \Delta S \qquad (1)$$

To minimize the losses in work one should reduce the entropy generation ΔS, by proper technical design and operation of the system. The method, both in entropy generation minimization or exergetic approach, is now vastly discussed and applied [1, 2, 3]. In cryogenic systems the most important sources of entropy generation is heat transferred to or generated at low temperatures.

NED CRYOSTAT

The Next European Dipole (NED) activity was launched within the CARE project in 2004, to promote the development of high-performance Nb_3Sn wire in collaboration with European industry and to assess the suitability of Nb_3Sn technology to the next generation of accelerator magnets [4]. Foreseen tests of thermal features of the new ceramic insulation require a superfluid helium cryostat. Heat transfer measurements should be realized in saturated He I

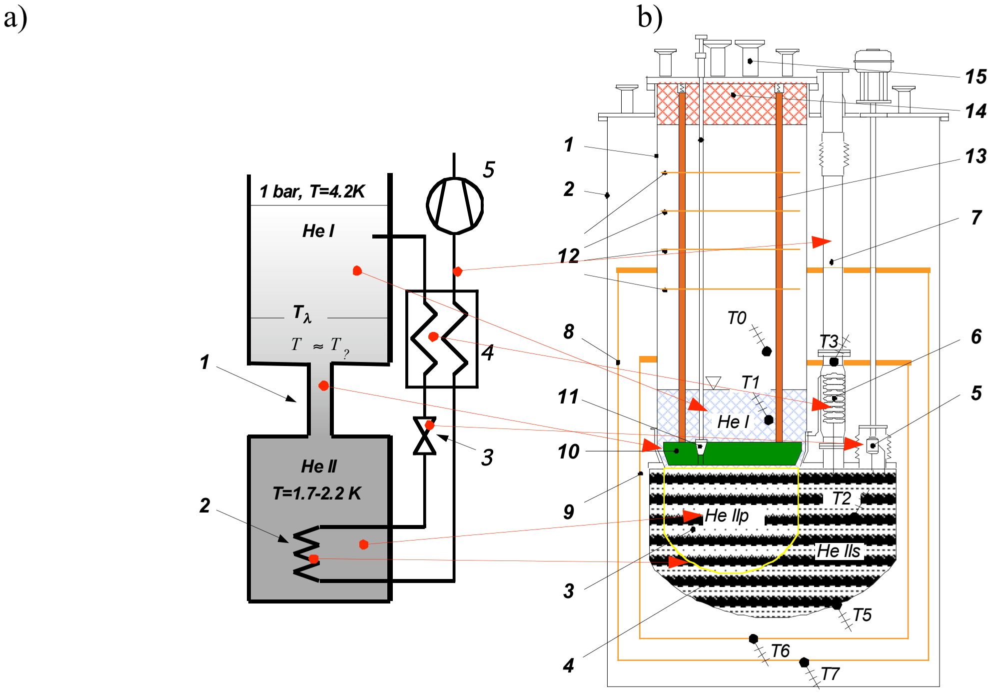

Figure 1. a) Claudet bath principle: 1 – constriction, 2 – He IIs/He IIp heat exchanger, 3 – J-T valve, 4 – recuperative heat exchanger, 5 –vacuum pump; b) NED cryostat scheme: 1 – He I vessel, 2 – vacuum container, 3 – He IIp vessel, 4 – He IIs vessel, 5 – J-T valve, 6 – recuperative heat exchanger, 7 – heat exchanger pipe, 8/9 – external/internal radiation shield, 10 – λ-plate, 11 – λ-valve, 12 – insert radiation shields, 13 – λ -plate supports, 14 – foam insulation, 15 – instrumentation ports, T0 – T7 temperature measurement points;

(4.2 K), in supercritical He (4.2 K – 5 K, 1 bar – 6 bar), and in pressurized He II (1.9 K, 1 bar). The cryostat has been constructed and commissioned at Wroclaw University of Technology in co-operation with CEA and CERN. The cryostat design is based on the Claudet bath principle (see figure 1a). The volume of the He IIp vessel is 8.5 l. He IIp vessel is eccentrically placed inside the He IIs vessel of 25 l volume. Pressurized superfluid helium II (He IIp) is produced from a liquid helium I (He I) refrigerated by a saturated helium II (He IIs) flowing through a heat exchanger immersed in He IIp bath. He IIs is produced from the He I in a throttle process realized on a Joule-Thomson valve preceded by a recuperative heat exchanger. Flow through the J-T valve and low pressure on the valve outlet is forced by a high capacity vacuum pump. Because of this, the cryostat is able to maintain He IIs temperature of about 1.8 K at 16 mbar. The volume of the He IIp vessel is 8.5 l. He IIp vessel is eccentrically placed inside the He IIs vessel of 25 l volume. Estimated total heat flux to the liquid helium in the cryostat is of about 3 W, 1 W is transferred through the thermal insulation.

NED CRYOSTAT THERMAL INSULATION

The design of the NED cryostat is nitrogen free. The cryostat thermal insulation system is composed of two high purity copper radiation shields covered with superinsulation and thermally coupled with the cryogenic vessel – see Figure 1. High purity copper guarantees temperature homogeneity of the shields. The shield temperature is practically the same as the temperature of the shield joint with the vessel. The scheme of the heat transfer through the

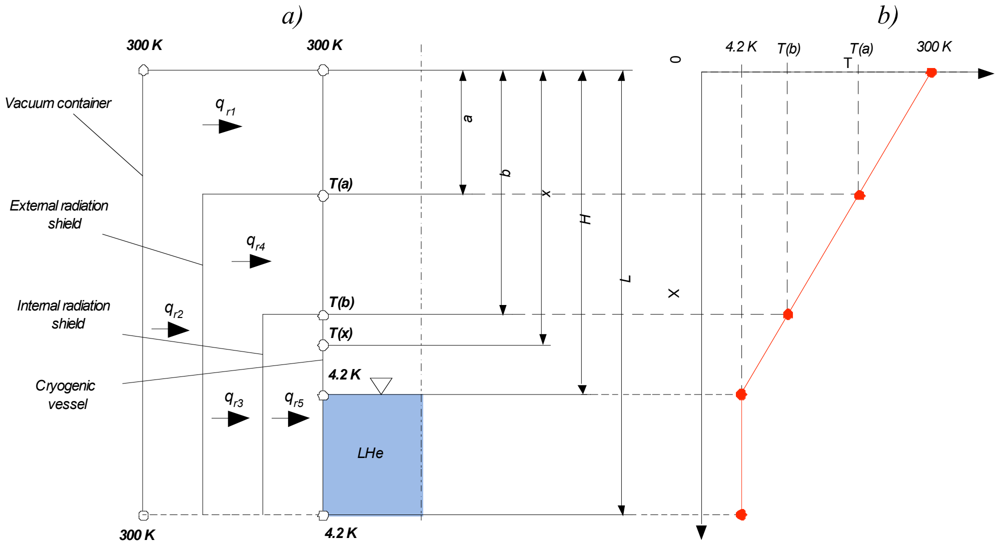

Figure 2. *a)* Scheme of the heat transfer through thermal insulation, *b)* temperature gradient along cryogenic vessel

cryostat thermal insulation is presented in Figure 2.a. Heat is transferred from the vacuum container to the cryogenic vessel via the following paths:

- Between the top of the cryogenic vessel and the external radiation shield coupling point *a,* a heat flux q_{r1} is directly radiating from vacuum container to the vessel.
- The remaining heat radiating from the container q_{r2} reaches the external radiation shield surface.
- From the external radiation shield, a heat flux q_{r4} is directly transferred to the cryogenic vessel between points *a* and *b*, while heat flux q_{r3} is radiating from the external shield to the internal shield.
- From the internal shield heat q_{r5} is transferred to the cryogenic vessel.

OPTIMIZATION OF THE THERMAL SHIELDS LOCATIONS

The optimization of the shields thermal coupling points location *a* and *b* is based on the following assumptions:

- Temperature profile along the cryogenic vessel from the cryostat top to liquid helium level is linear (see Figure 3.b) and along liquid helium is constant:
- Shields temperatures *T(a)* and *T(b)* are constant and equal to cryogenic vessel wall temperatures at the shield – vessel thermal coupling point.
- The internal radiation shield and the cryogenic vessel are covered with 10 layers of superinsulation, when the external radiation shield is covered with 20 layers superinsulation.
- Superinsulation layer density $\overline{N}$=25 layer/cm.

Heat transfer between two parallel surfaces of the l length and 1 m width with temperature profiles $T_1(x)$ and $T_2(x)$ is equal to:

$$\dot{Q}_r = \int_0^l q_r\left(T_1(x), T_2(x), N\right) dx \,. \tag{2}$$

Entropy generation in this case can be calculated from:

$$S = \int_0^l q_r\left(T_1\left(x\right), T\left(x\right)_2, N\right) \cdot \left(\frac{1}{T_2\left(x\right)} - \frac{1}{T_1\left(x\right)}\right) dx \,. \tag{3}$$

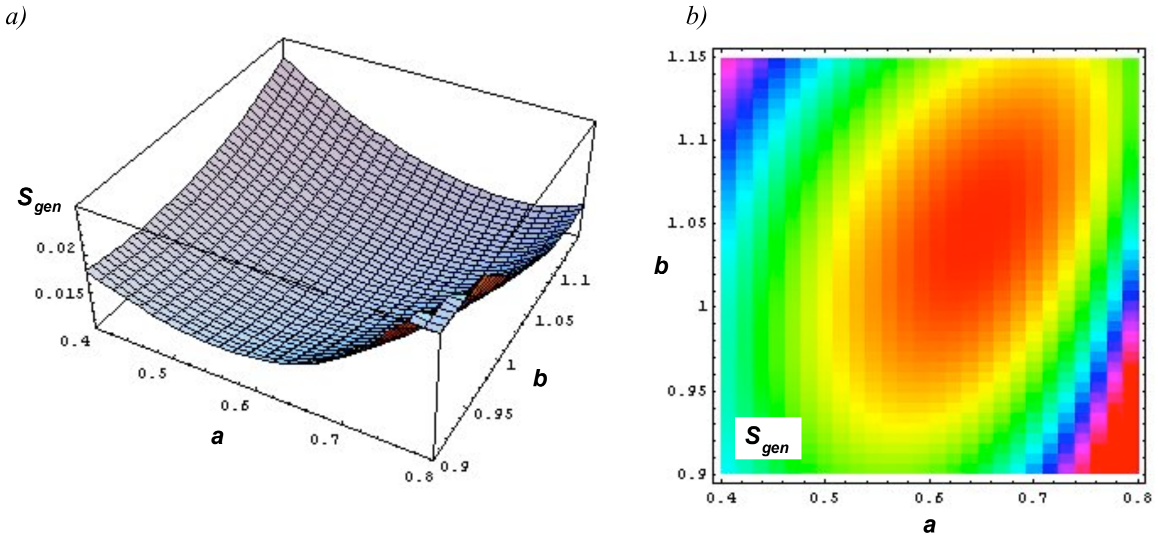

Figure 3. Numerical calculation of the optimal shields coupling points localization results: *a)* - values and *b)* – minimum image of the entropy generation in analyzed system in function *a* and *b* parameters

Applying the equation (3) for calculation of q_{r1} to q_{r5} (compare figure 2a) it can be shown that the entropy generated is a function of *a* and *b* only (see figure 2).

$$S_{gen} = f(a,b) \tag{4}$$

An optimization criterion based on the entropy minimization is:

$$S_{gen} = \sum_i S_i = \min \tag{5}$$

where S_i denotes entropy generated by q_{ri} heat flux.

Figure 3 shows the numerically calculated values of the entropy generated as function of *a* and *b* parameters. The minimum of the entropy generation is achieved for $a = 0.64$ m and $b = 1.02$ m, which correspond to an external shield temperature *T(a)*=137 K and internal shield temperature *T(b)*=38 K.

ACKNOWLEDGEMENTS

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