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Influence of tailored MLI for complex surface geometries on heat transfer

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Abstract. Complex, non-developable surfaces require a tailored multi-layer insulation (MLI) for lowest heat load. The most experiments showing the heat transfer through MLI are performed under quasi-ideal conditions determining the principle insulation quality. But the surface to be insulated in real cryostats implies feed-throughs and other non-developable surface parts. The thermal performance of MLI is degraded significantly at cutting points. To investigate this degrading effect a LN_2-filled cylinder with a diameter of 219 mm and a length of 1820 mm was insulated with MLI and the heat load was measured by means of calorimetry. In addition the heat load to an insulated cylinder with eighteen branches was measured. Both cylinders have the same surface of 1.37 m^2 for a comparison of the results. This article describes the experiments with different ways of tailoring the MLI for the cylinder with branches and discusses their results. It was shown that the cutting points at the branches have a significant degrading influence on the thermal performance of MLI.

1. Introduction

Thermal insulation plays a decisive role for an economic operation of cryogenic facilities like liquid storage systems due to the high temperature difference between ambient and cryogenic temperatures (< 120 K), the very low latent heats of the most cryogenic fluids and the very low efficiency in producing cryogenic temperatures. Multilayer insulation (MLI) has the highest potential to be the best insulation as can be seen in Fig. 1. Disadvantages of MLI are the poor predictability of its thermal performance and its degrading effects, e.g. disproportionate increase of the heat load to mechanical loads, gaps at cut-off points or by increasing the residual gas pressure. Cuts cannot be avoided for non-developable surfaces like spherical surfaces, T-junctions or feed-throughs. In this article non-developable is used to describe structures for which no two-dimensional shape can be developed without any cut to adjust to the structure's surface. Furthermore MLI is expensive and has to be manually installed at complex surfaces which require a lot of experience to avoid the above mentioned degrading effects. Lehmann described some of these degrading effects in detail [1].

The insulation quality of MLI is often measured by means of calorimetry or by using a heat meter. The boundary conditions are quasi-ideal and describe the best performance of heat load $\left(\dot{q}\ [\mathrm{W/m^2}]\right)$ or heat conductivity $(\lambda\ [\mathrm{W/(m{\cdot}K)}])$ if flat or developable surfaces are used for the calorimetry method. However as shown in Fig. 1 the values of heat conductivity for MLI spread about one order of magnitude. Reasons for this effect are differences of the boundary conditions for different measuring devices. But also the boundary conditions during the manual installation are different and result in different heat loads. For example the pulling force for wrapping the MLI around a cylinder is normally not fixed and results in different layer densities and so different mechanical loads.

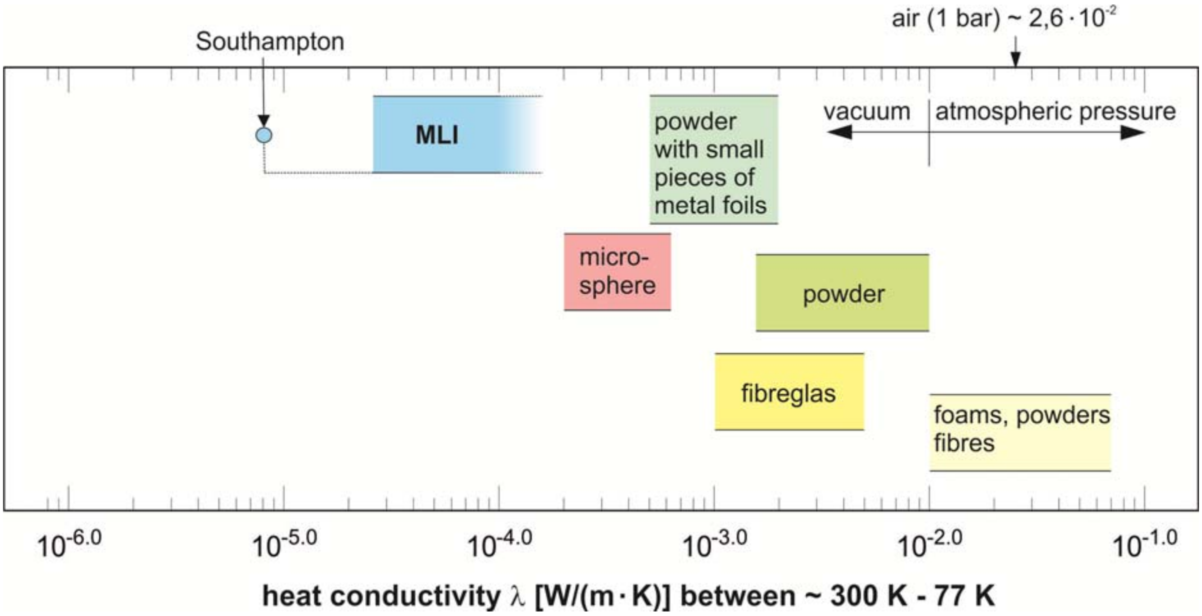

Figure 1. Overview of heat conductivities of different insulation materials between 300 K – 77 K

The realisation of such best values, obtained under such quasi-ideal conditions in technical applications is more than difficult or impossible because of non-ideal conditions. Each Helium vessel has a spherical bottom and a neck hence a T-junction which requires a tailored MLI.

For the investigation of the degrading effects on such T-junctions a cylinder with eighteen branches has been constructed. The high number of T-junctions should ensure a dominant degrading effect on the heat load. For comparison a smooth cylinder (developable surface) with the same surface (1.368 m^2) was insulated and the heat load was measured.

2. Test facility

The thermal insulation test facility (THISTA) of the Institute for Technical Physics (ITEP) of the Karlsruhe Institute of Technology (KIT) was used for the experiments shown in Fig. 2.

The measurement principle is calorimetric. The heat flux penetrating the insulation material is transported to the surface of the boiling cryogen (LN_2) by convection in the cryogen bath. A detailed description of the test facility and the evaluation method is described in [2].

Here the test modules are cylinders, a smooth one and one with eighteen branches. The geometry is described in Table 1.

The accuracy is calculated with the error propagation law by Gauss. For these experiments the accuracy for the heat flux density is about $\Delta\dot{q}_c$=5%. It should be noted that this evaluation method is only valid for a convective heat transfer in the boiling bath. At bubble or film boiling conditions other effects have to be taken into account.

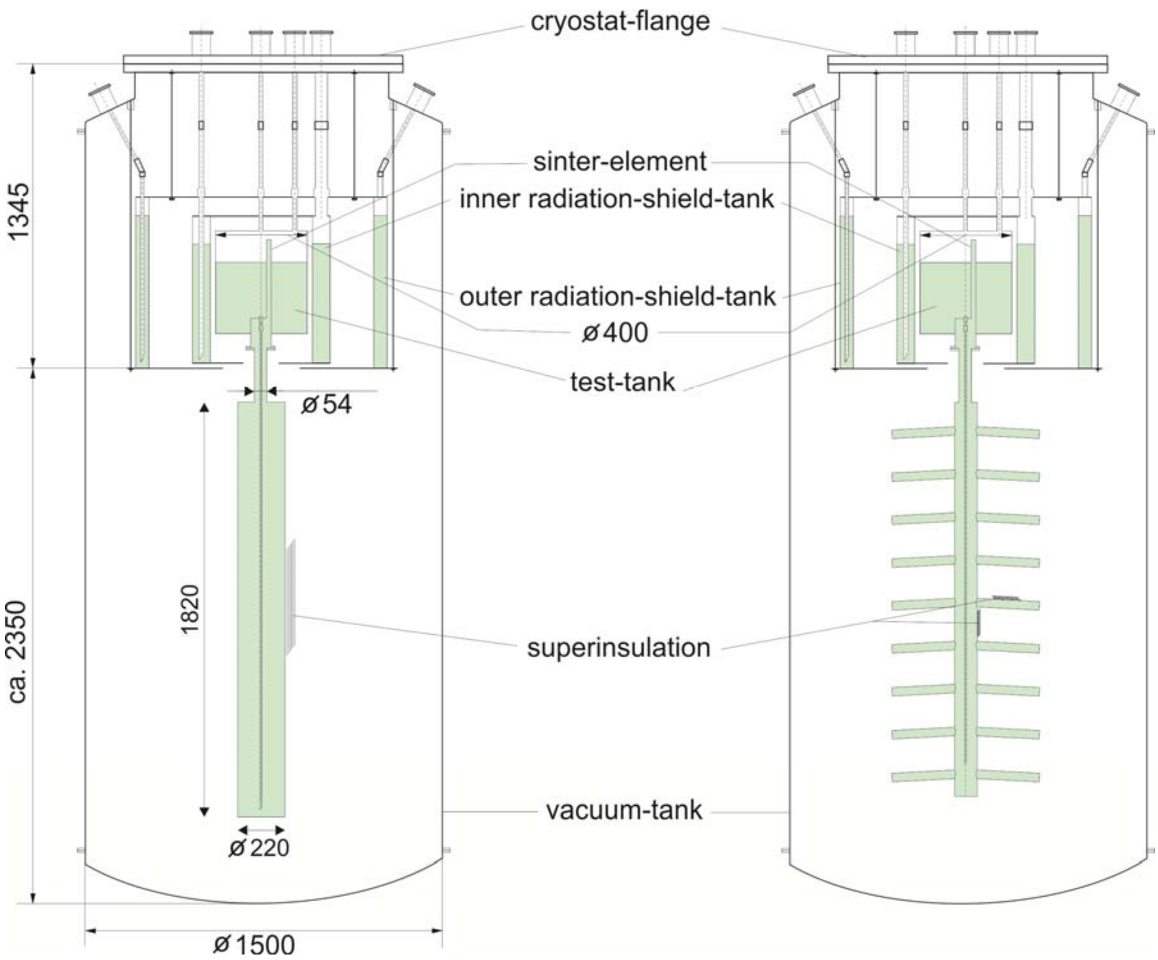

Figure 2. Thermal insulation test facility (THISTA) with a smooth cylinder and a cylinder with eighteen branches

Table 1. Geometries of the test modules

	smooth cylinder A	**cylinder with eighteen branches B**
length of main cylinder	1820 mm	1810 mm
diameter of main cylinder	219 mm	105 mm
length of branches		282 mm
diameter of branches		40 mm
number of branches		18
inclination of the branches to the horizontal line		3°
surface	**1.368 m^2**	**1.368 m^2**
volume	0.06224 m^3	0.01658 m^3
surface / volume	21.98 m	82.49 m

3. Results and Discussion

3.1. Tests without thermal insulation

The first test was performed measuring the heat load on both cylinders without thermal insulation. Here the heat load for the smooth cylinder (A) calculated according equation (1) is equal to $\dot{q}_{A1}=120.85\ W/m^2$. The heat load for the cylinder with the eighteen branches (B) is equal to $\dot{q}_{B1}=19.27\ W/m^2$. The big difference of these heat load results requires some remarks. Because of no contact points between the warm and the cold wall (see Fig. 2) and a negligible heat transfer by residual gas conduction at a vacuum pressure of about 10^{-6} mbar the heat load is caused by thermal radiation. Even if the heat load for the smooth cylinder is in the region of the beginning of bubble boiling this value of 120 W/m^2 can be calculated with:

$$\dot{q}_{A1} = \frac{\sigma \cdot (300^4 - 77^4)}{\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_w} - 1} \quad (1)$$

with: σ: Stefan-Boltzmann constant
$\varepsilon_c \approx 0.27$: emission coefficient for the cold surface
$\varepsilon_w \approx 0.94$: emission coefficient for the warm surface (vacuum vessel made of grey iron, see [3]).

On the other side even if the cylinder (B) has the same surface as cylinder (A) the measured heat load is much lower because of mainly three effects:

1. While the view factor of cylinder (A) is equal to $\varphi_{A\text{-}cw} = 1$, the view factors for cylinder (B) are $\varphi_{B\text{-}ww} > 0$ and $\varphi_{B\text{-}wc} < 1$. So cylinder (B) sees itself which reduces the heat load.
2. Because of the low inclination of the branches to the horizontal line and so the low flow velocity of the rising fluid the evaporating liquid generates a gas film on the inner top side of the branches according to Fig. 3. The gas films of the single branches rise up in the vertical part of the cylinder and are summed up. Consequently there is a certain region in cylinder (B) filled with gas, which acts as an insulation layer on the inner surface.
3. The heat load to this gas film causes a superheating of the rising gas. According to the calorimetric measurement principle the heat load is equal to the measured mass flow times the latent heat. A superheating of the rising gas is not considered which results in an error resulting in a too low calculated heat load.

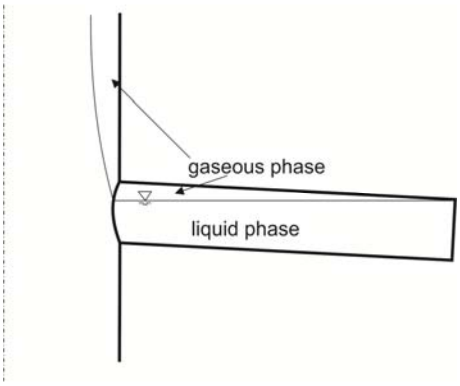

Figure 3. Gaseous and liquid phase in one of the branches of cylinder (B)

Different heat loads occur because of the different geometries of both cylinders. Hereafter the heat loads on the cylinders without thermal insulation are used as reference values.

3.2. Tests with different tailored MLI on the cylinder with eighteen branches

All tests are performed with 12 layers of MLI. Except for the test B10 of RUAG the MLI of JEHIER is used.

The lowest value of heat load was achieved by covering cylinder (B) completely with two blankets as shown in Fig. 4. Here only a heat load of $\dot{q}_{B2}$=3.27 W/m^{2}comes up. This kind of tailoring the MLI ignores the complex structure and can only be used for cryostats with cold components on the same temperature level.

Figure 4. Whole covering of the cylinder with branches

The best tailored variant was performed by the company RUAG Space GmbH using Coolcat 2 NW. This is a polyester foil, double-side aluminized, perforated and interleaved with layers of non-woven polyester spacer material. The polyester MLI blankets are cut to shape using numerically controlled laser cutting machines. The design featured several methods to minimize heat transfer through the MLI. All blankets where closed featuring butt-joints by covering the latter with Coolcat BR-50 low emissivity adhesive tape. Figure 5a shows the insulated cylinder (B). In Figure 5b the detail view of interface between one arm segment and the main cylinder body is shown. In a first step each arm got a 6 layer reflective foil and 6 layer spacer blanket applied. The flaps from the arms reach onto the main cylinder. After that a blanket is applied over the cylinder barrel and closed on one side. The interface points of the arms are cut into little triangles reaching onto the arm-segment. This process is repeated with the second sub-blanket consisting of 6 layer reflective foil with 6 layer of spacer. The butt-joints of the second sub-blankets are carefully placed in different positions from the first set of sub-blankets. This kind of tailoring the 12 layers of MLI causes a heat load of $\dot{q}_{B10}$=4.2 W/m^2.

For other variants of tailoring the MLI blankets two concepts are pursued. One is to minimize the heat load by realizing a good thermal insulation at the T-junctions and another one is to minimize the heat transfer surface by using as little MLI material as possible to cover cylinder (B). As done for the most applications the MLI blanket roll from Jehier was cut and tailored with a sharp knife and the loose 12 layers of one blanket are connected by small strips of aluminum tapes.

Figure 5a. Cylinder (B) with 12 layers MLI of RUAG

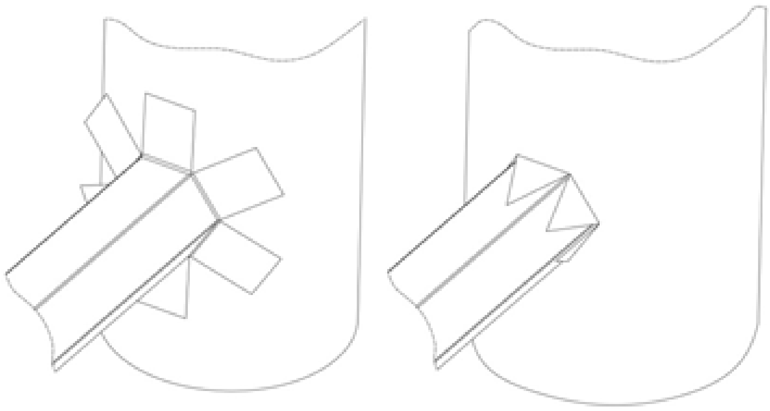

Figure 5b. Detail view of MLI connection at T-junction

Another variant is to realize a spiral wrapping around the cylinder and branches with a small roll of MLI as shown in Fig. 6.

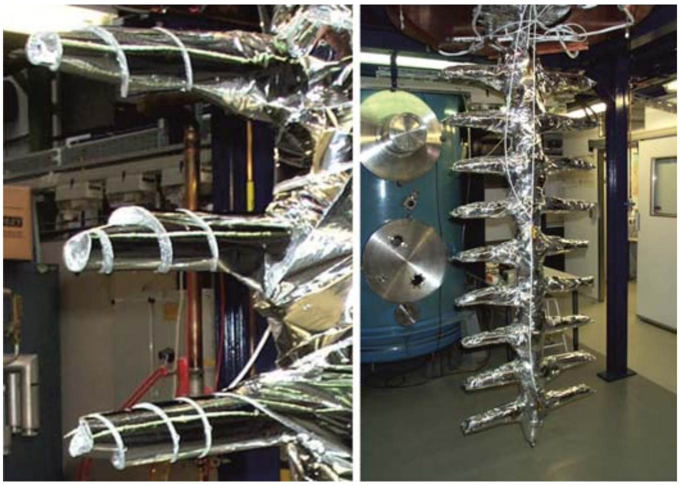

Figure 6. Insulation of cylinder (B) by spiral wrapping of small MLI band

The results of all tests performed are shown in Fig. 7. The heat load on cylinder (B) without thermal insulation serves as reference point. Column (A2) shows the heat load of cylinder (A) with 12 layers of insulation relative to (B1). This result of $\dot{q}_{A2}=1.17\ W/m^2$ shows the principle performance of 12 layers MLI on a developable surface so under quasi-ideal conditions. The other tests (B2 – B10) with tailored MLI blankets around cylinder (B) show higher heat loads because of the degrading effects coming up with this non-developable surface.

The tests (B3, B4, and B5) following the concept of minimizing the heat load by realizing a good thermal insulation at the T-junctions result in a mean value of $\overline{\dot{q}_{B3,B4,B5}} = 5.34\ W/m^2$which is 21.4% higher than the value achieved by RUAG. The tests (B6, B8 and B9) following the concept of minimizing the heat transfer surface result in a mean value of $\overline{\dot{q}_{B6,B8,B9}} = 7.62\ W/m^2$ which is 29.9% higher than the mean value of the other concept.

The spiral wrapping around the geometry of cylinder (B) with a small roll of MLI results in a heat load of $\dot{q}_{B7}=7.1\ W/m^2$. The main advantage of this kind of insulation is the low time effort for preparation. In comparison to the other ways of insulation no cutting of tailored sections is required.

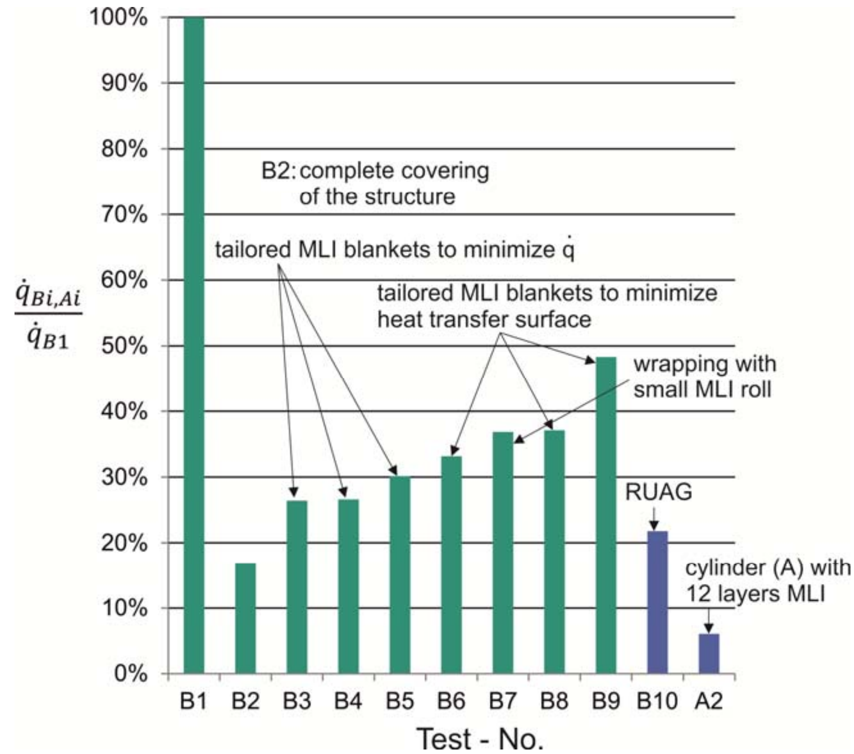

Figure 7. Heat loads for different kinds of tailoring 12 layers of MLI on cylinder (B)

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4. Conclusions

Complex, non-developable surfaces require a tailored multi-layer insulation (MLI) for lowest heat loads. To investigate the degrading effect of cutting points at T-junctions on the insulation quality of MLI a cylinder with eighteen branches was constructed and insulated in different ways. For comparison the heat load on a smooth cylinder with the same surface and the same number of MLI layers was measured. The calorimetric measurement principle was used by measuring the evaporating mass flow of the LN_2-filled cylinders positioned in a vacuum tank.

It could be shown that a complex structure with non-developable surface gets always a higher heat load than the simple structure with developable surface. The best tailored MLI insulation for the cylinder with eighteen branches generates a 3.6 times higher heat load than the same number of layers on the smooth cylinder. However different ways of tailoring the MLI around this complex cylinder with T-junctions show that a good concept, the use of proper tailor tools and a careful installation result in lower heat loads. A spiral wrapping around the complex geometry with a small roll of MLI results in a 1.7 times higher heat load than the best tailored variant, so 7.96 times higher than the heat load for the same number of layers on the smooth cylinder.

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