Experimental investigation on combination of vapor cooled shield (VCS) and multilayer insulation (MLI) for cryogenic application

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Abstract. The long-term storage of cryogenic propellants on orbit under thermal and pressure control is a promising enabling technology for future space exploration. The combination of vapor cooled shield (VCS) and multilayer insulation (MLI) is considered as an effective passive thermal control method for such missions. To experimentally investigate the thermal insulation performance of VCS and MLI combination (MLI/VCS), a cryogen boil-off calorimeter system has been designed and fabricated. It is capable of measuring the heat flux through the VCS and MLI combination, as well as the temperature profiles both on the VCS and inside the MLI. The insulation effectiveness of MLI/VCS is evaluated with liquid nitrogen as the simulated cryogen in the warm-boundary temperature range from 200 K to 350 K. For the warm boundary temperature of 350K case, the insulation performance comparison between MLI/VCS and MLI only is conducted. In addition, the heat transfer behaviour within the insulation combination is discussed in detail.

1. Introduction

Cryogenic propellants are increasingly utilized in space missions owing to their high specific impulse and excellent environmental friendliness. Propulsion systems prefer to have propellants stored as liquid rather than gas due to the hundred-times increase in density and elimination of high pressure which significantly reduces the mass demand of the tanks required for the spacecraft [1]. However, owing to the ultra-low storage temperature of the liquids, one of the main problems encountered in on-orbit cryogenic storage technology is how to suppress the heat penetration from the outer space thermal radiation.

Multilayer insulation (MLI) in vacuum has been widely used in cryogenic tanks. Early studies showed that its equivalent heat conductivity can reaches as low as 10⁻⁵ W/(m.K) [2]. However, even if heat flux as low as 1 W/m² leaks into the tank, the internal pressure will still increase continuously because of the propellants boil-off. When the upper limit of pressure is approached, part of the cryogenic propellant vapor has to be vented, in the fact that the state-of-the-art space-used cryocooler is not powerful enough to get rid of all the heat leakage into the tank [3]. Since the vented vapor is still very cold (slightly above its saturation temperature), it can be exploited to contribute to the suppression of the heat penetration through the MLI.
The concept of introducing a vapor cooled shield (VCS) embedded in MLI has been studied theoretically in early years by Scott [4]. Scott analyzed the thermal performance of a vacuum-insulated vessel after the VCS was introduced. The results implied that the evaporation rate of a vapor-cool shielded LH$_2$ vessel decreases by approximately 62% compared to the unshielded one. Liggett et al. [6, 7] evaluated experimentally the performance of the VCS and MLI combination (VCS/MLI) in an LH$_2$ test facility. Their measurements at steady state indicated that the boil-off rate of LH2 using a single VCS achieves 35% reduction compared to the case without VCS at a given warm boundary temperature of 287K. Assuming a uniform temperature profile on the VCS, Kim et al.[8] established a one-dimensional model that predicted results of double-VCS configurations with better performance in series than in parallel. Babac[9] improved Kim[8]’s model by considering the two-dimensional (radial and axial) conductance. Lebar et al.[10] used the Boeing Design Sheet tool to investigate and optimize the thermal performance of the MLI, the thermodynamic vent system (TVS) and the VCS combination architecture. They proposed an “integrated” configuration which has LH$_2$ vented only and has the LO$_2$ tank cooled by the vented H$_2$ gas through a VCS to realize zero boil-off of the LO$_2$ tank. For on-orbit cryogenic storage tank application, Jiang et al.[11] optimized the thermal performance of composite insulation containing VCS, foam, and MLI. Their results showed that the heat flux entering the tank can be reduced by 59.6% for LH$_2$, 26.8% for LN$_2$, 22.7% for LO$_2$, and 20.3% for LCH$_4$ tanks respectively after the VCS is introduced at proper position. Zheng et al. [12] numerically studied the VCS and MLI combination in a LH$_2$ tank and found that after the coupling optimization of VDMLI and VCS, heat flux can be reduced by 83.12% than using MLI.

As shown above, some studies on VCS’s thermal performance had been performed, however the conclusions from different investigators are not consistent with each other. In addition, only a few experimental studies were conducted. In the present paper, an experimental setup using liquid nitrogen as oxygen simulant has been designed and fabricated to investigate the insulation performance of VCS and MLI combination (VCS/MLI). The temperature profiles within the VCS/MLI under different warm boundary conditions will be compared. Subsequently, the effect of warm boundary temperature on the VCS/MLI’s insulation performance will be investigated. In addition, temperature profiles within MLI and corresponding heat flux into the tank will be compared and discussed regarding with or without the VCS.

2. Experimental setup

2.1. Cryogenic calorimeter system

To investigate the thermal performance of high performance insulation structure (MLI/VCS combination or MLI only), a liquid nitrogen boil-off calorimeter system was designed and fabricated as shown in Fig. 1 and Fig. 2. It can be used to measure the heat flux through the insulation structure as well as the temperature profiles within it. The experimental setup consists of a cryogenic calorimeter, a high vacuum pump unit, temperature sensors, differential pressure gauges, a flow meter and a multichannel data acquisition system.

The cryogenic calorimeter involves three cylindrical liquid nitrogen vessels: the upper guard vessel, the testing vessel and the bottom guard vessel. The height and diameter of the testing vessel are 400 mm and 200 mm, respectively. Inside the testing vessel, three piece of copper fins are installed along the vertical direction to eliminate thermal stratification between the vapor and liquid phases and thus to ensure all the leaking-in heat being used to evaporate liquid instead of heat vapor. The upper guard and bottom guard vessels are connected to each other and act as isothermal protectors to avoid heat leakage into the testing vessel from its both ends. Two thermometers are mounted on both the top and bottom sides of the testing vessel to monitor the liquid level. Two vacuum jacketed funnels are set to allow smooth liquid nitrogen refilling for both guard and testing vessels.

A circular copper shield is introduced to control the warm boundary temperature (WBT) of insulation structure. It is not only wrapped with electric heating films but also connected to the copper blocks inserted in liquid nitrogen inside the upper guard vessel. During the experiments, cold energy provided
by liquid nitrogen from upper guard vessel is transferred continuously to the copper shield thus to realize a warm boundary temperature as low as 180K. Cooperating with the electric heater, the warm boundary temperature of the insulation structure can be controlled in a range from 180K to 380K, which is supposed to cover the most temperature boundary conditions on orbit. A PID Temperature Controller lakeshore 350 was employed to control the warm boundary temperature with the accuracy of ±0.05 K.

The vacuum unit consists of a backing pump and a turbo molecular pump whose capability of vacuuming the chamber is down to $10^{-3}$ Pa at room temperature and to $10^{-5}$ Pa after chilling down.
2.2. Insulation structure

MLI/VCS is used for experimental testing. The schematic configuration of MLI/VCS is shown as Fig. 3. Aluminum 1060 was used to make the VCS. The Aluminum VCS used in experiment has a height and diameter of 400 mm and 270 mm, respectively. It is hung on the top flange through three thin fiberglass epoxy G10 rods. In order to reduce the heat leakage to the VCS, these three rods are hollow inside (= tubes) and fabricated with 10 holes on each. The corresponding heat leakage of each rod is as less as 0.01W. The VCS shield wall thickness is 1 mm. The image is shown as Fig. 4. Two MLI blankets are prepared, namely group 1 and group 2, which are located inside and outside the VCS, respectively. Each group contains 20 layers of double-aluminized mylar radiation shields and 20 layers of non-woven fiber cloth spacers. For group 1, it directly contacts the testing vessel wall thus to have a cold boundary temperature of around 78K. As the diameter of the VCS of 270 mm is larger than the outer diameter of group 1, there is a gap between VCS and the outer surface of group 1 MLI. In other words, the VCS does not directly contact with group 1 MLI. For group 2, it is wrapped directly on the outer surface of the VCS. During the experimental operation, vapor from the testing vessel flows into the VCS and goes through it, which takes away some of the heat flux entering insulation boundary and results in a reduction of heat flux getting into the testing vessel. To compare the insulation performance of the MLI/VCS and the MLI-only configurations without changing anything inside the vacuum chamber and not introducing any man-made interference, the MLI-only mode can realized by bypassing the VCS by blocking the VCS vent tube and opening the testing vessel vent tube. That is, it is not necessary to remove the VCS physically from the MLI blankets. In order to attain the temperature profile within the insulation structure, six platinum resistors PT-100 (labeled as T1 to T6) which are calibrated to have a precision of ±0.02 K are placed every ten layers of radiation shields which is shown in Fig. 3. It should be noted that, T1 directly contacts the vessel wall to measure the cold boundary temperature (CBT), and T4 directly contacts the VCS’s outer surface. During the experiment, all the measurements including temperature and flow rate are recorded by a multichannel data acquisition unit Keithley 2701.

2.3. Test method and measurement

During the experiment testing, the upper and bottom guard vessels as well as the testing vessel itself were fully filled with liquid nitrogen so that the temperature of the insulation structure at the inner side was kept the same as the cold boundary temperature. Two temperature sensors were mounted on the testing vessel’s upper and bottom sides respectively to monitor the liquid fullness of the testing vessel. An automatic liquid nitrogen refilling system was developed to maintain the fully-filled LN2 state in the guard vessel.

The boil-off gas flow rate \( \dot{V} \) (in sccm) of nitrogen is measured by a gas flow meter Honeywell AWM3100 which has a precision of ±1% FS. The nitrogen flow rate value is equivalent to the corresponding heat transfer into the liquid nitrogen testing vessel through the MLI by
where \( q \) is the heat flux into the testing vessel, in \( \text{W/m}^2 \); \( \dot{m} \) is the mass flow rate of the vented vapor which is calculated by equation (2), in \( \text{kg/s} \); \( h_{fg} \) is the latent heat of liquid nitrogen (J/kg), and \( A \) is the outer surface area of testing vessel, \( \text{m}^2 \).

It should be mentioned that, all the experimental conditions (include temperatures and flow rate) have reached final thermal equilibrium state, which additionally last at least of 24 hours before the data were taken for calculation.

3. Results and discussion

Testing of the MLI/VCS mode under four different warm boundary conditions (namely 200K, 250K, 300K and 350K) as well as the MLI-only mode under 350K condition have been conducted.

After installation of the insulation structure, the vacuum chamber was closed and isolated from the external atmosphere. The vacuum degree in chamber reached 5\( \times \)10\(^{-3} \) Pa by vacuuming for 4 days under room temperature condition. Then, both the guard vessel and testing vessel was fully filled with liquid nitrogen and the vacuum degree reached about 7\( \times \)10\(^{-5} \) Pa. For all those experiments, the vacuum degree in chamber was always in the range from 6.4\( \times \)10\(^{-5} \) Pa to 1.1\( \times \)10\(^{-4} \) Pa. Each temperature measurement point within the MLI/VCS was recorded. When the temperature fluctuation of each point within 24 hours gets less than 0.2 K, we can tell the system reaches thermal equilibrium. The performance of the MLI/VCS was evaluated after measuring the equilibrium temperature distribution and the evaporation rate for at least 24 hours. It took more than 30 days to finish the task of this manuscript.

3.1. Temperature profile within VCS/MLI combination

The temperature evaluations within the MLI/VCS during the complete process from the 250K equilibrium condition to the 300K equilibrium condition are presented in Fig. 5. It can be seen that it merely takes about 4 hours for the temperature at the outmost side of MLI (T6) to reach a new equilibrium. However, for the temperature on the 10\(^{th} \) layer of MLI (T2), the equilibrium process takes about 60 hours. It indicates that the heat transfer within the MLI/VCS is extremely slow because of its good insulation performance and thermal capacity. Moreover, it should also be noted that it takes about 3 days for the MLI/VCS adopted here to reach equilibrium.

![Fig. 5. Temperature distribution versus time](image1)

![Fig. 6. Temperature profile within MLI/VCS](image2)

When thermal equilibrium is established, the temperature profiles within the MLI/VCS at different warm boundary conditions are presented in Fig. 6. It can be seen that for all the cases, the temperature profile is always in a convex parabolic shape. The temperature profile always has the largest gradient.
curvature at the cold boundary (especially in the range of first 10 layers), while at the warm boundary side it has a much flatter curvature. The reason comes from the nature of radiation heat transfer when uniform density MLI is adopted. Early studies [2] showed that inside the MLI the heat conduction dominates near the cold boundary and the thermal radiation dominates near warm boundary. If a variable density MLI is adopted, a better linearity of the temperature profile can be achieved. Fig. 6 also indicates that the outmost temperature of the MLI/VCS is not equal to the copper shield which is used to control the warm boundary temperature, because the copper shield cannot directly contact MLI/VCS’s outmost surface. Therefore, in the subsequent contents, the warm boundary temperature is referred to the outmost surface temperature (T6) of MLI/VCS.

3.2. Effect of warm boundary temperature on VCS/MLI’s insulation performance
The heat flux entering the testing vessel was measured with warm boundary temperatures ranging from 223.2 K to 332.4 K, while the cold boundary temperature maintained around 78 K. The curve in Fig. 7 shows that the heat flux entering the tank increases with increasing warm boundary temperature. The heat flux entering the testing vessel is 0.74 W/m², 0.95 W/m², 1.35 W/m² and 2.01 W/m², respectively, when the warm boundary temperature is 223.2 K, 253.5 K, 291.8 K and 332.4 K. These heat flux values are even slightly greater than those in literature [13] which contains MLI only. The reason could be that either less than leading class performance of our MLI product or parasitic heat leakage of the tubing and support. However, the absolute result does not affect the relative behavior the experiments reveals. It can be also seen from Fig. 7 that the higher warm boundary temperature leads to larger heat flux growth rate. For example, the heat flux growth rate between 223.2 K to 253.5 K, 253.5K to 291.8 K, and 291.8 K to 332.4 K are 28.3%, 42.1% and 48.8%, respectively. The relative heat flux difference between 223.2 K and 332.4 K is as high as 63.2%. It indicates that the heat flux entering the cryogenic tank will depend greatly on the direction (towards the sun or not) on orbit.

3.3. Comparison of the insulation performance with/without VCS
To comparatively evaluate the effect of VCS on the insulation structure’s thermal performance, a MLI-only case at warm temperature of 332.4 K has been conducted. The temperature profiles within the insulation structure with or without VCS are shown in Fig. 8. Although the temperature curves with or without VCS are close to each other, actually almost all the temperature values on the same layers for the case with VCS are lower than that for case without VCS. Taking T4 (temperature sensor attached on VCS) as an example, the temperature value decreases from 304.6 K to 299.4 K after the VCS being activated (not being bypassed). It indicates that the cryogenic vapor does absorb heat penetrated from the environment and is capable of decreasing the temperature gradient between the VCS and the vessel wall. Meanwhile, the other temperature sensors which are attached on the MLI layers also decrease
somewhat. For example, $T_2$ decreases from 252.3 K to 249.6 K; $T_3$ decreases from 299.4 K to 294.7 K, and $T_5$ decreases from 318.8 K to 316.1 K. The corresponding heat flux reduction is shown in Fig. 9. When only MLI is used (VCS not activated), the heat flux is 2.50 W/m², which decreases to 2.01 W/m² after the VCS is activated. That is to say, it brings a reduction by 19.6%. Although temperatures within MLI drops not greatly, the heat flux drops 19.6%. The reason is parasitic heat leakage existing in the connecting tube between the testing vessel and VCS. The vented vapor is heated to a relatively high temperature before it entered VCS. However, this doesn’t influence the effectiveness of VCS because the cold energy of the vented vapor is fully utilized. According to our previous simulation work [11], the effect of VCS on LN2 tank and LO2 tank are fairly close. Therefore, it can be inferred that the benefit of venting loss reduction from installing a VCS to a same size LO2 tank may be around 20%.

4. Conclusion

An experimental setup for measuring the thermal performance of MLI/VCS or MLI-only was designed and constructed. The influences of warm boundary temperatures on the MLI/VCS combination were investigated. A comparison between with and without the VCS was conducted. The following conclusions can be drawn from the study:

1. The thermal equilibrium process within the MLI/VCS is extremely slow. It takes about 72 hours for the MLI/VCS to get steady.

2. Warm boundary temperature has significant influence on the MLI/VCS’s insulation performance. The heat flux increased by 63.2% when the warm boundary temperature increases from 223.2 K to 332.4 K for a liquid nitrogen vessel.

3. VCS improves the insulation structure’s thermal performance compared to MLI only. The heat flux can be reduced by 19.6% for LN2 tank after the VCS being installed.

5. References

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