

Research of the cold shield in cryogenic liquid storage

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Abstract. To realize zero boil-off storage of cryogenic liquids, a cryocooler that can achieve a temperature below the boiling point temperature of the cryogenic liquid is generally needed. Taking into account that the efficiency of the cryocooler will be higher at a higher operating temperature, a novel thermal insulation system using a sandwich container filled with cryogenic liquid with a higher boiling point as a cold radiation shield between the cryogenic tank and the vacuum shield in room temperature is proposed to reduce the electricity power consumption. A two-stage cryocooler or two separate cryocoolers are adopted to condense the evaporated gas from the cold shield and the cryogenic tank. The calculation result of a 55 liter liquid hydrogen tank with a liquid nitrogen shield shows that only 14.4 W of electrical power is needed to make all the evaporated gas condensation while 121.7 W will be needed without the liquid nitrogen shield.

1. Introduction

With the development of cryogenic technology, the application of cryogenic liquids, such as liquid oxygen (LO₂), liquid nitrogen (LN₂), liquid hydrogen (LH₂) and liquid helium (LHe), is becoming more and more extensive. For example, LH₂ has the advantages of high specific energy density, non-toxic and non-polluting. It is considered to be the most economical and efficient propellant and space fuel for lunar exploration, Mars exploration, and even more long-range deep space exploration [1]. Due to a large temperature difference between the ambient and the cryogenic liquid, heat leakage is inevitable. Accordingly, thermal insulation measures are needed for cryogenic liquid tanks to prolong its storage time. Insulation technology can be divided into two categories. One is a passive technique such as multi-layer insulation, spray foam insulation and vapor cold shield. The other is an active insulation technology, in which a cryocooler is connected to the tank to reject the heat leakage. Generally, passive thermal insulation technology is the basis and prerequisite for active thermal insulation technology.

For active insulation technology, it is common practice to use a cryocooler to condense the evaporated gas directly back to the tank. For example, a 20 K cryocooler should be adopted in LH₂ storage [2, 3]. Taking into account that the efficiency of the cryocooler will be higher at a higher operating temperature, as figure 1 shows [4], a novel thermal insulation system is proposed that uses a sandwich container filled with cryogenic liquid with a higher boiling point as a cold radiation shield between the cryogenic tank and the vacuum shield in room temperature to reduce the electricity power consumption. Different cold shield temperatures can be obtained by controlling the pressure of the cryogenic liquid inside the cold shield, and the relationship between the boiling point temperature of



LN₂ and its pressure is shown in figure 2. A two-stage cryocooler or two separate cryocoolers are adopted to condense the evaporated gas from the cold shield and the cryogenic tank.

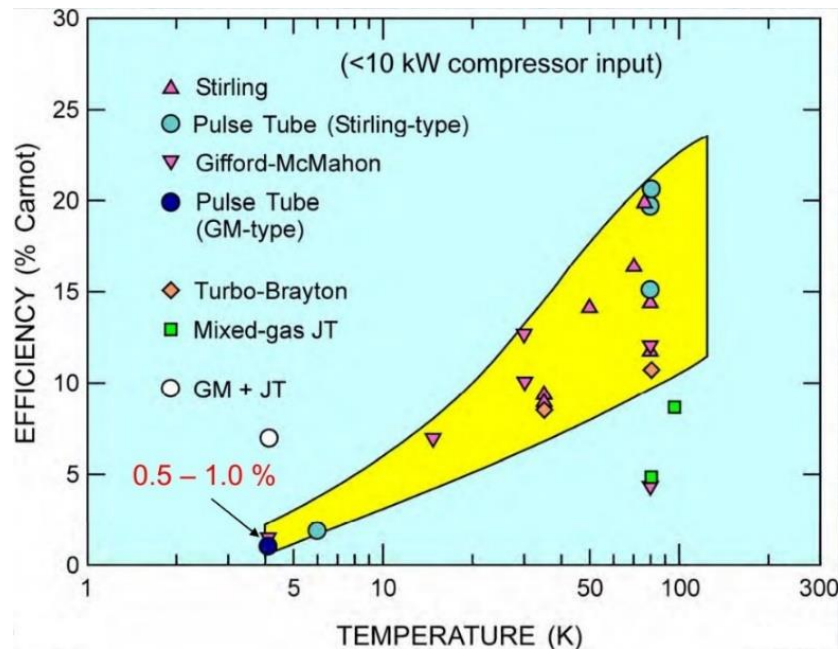


Figure 1. Efficiency of cryocoolers as a function of operating temperature [4].

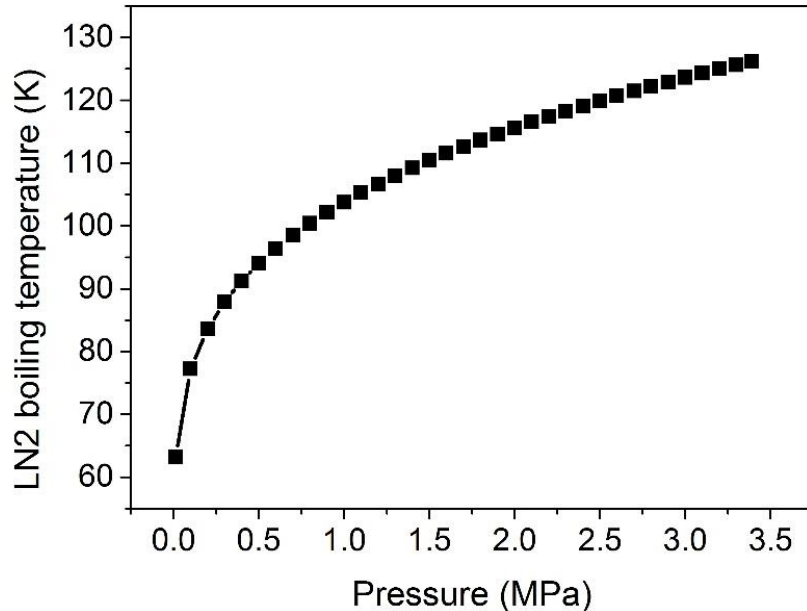


Figure 2. The relationship between the LN₂ boiling temperature and pressure.

2. LH₂ tank model and calculation method

Figure 3 is the schematic of the proposed thermal insulation structure proposed in this paper, a sandwich container filled with LN₂ is installed between the LH₂ tank and the vacuum shield in room temperature to reduce the heat leakage. The outer wall of the LH₂ tank and the sandwich container are wrapped with multi-layer insulation (MLI) materials. The shape and size of the LH₂ tank is based on a 55 L container with an external surface area of 0.733 m².

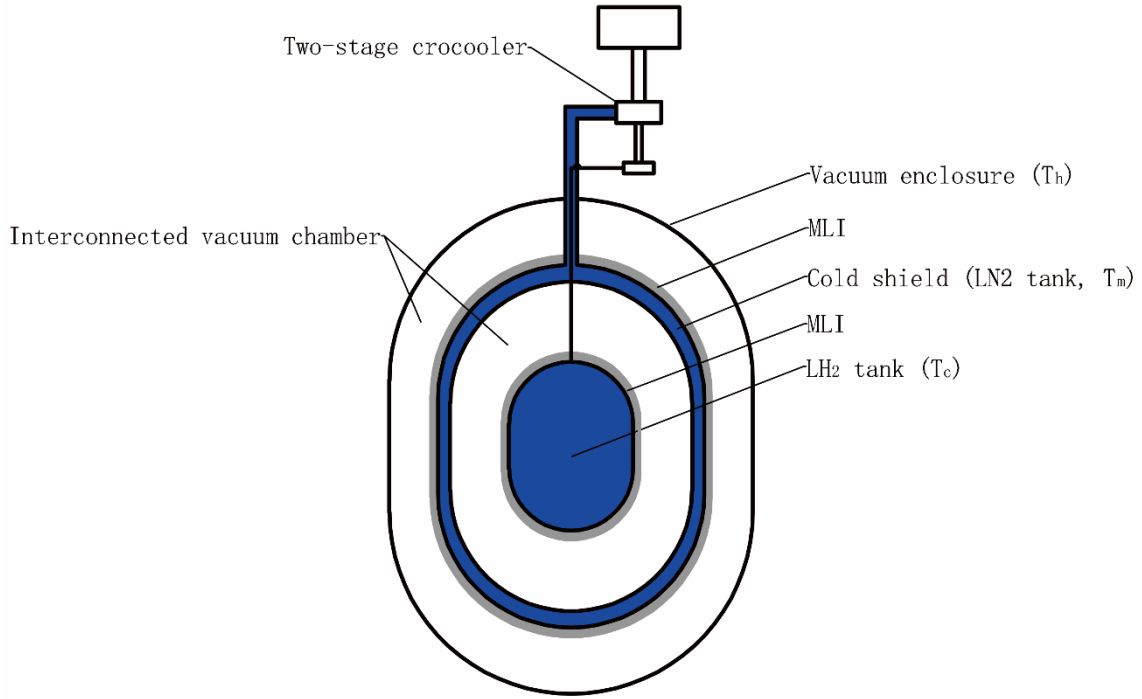


Figure 3. The schematic of the proposed thermal insulation system.

The modified Lockheed method is used to simulate MLI performance and accounts for three modes of heat transfer: thermal radiation between shields, gas conduction, and solid conduction through the separator materials, as shown in formula (1) ~ (3) [5, 6].

$$q_r = \frac{B\epsilon\sigma(T_H^{4.67} - T_C^{4.67})}{N} \quad (1)$$

$$q_g = 0.5\omega CP(T_H - T_C) \quad (2)$$

$$q_s = \frac{A(N^*)^n T_m(T_H - T_C)}{N} \quad (3)$$

Where A, B, C and ω are all empirical parameters and P is pressure in torr, T is temperature in degree K, N^* represents layer density, N presents the number of radiative shields, T_m represents the average temperature of hot and cold boundaries ($T_m = (T_H + T_C)/2$), T_H is the temperature of hot boundary, and T_C is the temperature of the cold boundary.

The total heat leakage can then be expressed as:

$$q_{total} = \frac{Y_s(N^*)^{2.63} T_m(T_H - T_C)}{N} + \frac{Y_R \epsilon(T_H^{4.67} - T_C^{4.67})}{N} + \frac{Y_G P^*(T_H^{0.52} - T_C^{0.52})}{N} \quad (4)$$

Where P^* is the pressure within the insulation as a function of position and local temperature. In the calculation, Y_s , Y_R and Y_G are empirical coefficient decided by material and its installation. In reference [6], for perforated aluminized reflectors, nitrogen gas and glass tissue spacer material, the suggested value of Y_s , Y_R and Y_G are 7.03×10^{-8} , 7.07×10^{-10} and 1.46×10^{-4} , respectively. For the composite insulation system, Y_s , Y_R and Y_G can be modified by the experimental results.

3. Results and discussions

For comparison, the heat leakage of the LH₂ tank without cold shield was firstly calculated. Figure 4 shows the relationship between heat leakage and the layers of MLI. It can be seen that the heat decreases as the thickness of the insulation layer increases, but the change rate is decreasing. One reason is that as the thickness of the multilayer insulation increases, the surface area of the external radiation is also growing. Further, too many layers will result in deterioration of the vacuum inside the MLI, then the heat leakage from gas conduction will increase. Therefore, there is an optimum value for the thickness of the MLI.

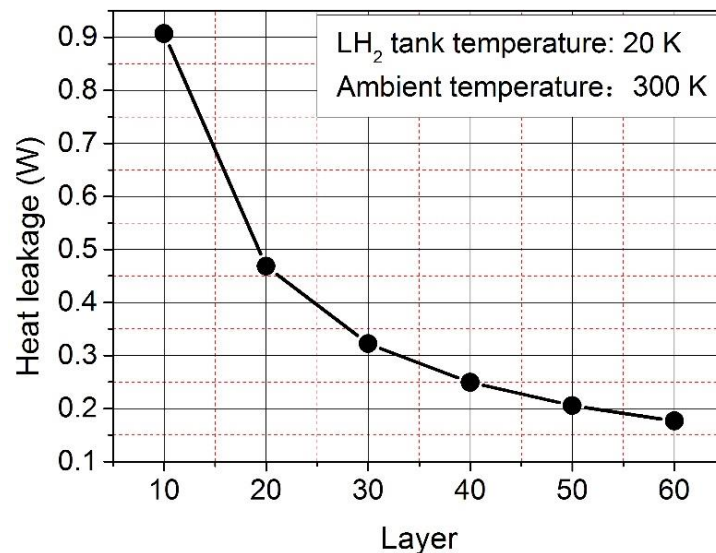


Figure 4. The relationship between heat leakage amount and number of MLI layers.

After installation of the cold shield, the heat leakage of LH₂ tank variation with the cold shield temperature is shown in figure 5. The pressure of LH₂ tank is 0.1 MPa, corresponding to a boiling temperature of 20 K. There are 30 layers of MLI wrapped the outside wall of the LH₂ tank. Comparing figure 5 with figure 4, it can be found that the heat leakage can be significantly reduced by installing the cold shield. For example, the heat leakage amount is only 20 mW when the cold shield is employed (80 K), while without the cold shield, the value is as high as 200 mW.

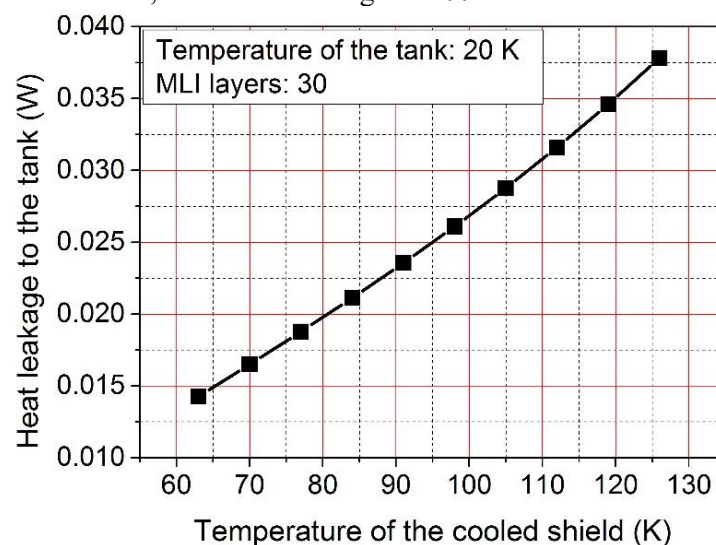


Figure 5. The relationship between the LH₂ tank heat leakage amount and the temperature of the cold shield.

The calculation results of heat leakage between the cold shield and the vacuum shield at room temperature is shown in figure 6. It can be seen that the change in the amount of leakage heat caused by the temperature change of the cold shield is not significant. This is because the emissivity of the radiation-resistant material decreases with decreasing temperature, and its value is relatively small at low temperatures. However, as shown in figure 1, when the temperature of the cold shield is increased, the efficiency of the cryocooler can be greatly improved, so that the input power consumption of the cryocooler can be effectively reduced.

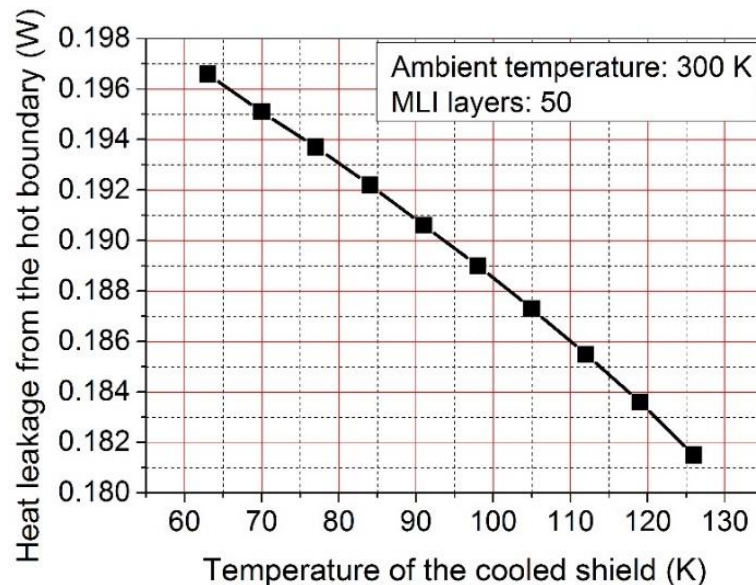


Figure 6. The relationship between the heat leakage from the vacuum shield in room temperature and the temperature of the cold shield.

Taking the test results of high frequency pulse tube cryocooler developed by Technical Institute of Physics and Chemistry Chinese Academy of Sciences as an example: the efficiency of the developed 20 K stirling-type pulse tube cryocooler is about 2.3% [7], while the developed 80 K stirling-type pulse tube cryocooler efficiency is as high as 24.2% [8]. The calculation results of table 1 show that less than 15 W of electricity power is needed to make the evaporated gas condensation (of which 12.2 W used to condense the gas evaporated from the LH₂ tank and the other 2.2 W for gas evaporated from the cold shield). However, if without the LN₂ cold shield, the input electricity power is as high as 121.7 W.

Table 1. The needed electricity power to realize zero boil-off storage of LH₂.

	LH ₂ tank heat leakage	LN ₂ cold shield heat leakage	Electricity power needed
Without cold shield	200 mW (20-300 K)	0	121.7 W
With cold shield	20 mW (20-80 K)	193 mW(80-300 K)	14.4 W

4. Conclusions

The efficiency of the cryocooler increases with the increasing of its operating temperature. For the active insulation technology of cryogenic liquid storage, the simulation results show that the required input electricity power can be reduced significantly by installing a sandwich container filled with an another cryogenic liquid with a higher boiling temperature between the cryogenic tank and the vacuum shield in room temperature. The calculation result of a 55 liter LH₂ tank with a LN₂ shield shows that only 14.4

W of electricity power is needed to make the evaporated gas condensation while 121.7 W will be needed without the cold shield. Due to the emissivity of the radiation-resistant material decreasing with decreasing temperature, and its relatively small value at low temperatures, thus the heat leakage difference caused by the temperature change of the cold shield is not significant. Therefore, it is feasible to increase the temperature of the cold shield by increasing the cryogenic liquid pressure, so that the cryocooler can be operated in a higher temperature and consume a lower input electrical power.

5. References

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