

PAPER • OPEN ACCESS

## Calculation and position optimization on vapor cooled shield for liquid hydrogen storage

To cite this article: Jianpeng Zheng *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **502** 012080

View the [article online](#) for updates and enhancements.

# Calculation and position optimization on vapor cooled shield for liquid hydrogen storage

Jianpeng Zheng<sup>1,2</sup>, Liubiao Chen<sup>1\*</sup>, Chen Cui<sup>1</sup>, Yuan Zhou<sup>1,2</sup>, Junjie Wang<sup>1, 2\*</sup>

<sup>1</sup> Chinese Academy of Sciences, Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, China

<sup>2</sup> University of Chinese Academy of Sciences, China

E-mail address: chenliubiao@mail.ipc.ac.cn; wangjunjie@mail.ipc.ac.cn

**Abstract:** The ZBO (zero boil off) storage of liquid hydrogen (LH<sub>2</sub>) has broad prospects in aerospace and civil market. Because of low critical temperature and volatility, LH<sub>2</sub> tank poses severe requirements to the insulation system (multilayer insulation (MLI) is considered to be the most promising). In order to reduce heat leak into tank, vapor cooled shield (VCS) was set up to cool the MLI by retrieving the cold energy of discharged low temperature GH<sub>2</sub>. In this study, a simplified physical model is established to investigate the optimal position of VCS in MLI, and the influence of various factors on the performance of VCS has been analysed. Taking the minimum heat leak as the target, the best installation position is around 50% in MLI (inside looking outward) for the given condition. The heat leak of the tank can be reduced by 48.03% at most.

## 1. Introduction

Hydrogen is expected to be a clean and recyclable energy carrier after the fossil fuel. Its energy density is relatively low when H<sub>2</sub> is stored in the low-density gaseous state. When H<sub>2</sub> is stored in cryogenic liquid state, multilayer insulation (MLI) is considered to be the most promising technology, which has been widely used in the storage of rocket cryogenic propellants [1].

In the LH<sub>2</sub> tank, the temperature of the new vaporized GH<sub>2</sub> is only slightly higher than that of its boiling point. Compared with the vaporization heat of H<sub>2</sub> (0.1MPa, 448.90 kJ/kg), the sensible heat from boiling point to 300 K is much greater (3509.75 kJ/kg). How to make use of the sensible heat is of great importance for LH<sub>2</sub> storage. In order to reduce the evaporation rate of LH<sub>2</sub> insulated by MLI, vapor cooled shield (VCS) was put forward, whose basic principle was to cool the MLI by retrieving the cold energy from discharged low temperature GH<sub>2</sub> [2].

## 2. Physical model and assumptions

For LH<sub>2</sub> storage, a simplified physical model has been established to investigate the optimal



position of VCS in MLI to reduce the heat leak into the tank. In this model, the influence of various factors ( $\text{GH}_2$  sensible heat recovery efficiency, MLI thickness, boundary temperature) on the performance of VCS has been analyzed [3].

## 2.1 Assumptions

This paper assumes that the tank and insulation system stay in thermal steady state, and we make the following assumptions:

- (1)  $\text{LH}_2$  in tank is maintained at 0.1 MPa, and the corresponding boiling point in the calculation is taken as 20 K ;
- (2) The vacuum of external environment is kept above  $5 \times 10^{-3}$  Pa;
- (3) The VCS material has high thermal conductivity and VCS keeps uniform temperature;
- (4) Thermal contact resistance between cold shield and adjacent MLI can be ignored, and their temperature remains the same.

## 2.2 Calculation model

The aluminum alloy tank is spherical with a radius of 0.3 m. The composite insulation system outside the tank consists of MLI and VCS, as shown in Figure 1. The thermal conductivity of aluminum alloy is excellent, and the surface temperature of tank is  $\text{LH}_2$  temperature. When the tank and insulation system reach steady state, the heat transfer process is shown in Figure 2.

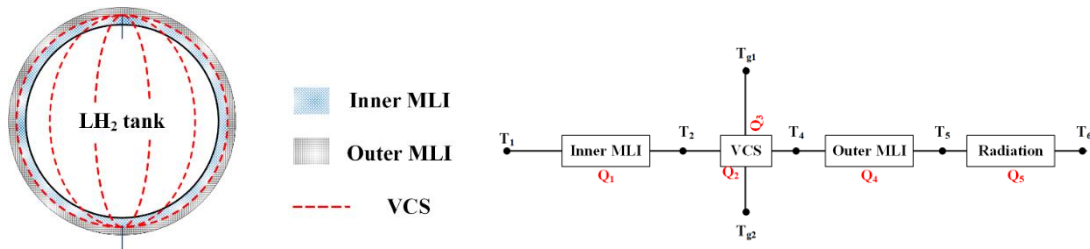


Figure1. Schematic diagram of VCS      Figure 2. Schematic diagram of heat transfer process

The heat leak through the inner MLI can be obtained by [4]:

$$Q_1 = \frac{K_{12}(T_2 - T_1)A_{12}}{L_{12}} \quad (1)$$

$A_{12}$  --the effective area of inner MLI;  $L_{12}$  --the thickness of outer MLI;  $K_{12}$  -- Average apparent thermal conductivity of inner MLI.

The heat leak through VCS includes three parts:  $Q_2$  to inner MLI,  $Q_3$  to the cold  $\text{GH}_2$  flowing through VCS and  $Q_4$  from outer MLI.

$$Q_2 = Q_1; \quad Q_3 = \dot{m}(h_{g2} - h_{g1}); \quad Q_2 + Q_3 = Q_4 \quad (2)$$

$\dot{m}$  --  $\text{H}_2$  mass flow flowing through VCS;  $h_{g1}$   $h_{g2}$  -- Enthalpy of  $\text{H}_2$  flowing into and out of VCS.

The heat leak through the outer MLI can be obtained by:

$$Q_4 = \frac{K_{45}(T_5 - T_4)A_{45}}{L_{45}} \quad (3)$$

$A_{45}$  is the effective area of outer MLI;  $L_{45}$  --the thickness of outer MLI.  $K_{45}$  -- average apparent thermal conductivity of outer MLI.

Radiative heat transfers between outer MLI and environmental chamber can be obtained by:

$$Q_5 = \sigma \varepsilon_{56} (T_6^4 - T_5^4) A_5 \varphi_{56} \quad (4)$$

$\sigma$  -- Stefan Boltzmann constant,  $5.675 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$ ;  $\varphi_{56}$  --Radiation angle coefficient

$$\varepsilon_{56} = \frac{1}{\frac{1}{\varepsilon_5} + \frac{A_5}{A_6} \left( \frac{1}{\varepsilon_6} - 1 \right)} \quad (5)$$

$\varepsilon_5$  and  $\varepsilon_6$  --surface emissivity of materials.

### 2.3 Apparent thermal conductivity of MLI

There are three methods to calculate the heat leak through MLI: apparent thermal conductivity method, layer-by-layer model and Lockheed method. In this paper, the apparent thermal conductivity method is chosen to calculate the heat transfer through MLI. Apparent thermal conductivity of MLI can be calculated by semi-empirical Modified Lockheed equation in reference [5]. The fitting formula of apparent thermal conductivity in different temperature zones is obtained by MATLAB.

$$q_{total} = q_s + q_r + q_g \quad (6)$$

$$q_{total} = \frac{2.4E-4(N^*)^{2.63}[0.017 + 7E-6(800-T) + 0.0228\ln(T)](T_H - T_C)}{N_s} + \frac{4.944E-10\varepsilon(T_H^{4.67} - T_C^{4.67})}{N_s} + \frac{1.46E4P^*(T_H^{0.52} - T_C^{0.52})}{N_s} \quad (7)$$

$T_H$ ,  $T_C$ --Hot and cold boundary temperature of MLI;  $T=(T_H+T_C)/2$ ;  $P^*$ -- Environmental pressure, torr (1 torr $\approx$ 133.322 Pa);  $\varepsilon$  -- Emissivity of reflector material in MLI;  $N^*$ --Layer density of MLI,  $\text{cm}^{-1}$ ;  $N$ —Layer number of MLI.

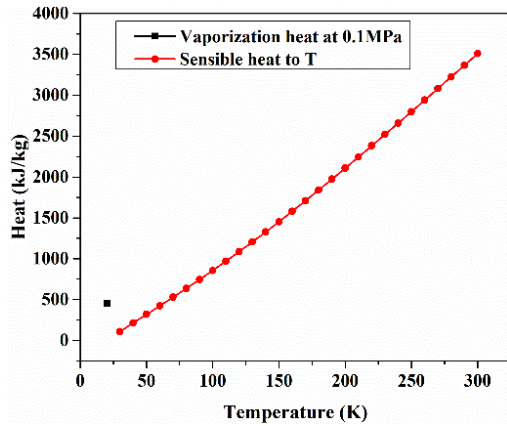


Figure 3. Heat of GH<sub>2</sub> from 20.32K to T

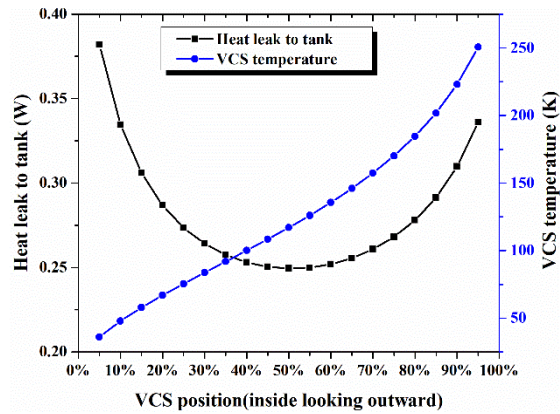


Figure 4. Optimization of VCS installation position

### 2.4 Vaporization heat and sensible heat of hydrogen

Taking the saturated hydrogen vaporization heat (0.1MPa) as the benchmark. The sensible heat recovery in VCS can be evaluated according to the discharge GH<sub>2</sub> temperature T, shown in Figure 3. The fitting formula of discharge GH<sub>2</sub> temperature T and sensible heat (from boiling point to T) is obtained by MATLAB.

## 3. Results and analysis

### 3.1 Optimization of VCS installation position

In the calculation, total thickness of inner MLI and outer MLI is 50 mm. The ambient temperature is 300 K. Assuming that the sensible heat has been completely recovered by VCS. Taking the minimum heat leak into the tank as the target, the best installation position is around 50% (inside looking outward) in MLI. As shown in Figure 4, the heat leak decreases and then increases, and the temperature of VCS decreases with position moving from 0% to 100%. The total heat leak of tank is 0.4799 W without VCS. After installation of VCS, the minimum leak heat is 0.2494 W in the 50% of MLI, and the maximum reduction is 48.03%.

### 3.2 Effect of sensible heat recovery efficiency on VCS performance

Figure 5 shows the effect of sensible heat recovery efficiency on VCS performance. VCS is installed in 50% of MLI, that is, the number of MLI layers inside and outside VCS is the same. The total heat leak of tank is 0.4799 W without sensible heat recovery. With the sensible heat recovery efficiency increasing from 10% to 100%, the heat leak decreased from 0.4151 W to 0.2494 W, and the temperature of VCS decreased from 181.5 K to 117.0 K. That is, the reduction of heat leak by VCS is 13.50%~48.03%.

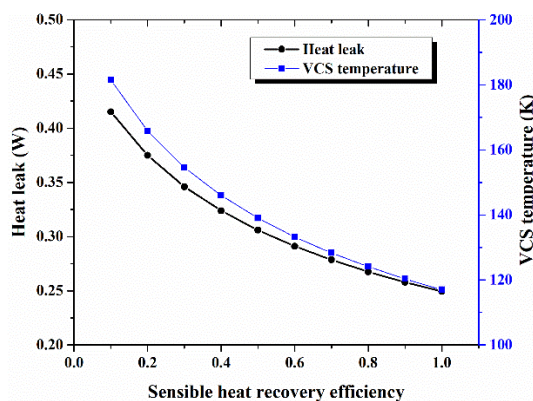


Figure 5. Effect of sensible heat recovery efficiency

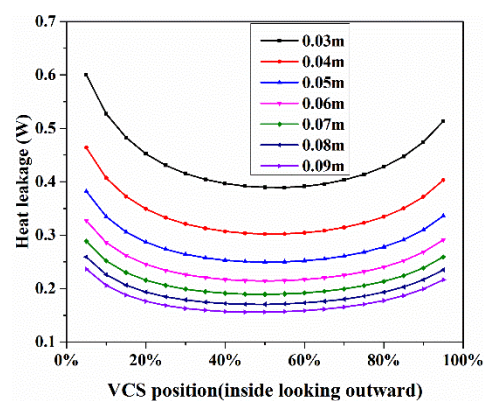


Figure 6. Effect of MLI thickness

### 3.3 Effect of MLI thickness on VCS performance

Figure 6 shows the effect of MLI thickness on VCS performance. With the increase of MLI thickness, the total heat leak of tank decreases continuously, and the amplitude decreases, which is consistent with the existing theory. From the analysis of the calculation results, with the increase of MLI thickness, the decrease of tank heat leak by VCS also increases slightly, and the best installation position of VCS moves inward (from 60% to 50% in MLI).

### 3.4 Effect of boundary temperature on VCS performance

Figure 7 shows the effect of boundary temperature on VCS performance. When VCS is close to the tank, the change of cold boundary temperature has a greater influence on it; otherwise, the change of hot boundary temperature has a greater influence. With the increase of  $T_C$ , the best installation position of VCS moves inward. The apparent thermal conductivity of MLI increases with the increase of temperature. With the increase of  $T_H$ , the optimal installation position of VCS also moves inward.

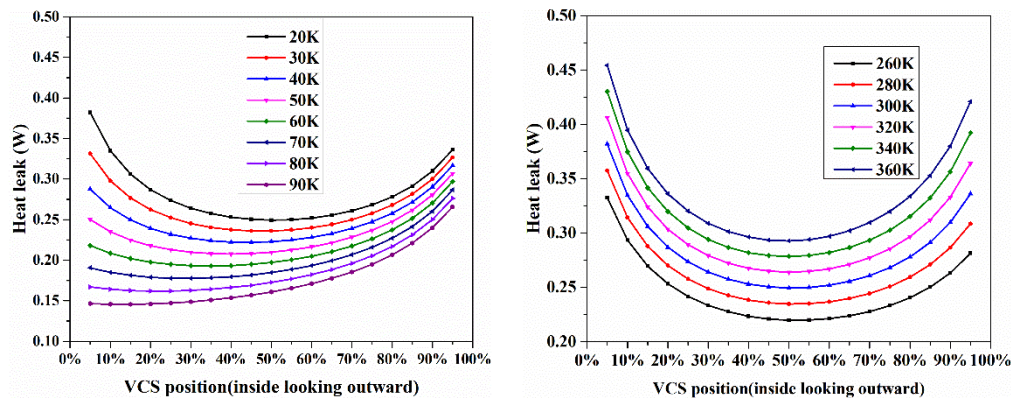


Figure 7. Effect of boundary temperature on VCS performance

#### 4. Conclusion

After installation of VCS, the overall insulation performance has been significantly improved by recovering the sensible heat of cold GH<sub>2</sub>. A simplified physical model has been established to optimize the insulation performance of VCS. The optimized VCS can lay a good foundation for the future ZBO system for LH<sub>2</sub> storage.

(1) Taking the minimum heat leak of the tank as the target, the best installation position is around 50% in MLI (inside looking outward) for the given condition. The heat leak of the tank can be reduced by 48.03% by the most.

(2) Sensible heat recovery efficiency, MLI thickness and boundary temperature have an effect on the optimal installation position of VCS. In order to achieve better insulation performance, the position of VCS should be determined according to MLI and application environment.

#### References

- [1] Plachta D W, Christie R J, Carlberg E and Feller J R 2008 *AIP Conference Proceedings* **985**(1) 1457-1466.
- [2] Chen L, Zheng J, Wu X, Cui C, Zhou Y and Wang J 2017 *IOP Conference Series: Materials Science and Engineering* **278**(1) 012194.
- [3] Dye S A, Johnson W L, Plachta D W, Mills G L, Buchanan L and Kopelove A B 2014 *Cryogenics* **64** 135-140.
- [4] Zheng J, Chen L, Cui C, Guo J, Zhu W, Zhou Y and Wang J 2018 *Applied Thermal Engineering* **130** 161-168.
- [5] Hedayat A, Hastings L J and Brown T 2002 *AIP Conference Proceedings* **613**(1) 1557-1564.

#### Acknowledgement

This research is supported by National Key R&D Program of China (No. 2018YFB0504603), the National Natural Science Foundation of China (No. 51706233, 51427806, U1831203), Strategic Pilot Projects in Space Science of China (No. XDA15010400), and Supported by Key Research Program of Frontier Sciences, CAS, Grant No. QYZDY-SSW-JSC028.