Experimental Research of Perforation Rate for Multilayer Insulation Used in Cryogenic Transfer Lines

B C Deng¹², S Q Yang¹, X J Xie¹*, D W Wu¹², W Pan¹, X M Li¹² and Q Li¹²
¹ State Key Laboratory of Technologies in Space Cryogenic Propellants (Technical Institute of Physics and Chemistry, Chinese Academy of Sciences), Beijing 100190, China
² University of Chinese Academy of Sciences, Beijing 100190, China

* Corresponding author, E-mail: xiexiujuan@mail.ipc.ac.cn

Abstract. In this paper, thermal performance through perforated multilayer insulation (PMLI) is experimentally investigated using a cryogenic transfer line test platform. PMLI consisting of double-aluminized Mylar and silk netting for 25 layers cm⁻¹ and 50 layers was tested. The experimental results show perforation rate has an optimum value of 0.39% and the corresponding heat flux and effective thermal conductivity reach a minimum value of 2.61 W/m² and 2.31×10⁻⁴ W/(m·K). In addition, both q and kₑ increase with rise of absolute pressure in vacuum jacket and the absolute pressure should be maintained lower than 0.01 Pa at least. The research of optimal perforation of PMLI in this study offers reliable experimental basis for manufacturing perforated multilayer insulation cryogenic transfer lines.

1. Introduction
Multilayer insulations (MLI) are extensively used in space vehicle and cryogenic systems because of its super insulation performance, light weight and little pollution. MLI material is a combined system consisting of low emissivity reflectors and low conductivity spacers. Uses of MLI systems generally fall into the following categories: storage, transfer, thermal protection, and low-temperature processes [1]. Transfer applications include hospital oxygen piping systems, propellant loading systems, railroad tank cars, transport ships, liquefied natural gas pipelines, portable tankage of various sizes, and cryogenic transfer line. In order to reduce the heat leakage into cryogenic refrigerator, cryogenic transfer line is an important part usually used to transfer liquid helium and supercritical helium in large-scale helium refrigerator [2]. The thermal performance of cryogenic transfer line directly influences large-scale helium refrigerator. So the performance of multilayer insulation materials is crucial for cryogenic transfer line.

Many of studies about heat transfer model and testing are focus on multilayer non-perforated insulation material [3-6]. In order to make the MLI outgas quickly and decrease the effect of gas conduction, perforation is usually adopted in MLI. However, there is litter literature on perforated multilayer insulation (PMLI). MLI having perforated shields has analyzed radiant heat transfer in [7]. And a theoretical model of the heat transfer processes in perforated multilayer insulation was proposed in [8]. In addition, numerical models of one dimension for perforated MLI were presented in [9]. The heat leakage of each perforation or hole with 1 mm diameter has been experimentally measured for 0.31 mW [10]. Previous researches above mentioned have not experimentally analyzed the perforation rate of PMLI used in cryogenic transfer line. Therefore, in this paper, thermal performance of PMLI is
experimentally investigated for different perforation rate at different vacuum pressure using a cryogenic transfer line test platform. Heat flux and effective thermal conductivity of PMLI for different perforation rates were obtained. Through analyzing thermal performance of PMLI, the optimized perforation rate of PMLI would be presented and improved the insulating effect.

| Nomenclature | Definition |
|--------------|------------|
| MLI          | Multilayer insulation |
| PMLI         | Perforated multilayer insulation |
| $T$          | Absolute temperature, K |
| $k$          | Thermal conductivity |
| $Q$          | Heat leakage, W |
| $g$          | Heat flux of PMLI, W/m$^2$ |
| $D_o$        | Inner diameters of test pipe, m |
| $l$          | Length of pipe, m |

| Subscripts   | Definition         |
|--------------|--------------------|
| $\delta$     | Thickness of MLI   |
| $G_e$        | Flow rate of evaporated gas |
| $\rho$       | Density            |
| $h_f$        | Latent heat of vaporization |
| $\epsilon$   | Effective          |
| $h$          | Hot boundary       |
| $c$          | Cold boundary      |

2. MLI used in cryogenic transfer lines
A three-channel coaxial liquid helium pipe is designed in [11]. The inner pipe supplies liquid helium. The space between the inner pipe and middle pipe transfers returned gaseous helium. Fig. 1(a) shows a simplified cryogenic transfer lines and PMLI material were wrapped around the outer surface of middle pipe. It would have a room as a vacuum jacket between PMLI and outer pipe, which is evacuated to reduce heat leak by convection and conduction in the residual gas. A triangle support made of G10 is installed between middle pipe and outer pipe to avoid a thermal bridge due to direct contact. The arrangement of PMLI in test pipe was shown in Fig. 1(b). Temperature sensors were installed in double-aluminized Mylar surfaces every 10 layers. Typical PMLI materials for different perforation rates were shown in Fig. 1(c).

![Figure 1](image1.png)

Figure 1. Schematic drawings of PMLI used in cryogenic transfer lines
The perforation rate of reflector is given by $\varphi = \frac{A_p}{A_t}$. The $\varphi$ is the perforation rate. And $A_p$ and $A_t$ are the area of perforated hole and total area of reflector wrapped in test pipe. In addition, the key geometrical parameters for PMLI tested are given in Table 1.

### Table 1. Key geometrical parameters for PMLI testing

| Test material | Type               | $\delta$(cm) | Weight (kg/m$^2$) | Layer density (layer/cm) | Number of layers | Mean area (m$^2$) |
|---------------|--------------------|---------------|-------------------|--------------------------|------------------|------------------|
| PMLI          | Double-Aluminized  | 0.001         | 0.004             | 25                       | 50               | 0.684            |
| Mylar         | silk netting       | 0.008         | 0.006             |                          |                  |                  |

3. **Test platform and experimental method of cryogenic transfer lines**

The thermal performance of PMLI materials was measured using a test platform of six-meters cryogenic transfer lines with the merits of easily disassemble outer pipe and changeable MLI as shown in [11]. The test platform with static boiloff calorimetry method is illustrated in Fig. 2. The principle of heat leakage measurement is the liquid nitrogen boil-off calorimetry method. The test platform mainly includes 2-meters test pipe, two guarded pipes, vent pipe, vacuum pump system, flow meter and vacuum gauge, temperature sensors, vacuum gauge and data acquisition system. PMLI were wrapped in 2-meters test pipe shown in Fig. 1(b). Test pipe and two guarded pipes are maintained at the same cold boundary temperature of approximately 78 K. The warm boundary temperature is room temperature about 303 K. The cold vacuum pressure in the vacuum jacket was maintained in the range of $1 \times 10^{-3}$ Pa by active vacuum pump.

Through the test platform, thermal performance of PMLI can be measured and researched for different perforation rates. The steady-state heat leakage $(Q)$ is the basis for calculating thermal properties including effective thermal conductivity $(k_e)$ and heat flux $(q)$ of PMLI. The calculated equations were shown as following.

\[
Q = G_c \rho h t
\]
\[
k_e = \frac{Q}{\ln \left( \frac{D_0 + 2\delta}{D_0} \right)}
\]
\[
q = \frac{Q}{\pi l \left( \frac{D_l}{D_l + \delta} \right)}
\]

![Figure 2. Schematic drawings of test platform of cryogenic transfer lines](image-url)
A summary of the measurement uncertainties for the test platform are given in Table 2.

Table 2. Uncertainties of the cryogenic test platform

| Physical quantity | Sensor | Units | Uncertainty |
|-------------------|--------|-------|-------------|
| $G_v$             | Alicat 50 flow meter | L/min | 0.8%RD+1%FS |
| $D_0, \delta, l$  | Vernier caliper | m | 0.2% |
| $T$               | PT-100 resistor | K | ±0.1 K |

Based on Eq. (1), (2) and (3) and error propagation theory, the overall uncertainty of $Q$, $q$ and $k_e$ are estimated to be 4.1%, 4.1% and 4.2%, respectively.

4. Result and Discussions

Because of super insulating performance and lightweight MLI has widely been applied in the cryogenic refrigerator and cryogenic transfer line. In this part, PMLI materials consisting of Double Aluminized Mylar reflector and silk netting spacer were chosen used to experimentally research the influence of perforation rate and vacuum absolute pressure based on test platform and experimental method of cryogenic transfer lines. The layer density and number of layer of MLI were 25 layers cm$^{-1}$ and 50 layers, respectively. And perforated multilayer insulation material properties were listed in Table 1. So the experimental results are summarized as following.

4.1 Influence of perforation rate for PMLI

![Variation of heat flux and effective thermal conductivity with perforation rate](image)

**Figure 3.** Variation of heat flux and effective thermal conductivity with perforation rate

Fig. 3 shows the variation of heat flux and effective thermal conductivity with perforation rate at high vacuum, respectively. It is observed that heat flux and effective thermal conductivity vary obviously with the perforation rate. As perforation rate increase heat flux and effective thermal conductivity decrease firstly, then increase. The reason is that the radiation heat flux increases whereas the conduction heat flux decreases with the increasing of perforation rate. Meanwhile, the perforation rate has an optimum value of 0.39% and the corresponding heat flux and effective thermal conductivity reach a minimum value of 2.61 W/m$^2$ and $2.31 \times 10^{-4}$ W/(m·K). As shown in Fig. 3, the variation of heat flux and effective thermal conductivity are in good agreement with the theoretical data by P. Li et al. [9], in which the layer density is 20 layers cm$^{-1}$ and the optimum perforation rate is 0.4%. In addition, the increasing of perforation rate may result in heat flux increase obviously and degraded performance of PMLI.

4.2 Thermal performance of PMLI at different vacuum level for different perforation rate
The influences of absolute pressure from $1 \times 10^3$ Pa to 5 Pa on heat flux and effective thermal conductivity were presents in Fig. 4. As is obvious from Figures, both $q$ and $k_e$ increase with rise of absolute pressure. And there is a small spread of $q$ and $k_e$ for perforation rates of 0.39%, 0.79% and 3.14% when absolute pressure lower than 0.01 Pa. So the absolute pressure in vacuum jacket should be maintained lower than 0.01 Pa at least. With the absolute pressure increasing, both $q$ and $k_e$ for perforation rate 0.39% increase much faster than that of 0.79% and 3.14%. When absolute pressure in the vacuum jacket increased, the residual gas conduction is dramatically increasing and the gas entering the space between the reflectors, which resulting in degradation performance of PMLI.

5. Summary

PMLI materials are experimentally researched based on cryogenic transfer line test platform. The perforation rate has an optimum value of 0.39% for PMLI of 25 layers cm$^{-1}$ and 50 layers, and the corresponding heat flux and effective thermal conductivity reach a minimum value of 2.61 W/m$^2$ and $2.31 \times 10^{-4}$ W/(m·K). Meanwhile, influences of absolute pressure from $1 \times 10^3$ Pa to 5 Pa on heat flux and effective thermal conductivity were obtained. Both $q$ and $k_e$ increase with the rise of absolute pressure. And the absolute pressure in vacuum jacket should be maintained lower than 0.01 Pa at least.

References

[1] Fesmire J E, Johnson W L 2018 Cryogenics 89 58-75
[2] Fydrych J and Chorowski M et al 2010 AIP Conference Proceedings vol 1218 pp 1103-10
[3] Shu Q S, Fast R W and Hart H L 1985 Advances in Cryogenic Engineering pp 455-63
[4] Bapat S L, Narayankhedkar K G and Lukose T P 1990 Cryogenics 30 (8) 700-10
[5] Sun P J, Wu J Y, Zhang P, Xu L and Jiang M L 2009 Cryogenics 49 (12) 719-26
[6] Dye S A, Tyler P N, Mills, G L and Kopelove A B 2014 Cryogenics 64 (1) 100-4
[7] Tien C and Cunnington G 2013 Presented at the AIAA 58th Thermophysics Conference, AIAA 73-718, 1973
[8] Zhitomirskij I S, Kisslov A M and Romanenko V G 1979 Cryogenics 19 (5) 265-68
[9] Li P, and Cheng, H 2006 Applied Thermal Engineering 26 (16) 2020-26
[10] Johnson W L et al 2017 IOP Conf. Series: Materials Science and Engineering 278 (1) 012017
[11] Deng B C et al 2017 IOP Conf. Series: Materials Science and Engineering 278 (1) 012197

Acknowledgements

This work was supported by the fund of National Research and Development Project for Key Scientific Instruments. (ZDYZ2014-1)