Measurement of Apparent Thermal Conductivity of Insulation Materials at Cryogenic Temperatures

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Abstract. Efficient storage of cryogenic liquids such as liquid oxygen and liquefied natural gas depends on the development of reliable and high-performance insulation materials. However, thermal conductivity data for many potential candidates, including cellular glass, polyisocyanurate, and aerogel, remain limited under cryogenic and atmospheric pressure conditions. In this study, a dedicated experimental apparatus was designed and constructed to measure the apparent thermal conductivity of representative insulation materials. Tests were carried out on cellular glass slabs, high-density polyisocyanurate, aerogel blankets, and nitrile rubber curved panels at liquid-nitrogen temperatures and above. The results indicate that aerogel blankets exhibit the best insulation performance, with an apparent thermal conductivity as low as 0.0063 W/(m·K) at 110 K, significantly outperforming the other tested materials. These results offer valuable references for the selection, optimization, and practical application of insulation materials in cryogenic storage tanks.

1. Introduction

With the continuous growth of global energy consumption and increasing attention to carbon emissions, the development of efficient thermal insulation materials has become a key approach to achieving sustainable development. A variety of novel insulation materials have emerged and are being applied in buildings, industry, transportation, and aerospace to optimize thermal management, improve energy efficiency and device performance, and reduce operational costs. Multi-layer insulation (MLI) exhibits an apparent thermal conductivity as low as 10^{-6} to 10^{-5} W/(m·K) under high vacuum conditions[1]. However, in practical applications, thermal insulation materials are also frequently exposed to ambient atmospheric conditions, where their thermal performance is affected by multiple factors such as gas permeation, humidity, and radiative heat transfer. Therefore, a thorough investigation of the thermal conductivity characteristics of insulation materials across a wide temperature range and under atmospheric conditions is essential. Such studies can provide guidance for optimizing insulation in building envelopes and spacecraft, as well as theoretical support for designing insulation systems for extreme environments, such as space vacuum or high-pressure hydrogen storage.

Nikpourian et al. used the guarded hot plate method and March method to measure the apparent thermal conductivity and thermal diffusivity of aerogel blankets and MLI under atmospheric pressure[2]. Kyeongho et al. reported the variation in apparent thermal conductivity

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of two types of aerogel blankets with vacuum pressure under cryogenic boundary temperatures of liquid nitrogen and liquid argon[3]. Additionally, the effects of vacuum level on the apparent thermal conductivity of foam insulation, perlite, and glass microspheres have also been studied[4,5]. However, there has been limited research on the thermal conductivity characteristics of insulation materials from cryogenic to room temperature under atmospheric environments. In this study, a low-temperature apparent thermal conductivity test system was established to measure the thermal conductivity characteristics of several common insulation materials under variable temperature conditions.

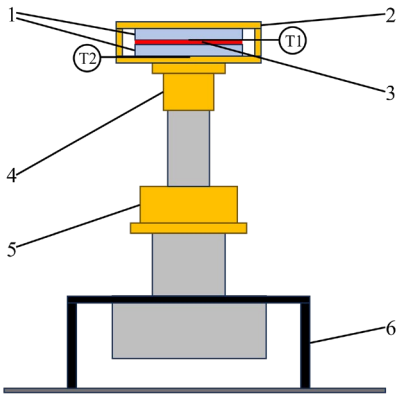
2. Experimental setup

Fourier's law of heat conduction, as shown in Equation (1), serves as the fundamental equation for thermal conduction. During the measurement of apparent thermal conductivity, heat transfer within insulation materials involves multiple mechanisms, including conduction, convective heat transfer, and radiative heat transfer. Apparent thermal conductivity is defined based on Fourier's law as the proportionality coefficient between the heat flux through the insulation material and the temperature gradient across its hot and cold surfaces. This parameter encompasses various modes of heat transfer under atmospheric conditions and can be used as a comprehensive metric for evaluating the thermal performance of insulation materials.

$$K_A = Q\frac{dx}{dT} \tag{1}$$

where K_A represents the apparent thermal conductivity of the insulation material in W/(m·K). Q represents the heat flux through the insulation material in W/m^2, dx is the thickness of the insulation material, in m, and dT is the temperature difference between the hot and cold surfaces of the material in K.

Based on this principle, the testing system is composed of a cryocooler, temperature sensors, a DC power supply, and a data acquisition unit. A Gifford-McMahon (GM) cryocooler from Sumitomo (Japan) is used as the cold source. Figure 1 shows a schematic diagram of the testing apparatus. The cold head of the cryocooler is connected to a copper square heat sink and fixed with screws. The insulation material under test is arranged on the heat sink in a "sample–heating film–sample" configuration. A copper shield in the shape of an open-bottom box is then placed over the assembly and fastened with screws to ensure tight contact among the heat sink, copper shield, samples, and heating film. Apiezon N-grease was uniformly applied at the interfaces to



1. Sample pair 2. Copper cover 3. Heating film
4. 1st Cold stage 5. 2nd Cold stage 6. Bracket

Figure 1. Schematic diagram of experimental setup

reduce thermal contact resistance. This arrangement helps to maintain consistent cold-side boundary temperatures for the sample pair, which is essential to ensure the heat generated by the heating film is evenly distributed between them.

To minimize heat exchange between the apparatus and the external environment, both the

Figure 2. Photograph of the experimental setup

copper shield and the cryocooler cold head are wrapped with five layers of aluminum-foil-covered elastomeric insulation foam. Figure 2 shows the device with the sample pair placed in position (before mounting the copper shield) and the actual setup after insulation wrapping.

During the experiment, PT100 resistance thermometers are used to measure the hot and cold boundary temperatures of the samples. The temperature signals are acquired using a NI-9217 data acquisition module, and the digital signals are connected to a computer for real-time monitoring and recording via LabVIEW software. A DC power supply delivers a constant current to the heating film. Since part of the power supplied by the DC source is lost through lead wires and does not contribute directly to heating the sample, the fitted relationship between the heating film resistance and temperature is established as shown in Equation (2). The heat flux through the samples is then calculated using Equation (3).

$$R = 0.007553t + 5.8481 \tag{2}$$

$$Q = I^2R/2 \tag{3}$$

Where R represents the resistance of the heating film in Ω, t denotes the characteristic temperature of the sample in K, and I is the current passing through the heating film in A.

Once the temperature fluctuation at the hot and cold boundaries remains within ±0.1 K for 30 minutes, the system is considered to be in thermal equilibrium. At this point, the apparent thermal conductivity of the material can be calculated based on the current from the DC power supply, the boundary temperatures, and the geometric parameters of the sample.

Photos of the measured samples are shown in Figure 3. High-density polyisocyanurate (HDPIR) is a rigid foam produced by the reaction of isocyanates with polyether polyols. It has a structure similar to polyurethane and features a high closed-cell content. Cellular glass slabs are inorganic porous materials made by high-temperature foaming of crushed glass. Nitrile rubber curved panels are flexible foamed materials suitable for covering irregularly shaped pipelines. Aerogel blankets are composed of nano-silica as the core material, reinforced with glass fibers.

While they provide excellent thermal insulation performance, their brittleness requires avoiding mechanical friction during use. These materials are commonly used in cryogenic insulation

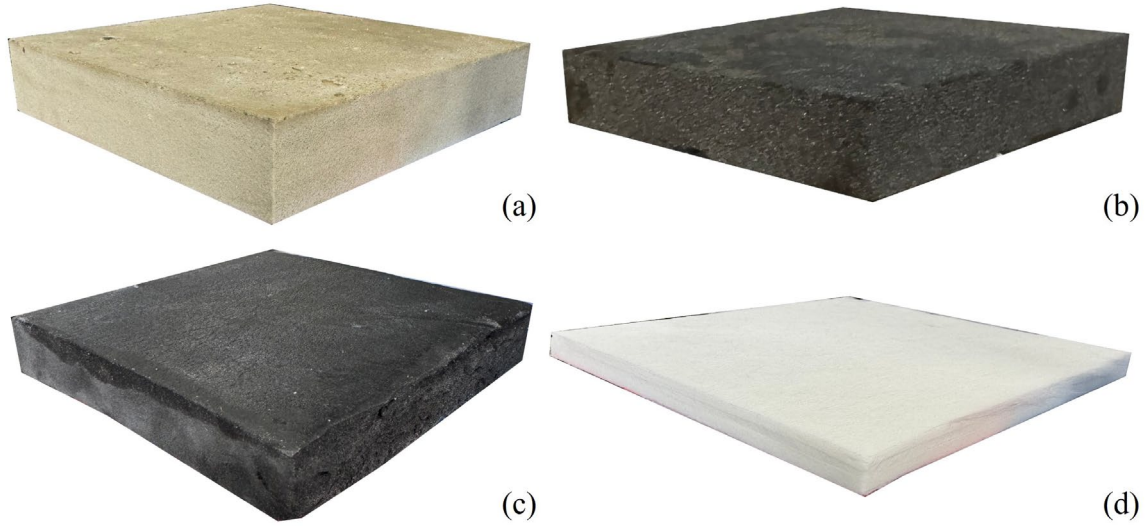


Figure 3. Physical image of sample (a)HDPIR, (b)cellular glass slabs, (c)nitrile rubber curved panels and (d)aerogel blankets

Table 1. Physical dimensions of samples

Insulation material	Size(m)
HDPIR	0.15×0.15×0.03
cellular glass slabs	0.15×0.15×0.03
nitrile rubber curved panels	0.15×0.15×0.024
aerogel blankets	0.15×0.15×0.01

applications, such as external insulation layers for rocket liquid oxygen tanks and LNG storage tanks. Therefore, their apparent thermal conductivity characteristics are measured. The physical dimensions of the samples used in the measurements are listed in Table 1.

3. Result discussion

The variation of the thermal conductivity of HDPIR in the temperature range from 100 K to 300 K under atmospheric conditions is shown in Figure 4. As illustrated in the figure, the thermal conductivity exhibits an almost linear increase with temperature. Specifically, the thermal conductivity of HDPIR is 0.03931 W/(m·K) at 104.24 K and increases to 0.07965 W/(m·K) at 298.97 K. Based on linear fitting, the relationship between the apparent thermal conductivity of HDPIR and temperature under atmospheric conditions can be expressed by Equation (4).

$$K_{HDPIR} = 2.012 \times 10^{-4}T + 0.1521 \quad (4)$$

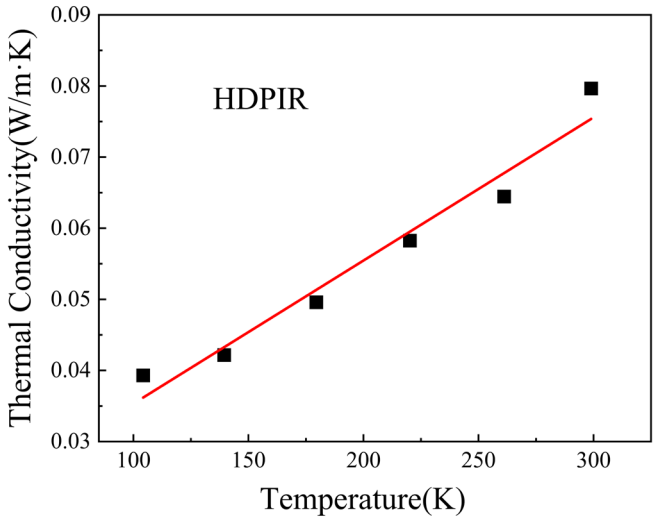


Figure 4. Temperature dependence of the apparent thermal conductivity of HDPIR

Figure 5 presents the variation of the thermal conductivity of cellular glass slabs in the temperature range of 95 K to 300 K under atmospheric conditions, which exhibits an approximately linear trend. At 96.96 K, the thermal conductivity of the cellular glass slabs is 0.02409 W/(m·K), and it increases to 0.06155 W/(m·K) at 299.12 K. A linear fit of the thermal conductivity data at different temperatures yields the relationship expressed by Equation (5).

$$K_{cellular\ glass} = 1.76 \times 10^{-4}T + 4.58 \times 10^{-3} \quad (5)$$

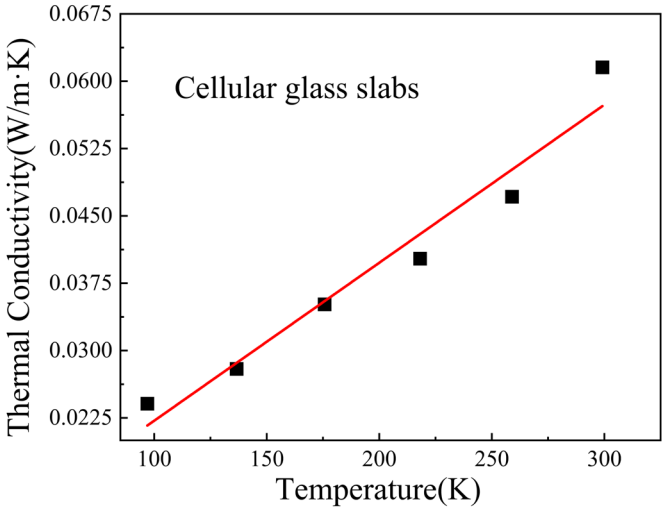


Figure 5. Temperature dependence of the apparent thermal conductivity of cellular glass slabs

Figure 6 shows the variation of the thermal conductivity of nitrile rubber curved panels in the temperature range of 90 K to 300 K under atmospheric conditions. At 91.57 K, the thermal conductivity of the nitrile rubber curved panels is 0.01272 W/(m·K), and it increases to 0.03328 W/(m·K) at 301.56 K. A linear fit of the thermal conductivity data at different temperatures yields the relationship expressed by Equation (6).

$$K_{Nitrile\ Rubber} = 1.00773 \times 10^{-4}T + 2.03 \times 10^{-3} \quad (6)$$

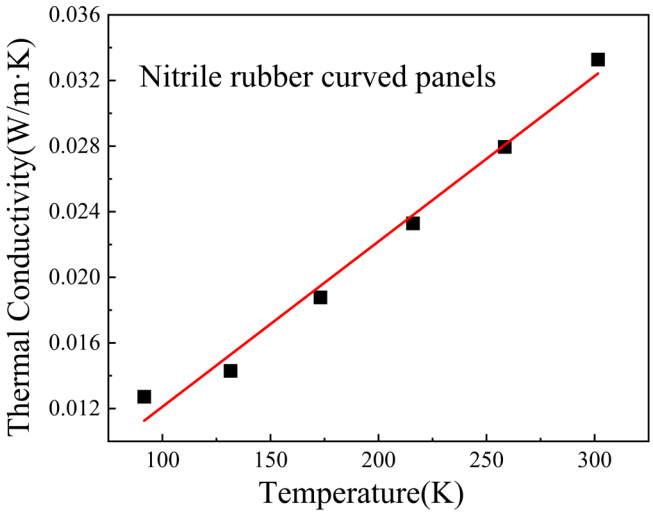


Figure 6. Temperature dependence of the apparent thermal conductivity of nitrile rubber curved panels

Figure 7 illustrates the variation of the thermal conductivity of aerogel blankets in the temperature range of 100 K to 300 K. At 109.67 K, the thermal conductivity of the aerogel blankets is 0.0063 W/(m·K), increasing to 0.01199 W/(m·K) at 301.16 K. A linear fit of the data yields the relationship between the apparent thermal conductivity and temperature of aerogel blankets under atmospheric conditions, as expressed by Equation (7).

$$K_{aerogel\ blankets} = 2.834 \times 10^{-5}T + 3.02 \times 10^{-3} \quad (7)$$

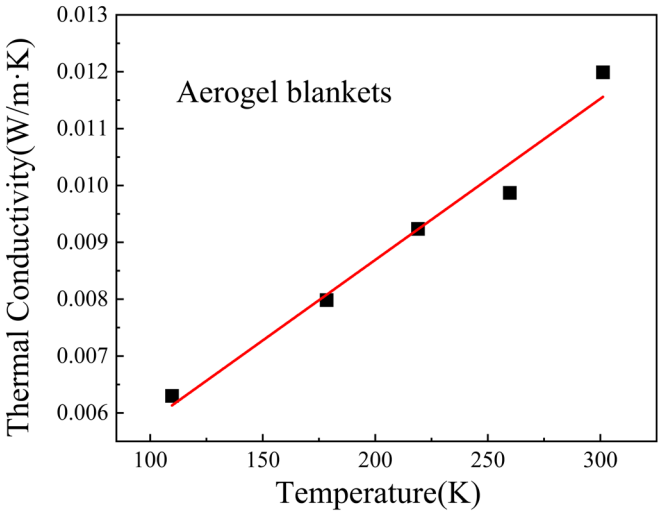


Figure 7. Temperature dependence of the apparent thermal conductivity of aerogel blankets

4. Conclusion

This study measured the apparent thermal conductivity of several insulation materials under atmospheric conditions over a temperature range of approximately 100 K to 300 K. The comparison of the fitted curves is shown in Figure 8, where the aerogel blankets exhibit the lowest

thermal conductivity. These findings provide valuable data to support the selection and application of insulation materials in cryogenic scenarios such as LNG storage tanks and cold chain logistics.

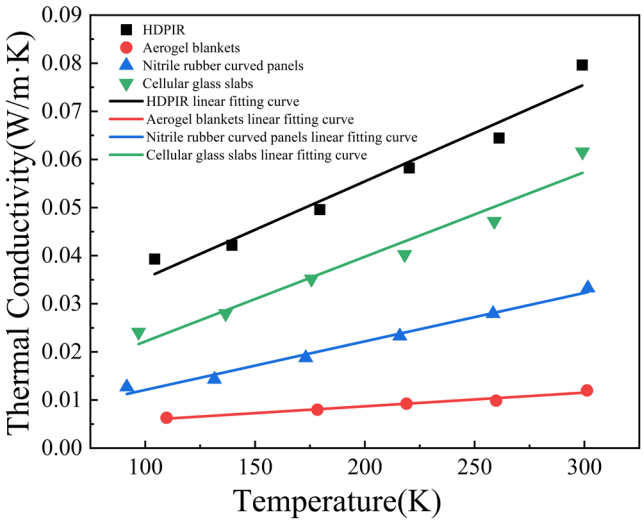


Figure 8. Temperature-dependent apparent thermal conductivity of four insulation materials

Acknowledgments

This work is supported by the China Postdoctoral Science Foundation (No. 2024M753312) and Tianjin Municipal Education Commission Scientific Research Program (No.2024KJ079).

References

[1] Deng B, Yang S, Xie X, Wang Y, Bian X, Gong L and Li Q 2019 *Cryogenics* **100** 114-122.
[2] Nikpourian H and Bahramian A R 2020 *Therm. Sci. Eng. Prog.* **20** 100751.
[3] Kyeongho K, Hyungmook K, Soojin S, Hwan O I, Changhee S, Hyung C Y, Yongchan K and Woo K S 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **171** 012093
[4] Yung K C, Zhu B L, Yue T M and Xie C S 2009 *Compos. Sci. Technol.* **69(2)** 260-264.
[5] Fesmire J E, Ancipink J B, Swanger A M, White S and Yarbrough D 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **278** 012198