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ARTICLE

Thermal Conductivity of Open Cell Aluminum Foam and Its Application as Advanced Thermal Storage Unit at Low Temperature

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Abstract: The development and characterization of new materials is of extreme importance in the design of cryogenic apparatus. Recently a kind of open cell aluminum foam was used for heat transfer enhancement at cryogenic temperature. Such aluminum foam was tested for cryogenic energy storage with a phase change material of nitrogen. The thermal conductivity of the open cell aluminum foam was studied. The thermal conductivities of the aluminum foam were measured between 50 and 170 K. The results show that the thermal conductivity increases with the temperature decreasing. Then the effects of thermal conductivity of open-cell aluminum foams on the performance of aluminum foam phase change material thermal storage unit were investigated. Nitrogen was selected as the phase change material. Temperature variations of the thermal storage unit during cooling and melting processes were tested. Test result shows that the maximum temperature difference between the up and bottom of the thermal storage unit is less than 0.5 K, much lower than the case without aluminum foam. It is concluded that as the thermal conductivity of thermal storage unit increases, both the container temperature difference and temperature variation of the thermal storage unit decrease.

Key words: open cell aluminum foam; thermal conductivity; thermal storage unit

Open cell aluminum foams is one of the rapidly developing metal with high porosity [1]. Since this kind of materials have a high surface area, relatively high thermal conductivity and low mass compared with other metals[2,3], they can be used in many applications such as heat exchangers and for liquid retention by capillarity for devices used in microgravity like thermal storage units[4]. Also, the solid ligaments in open cell aluminum foam make directly connected contacts which increase the effective thermal conductivity of the entire system. The attractiveness of aluminum-based foam material is being considered for practical heat-transfer enhancement technologies. In view of these developments, it is important to establish detailed methodologies and procedures for determining the important thermophysical properties of a specific open cell aluminum foam and thermal storage unit. In particular, knowledge of the thermal conductivity is essential for successful design and operation of high-performance thermal storage units.

The parameters affecting the thermophysical properties of foam metal include the conductivities of solid, porosities, geometrical parameters, etc. Although quite a few experimental works were done on measuring the thermal conductivity of the open cell aluminum foam, most of them focused on the room temperature property, published accounts on this subject at low temperature are scarce [5-7]. Besides, the reported works seldom analyzed the experimental results with consideration of the temperature variation of the thermal storage unit with open-cell aluminum foam. For thermal management of the units, open-cell aluminum foams filled with phase change materials can be used effectively to reduce temperature variation of the thermal storage unit. Various phase change materials can be used for thermal energy storage

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in the design of the thermal storage units. E. Fleming et al [8] investigated heat transfer enhancement of a heat thermal storage unit using water as the phase change material, by addition of open cell aluminum foam. D. C. Bugby et al [9] developed a 60 K thermal storage unit using nitrogen trifluoride as the phase change material, by addition of open cell aluminum foam. B. G. Williams et al [10] studied a nitrogen triple-point thermal storage unit which had an open cell aluminum foam core. A. P. Rijpma et al [11] designed a nitrogen triple-point thermal storage unit for cooling a SQUID magnetometer, which had a capacity of 7 Wh. I. Charles et al[12] measured a thermal storage unit which was able to store 10 J at 14 K, using the triple-point of hydrogen. However, the measurement data available in the literature on the temperature variation in a thermal storage unit seem to be at variance with each other. For the case of a thermal storage unit, similar data on the temperature variations are substantially mutually consistent. These difficulties clearly call for more focused and refined measurement programs to evaluate the principal thermophysical characteristics of open-cell aluminum foam and the thermal storage unit. The present study addresses these concerns.

The aim of the present work is to measure the thermal conductivity of open cell aluminum foam from 50 K to 170 K and explore its application on a thermal storage unit embedding with a phase change material of nitrogen. Systematic measurements reveal the thermal conductivity of the aluminum foam and temperature variation of the thermal storage unit under investigation. Empirical correlations are provided for the thermal conductivity and temperature variation of an aluminum foam based thermal storage unit. Features of the foam metal are suggested which would produce maximal heat transfer and minimal temperature variation throughout the thermal storage unit.

1 Experiment

Using wire-cut electrical discharge machining, bar shaped samples were prepared for thermal conductivity measurements and the parameters are summarized in Table 1. This technique was used because it cuts the sample without mechanical contact, avoiding any property change due to more aggressive cutting techniques. One extremity of the bar shaped aluminum foam was attached along approximately 5 mm to one copper block (base). One standard rhodium-iron resistance thermometer is thermalized to the cold head of the cryocooler and, on the upper extremity of the sample, a heater is also directly connected in order to establish a heat flux. The base is attached to the cold finger of a 2.5 W and 40 K[13] pulse tube cryocooler that was used to cool down the sample and to control the temperature. This set makes up the measurement cell shown in Fig. 1.

In order to measure only the thermal conductivity of the sample, two holes of 1.8 mm were drilled in the sample (distance between holes: 20 mm) to insert two standard platinum resistance thermometers, calibrated in Center of Cryogenic Metrology of Technical Institute of Physical and Chemistry, against standard rhodium-iron resistance thermometer. A layer of high thermal conductivity grease was used to assure a good thermal contact between the platinum resistors and the sample. Since the triple point of the phase change material is 63.15 K, this experimental set up was limited to measurements down to 50 K.

Table 1 Parameters of the sample

Material	PPI	Porosity	Diameter/mm	Height/mm
Aluminum foam	10	0.63	18	45

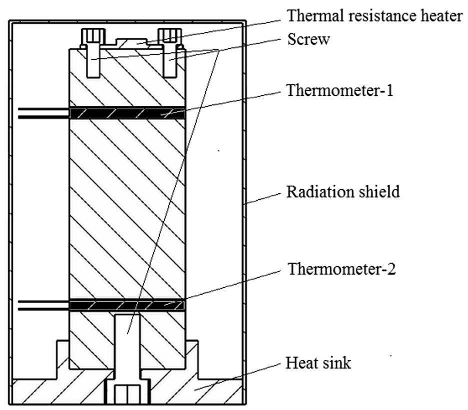

Fig. 1 Schematic of measurement cell of the thermal conductivity

To minimize the uncertainty associated to the measurements, for each cold head's temperature, the temperature difference between two temperature sensors on the sample should be low enough. Therefore, a heat power Q of 100 mW was applied in order to obtain a temperature difference between the standard platinum resistance thermometers. Using this point and the point obtained at null power, the thermal conductance between the standard platinum resistance thermometers was obtained. With this methodology (differential steady-state mode) [14], the thermal conductance of the sample was measured.

The thermal conductivity was calculated using the following relation:

$$K = Q\frac{L}{A(\Delta T_1 - \Delta T_0)} \tag{1}$$

where K is the thermal conductivity, Q is the heat power applied to the sample, L is the distance between the standard platinum resistance thermometers, A is the cross sectional area of the sample, ΔT_1 is the temperature difference between the standard platinum resistance thermometers with a power of 100 mW, and ΔT_0 is the temperature difference between the standard platinum resistance thermometers with null power.

In order to examine thermal conductivity enhancement of the thermal storage unit with open-cell aluminum foam, a test system was constructed. The open-cell aluminum foam has a diameter and height of 106 mm and 96 mm, respectively, which corresponds to a capacity of 7.2 kJ of the thermal storage unit. This capacity requires 0.36 kg of nitrogen, which corresponds to about 0.45 (liquid) liters. Fig. 2 shows a schematic view of the test set-up. The thermal storage unit container is supported by two stainless steel tubes, which also act as vent lines and supply lines. To charge the thermal storage unit, a two-stage Gifford-McMahon cryocooler was applied. It was connected to the thermal storage unit by means of copper sheets. To reduce the load to the thermal storage unit during the charging phase, the vent line and supply line of the thermal storage unit were coiled into helixes, which reduced the conductive heat load to the thermal storage unit and speeds up the charging process. In order to reduce radiative heat transfer between the thermal storage unit and the surroundings, 50 layers of multi-layer-insulation (MLI) supported by wire netting were attached to the container.

Fig.2 shows the thermal storage unit in more details. Mechanically, the unit is based on a hollow copper structure on which the open-cell aluminum foam can be mounted. The porous material is open-cell aluminum foam. According to specification the porosity is 63%, which was confirmed by comparison of weight and dimensions. As depicted in Fig.2b, the porous material is tightly connected to the copper rod and the thermal storage unit container. Since the porous blocks are initially 96.5 mm thick, this results in a small compression of the open-cell aluminum foam which reduces the thermal resistance. Overall, the thermal storage unit is able to contain about 1.45 L of nitrogen which corresponds to a capacity of 7.2 kJ.

2 Results and Discussion

2.1 Thermal conductivity of the aluminum foam

Thermal conductivity is a basic thermal property which indicates the ability to transport heat due to a given thermal gradient of a material. High thermal conductivity is desirable for applications such as thermal storage unit used for cooling detectors in order to keep homogeneous temperature and to reduce temperature variation during operation. The temperature dependence of the thermal conductivity of the test sample is shown in Fig.3. In Fig.3, results of aluminum from NIST and aluminum foam from the test set-up correspond to the right *Y* axis, whereas results of the nitrogen correspond to the left *Y* axis. The thermal conductivity of aluminum foam increases with decreasing of temperature over the test temperature range, which is similar to the tendency of the result of pure aluminum. Also, the average thermal conductivity of the test sample is about 22 W·(m·K)$^{-1}$ through the test temperature range, much higher than that of typical solid nitrogen around 60 K (1.6 W·(m·K)$^{-1}$). It is suggested that the open-cell aluminum foam is advantageous as a structural material which requests keeping homogeneous temperature, such as thermal storage unit.

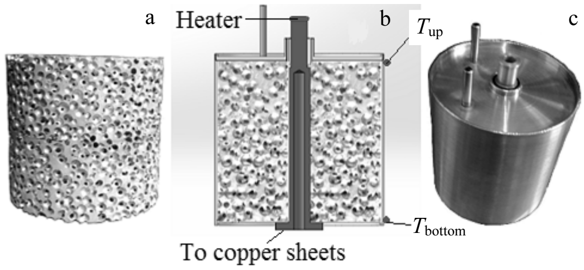

Fig.2 Open-cell aluminum foam used in the thermal storage unit (a), schematic of the thermal storage unit (b), and photograph of thermal storage unit (c)

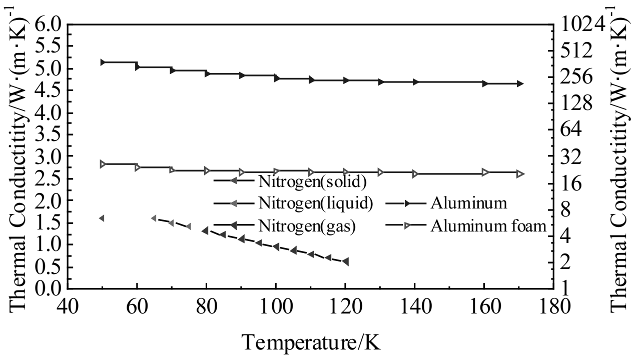

Fig.3 Thermal conductivity of the open-cell aluminum foam sample, aluminum and nitrogen

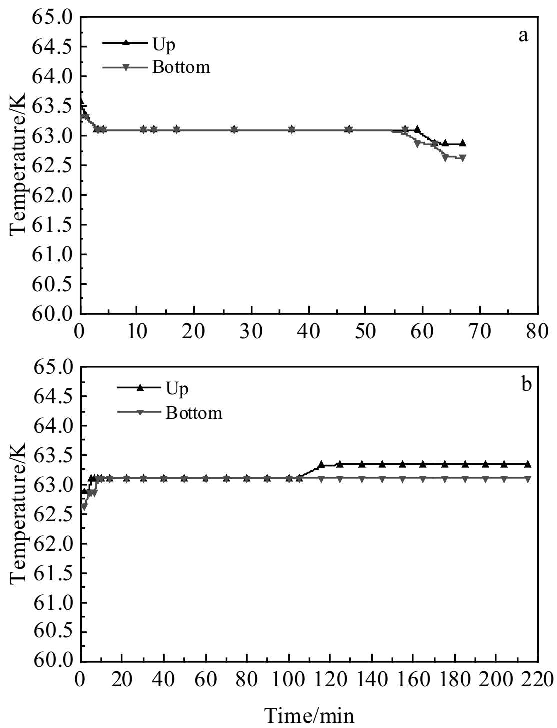

Fig.4 Plots of the thermal storage unit temperatures for the 0.5 W heat power case: (a) cooling process and (b) melting process

2.2 Test results of the thermal storage unit

Plots of Fig.4 displays the evolution of the temperatures T_{up}, T_{bottom} during the cooling and melting for the thermal storage unit with a heat power of 0.5 W.

Temperature of the phase change material is constant during the transition from solid to liquid, so, it is considered that temperature of the thermal storage unit does not change as the phase change material since the structure material is open cell aluminum foam. We use different heat loads (heat power of our experiments are 0.5 W and 2 W) to simulate temperature variation. Plots of Fig.5 displays the evolution of the temperatures T_{up}, T_{bottom} during the cooling and melting for another different experiment with a heat power of 2 W.

As can be seen from Fig.4, when the heating power of 0.5 W is applied, the temperature difference between two sensors of the container wall is less than 0.24 K during the cooling process and less than 0.1 K during the freeze process. In the case of the same thermal storage unit without open cell aluminum foam inside, this temperature difference would be higher than 6 K by simple calculation. And as Fig.5 shows, the temperature difference measured at the container bottom and the container up is the same as the results of Fig.4 during the cooling process and the freeze process of the thermal storage unit. And the temperature difference measured during the melting process is less than 0.5 K, whereas the heat power is four times as much as that of Fig.4. The temperament variations of the sensors at the up and bottom of the container

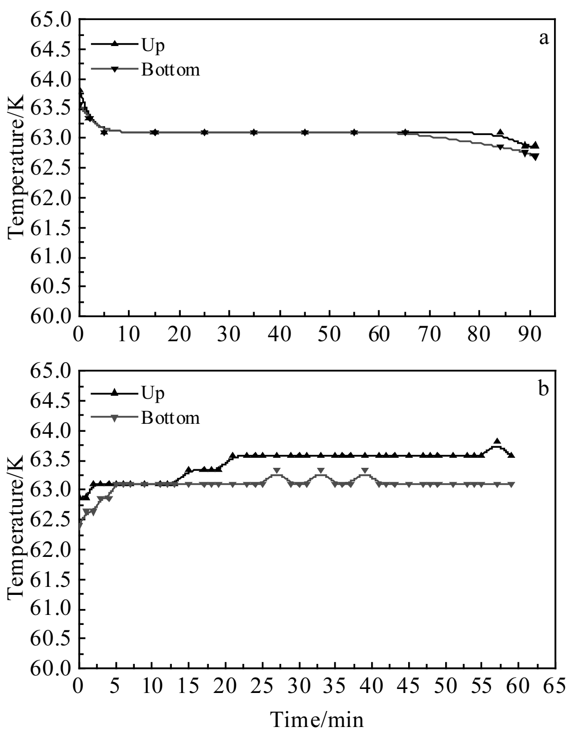

Fig.5 Plot of the thermal storage unit temperatures for the 2 W heat power case: (a) cooling process and (b) melting process

during melting process are less than 0.2 K. From both Fig.4 and Fig.5, it could be concluded that the main advantage of the thermal storage unit filled with open-cell aluminum foam is the much better thermal homogeneity between two temperature sensors of the container walls (T_{up} and T_{bottom}), even at a much higher heat power of 2 W. This better thermal homogeneity was interpreted as an improvement of the thermal conductivity of the thermal storage unit by introducing open-cell aluminum foam as the core material[15]. Also, the contact resistance between the walls and the liquid is caused by an increase of the wetted area due to capillarity effects[16,17].

Good heat transfer augmentation performances, low density and high thermal conductivity of the thermal storage unit make it suitable for cooling infrared detectors and other scientific instruments which require reduced levels of vibration, electromagnetic disturbance and the ability to absorb peak heat loads.

3 Conclusions

1) The thermal conductivity of aluminum foam increases with decreasing of temperature in the measurement from 50 K to 170 K, similar to the tendency of pure aluminum. The average thermal conductivity of open-cell aluminum foam is 22 $W\cdot(m\cdot K)^{-1}$, which is higher than that of solid nitrogen, showing it is advantageous as a structural material for keeping homogeneous temperature

2) Open cell aluminum foam is an advanced heat transfer enhance material, for which the temperature difference between two temperature sensors of the unit is less than 0.5 K whether the heating power is 0.5 or 2 W.

3) Open cell aluminum form is suitable for cooling infrared detectors and other scientific instruments.

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开孔泡沫铝的低温热导率测量及其低温蓄冷应用研究

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摘 要：新型材料的应用对低温装置的发展起具有重大意义。为提高低温蓄冷装置的温度均衡性，一种孔隙率为 63%的开孔泡沫铝材料最近在一种低温蓄冷装置中进行了实验研究。实验测试了样品从 50 K 到 170 K 的热导率，测试结果显示开孔泡沫铝在测试温度区间内热导率随温度降低而升高，其平均值为 22 $W\cdot(m\cdot K)^{-1}$。实验测试了开孔泡沫铝热导率对采用泡沫铝低温蓄冷装置的性能的影响。蓄冷装置中采用的相变材料为氮。实验中主要测试值为蓄冷装置在降温过程和融化过程中的温度值。实验结果显示，此装置上、下部分的最大温差小于 0.5 K，远小于不采用开孔泡沫铝时的温差。随着低温蓄冷装置热导率的提高，蓄冷装置上、下部温差以及单个温度测定的温度波动均减小。

关键词：开孔泡沫铝；热导率；蓄冷

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