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Measure of Apparent Thermal Conductivity of Er_3Ni Particles at 4~40 K and Heat Leakage of Regenerator

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Abstract: A low-temperature apparent thermal conductivity measurement apparatus for granular magnetic materials was developed. The apparent thermal conductivity of Er_3Ni under various helium pressures in the 4~40 K temperature range was measured, and then its thermal conduction factor was calculated. The test results in different temperature ranges show that the apparent thermal conductivity of Er_3Ni particles is 0.11~0.22 W/m·K under vacuum, corresponding to the thermal conduction factor of 0.31~0.53. When the pressure increases to 1.4~2.2 MPa, the apparent thermal conductivity tends to a definite value of 3 W/m·K, corresponding to the thermal conduction factor of 7. Furthermore, the heat leakage characteristics of the Er_3Ni regenerator under different operating conditions were studied, and a mixed filling scheme of particles and wire mesh was proposed to reduce the axial heat leakage between the cold and hot ends of the regenerator. The results show that the cooling performance can be improved after the nylon mesh and 316 L stainless steel mesh are filled in the Er_3Ni regenerator, and the reduction of heat leakage under 1.6 MPa helium pressure is as high as 12% and 8%, respectively.

Key words: Er_3Ni; low-temperature apparent thermal conductivity; magnetic material; cryocooler

The measurement of low-temperature physical properties and the improvement of physical properties are of great significance to the application of materials [1-8]. Taking the cryocooler research as an example, the specific heat of the conventional regenerator material stainless steel decreases sharply, resulting in extremely low working efficiency. At this time, magnetic materials such as Er_3Ni, $Er_{0.4}Pr_{0.6}$, and GOS are required, for their high specific heat capacity below liquid hydrogen temperature. For such rare metals, the measurement data of low-temperature specific heat capacity is already sufficient [9, 10]. In addition to the high specific heat capacity, the material also needs to have a low thermal conductivity to reduce heat leakage and improve cooling performance. However, for the low-temperature apparent thermal conductivity of regenerator materials below 40 K, few test data has been reported so far. At present, only the apparent thermal conductivity of lead, copper, and wire mesh at temperatures above 80 K have been measured by Lewis and Radebaugh of the National Institute of Standards and Technology (NIST) [11, 12]. The lack of low-temperature test data is because, unlike the testing of conventional materials[7, 13-15], the test of apparent thermal conductivity at low temperatures involves technical challenges such as particulate material with extremely small dimensions (<0.3 mm), the real-time pressure control of the low-temperature container for pressure changes caused by temperature changes, the use of cryogenic systems (down to 4 K below), and high-precision temperature control technology (temperature fluctuations < ±0.01 K).

In this research, using a 4 K Gifford-McMahon (GM) cryocooler, a low-temperature apparent thermal conductivity

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measurement apparatus suitable for the cryocooler regenerator was independently developed, and the apparent thermal conductivity of typical magnetic regenerator material Er_3Ni particles in different temperature ranges and under various pressures of helium was measured. The apparent thermal conductivity data and thermal conduction factor will fill the gaps of the data below the liquid nitrogen temperature zone, providing necessary data support for the design and optimization of cryocooler regenerators. In addition, based on the fact that the test apparent thermal conductivity of Er_3Ni is significantly higher than that of stainless steel mesh as conventional regenerator materials, an improved filling scheme of regenerator by mixing Er_3Ni particles with wire mesh was proposed to reduce the axial heat leakage between the cold and hot ends of the regenerator. The apparent thermal conductivity of mixed materials was measured to verify the effectiveness of the scheme. The principle of the self-developed apparent thermal conductivity measurement apparatus and the test method are innovatively introduced, and then the measured values of Er_3Ni under different working conditions are given. Finally, the mixed filling scheme is introduced and further experimentally verified.

1 Measurement Principle and Experimental Apparatus

The schematic of the cryocooler regenerator filled with Er_3Ni particles is shown in Fig. 1. Generally, it consists of a hot-end flange, a regenerator container, a cold-end flange, magnetic materials, and a regenerator container charged with helium. When a cryocooler works, the hot-end temperature of the regenerator is usually 15~40 K, while the present available cold-end temperature is close to 4 K with minimal cooling power. At present, lower temperatures and higher cooling power are two essential goals of cryocooler research[16-21].

The apparent thermal conductivity measurement is based on the steady-state longitudinal heat flow method, and its calculation formula is shown in Eq.(1). During the experiment, the cold-end temperature of the regenerator was stabilized at T_c by a GM cryocooler, while the hot-end temperature of the regenerator was controlled to a set value T_h by electric heating. The total electric heating power Q_t includes the axial heat leakage Q_s through the stainless steel wall of the regenerator container, and the heat leakage Q_m through the magnetic material Er_3Ni filled inside the regenerator. The thermal conductivity data of stainless steel can be queried from NIST so Q_s can be calculated based on the measured temperature at both ends of the regenerator. The apparent thermal conductivity of Er_3Ni particles can then be calculated when giving the length value and cross-sectional area value of the regenerator. Fig. 2 and Fig. 3 are schematic and photo of the self-developed apparent thermal conductivity measurement apparatus, respectively. In addition to the components mentioned above, the figures also present a charging and discharging control system for real-time controlling the helium pressure inside the regenerator (temperature changes cause gas pressure changes inside the regenerator), and the required vacuum and thermal insulation

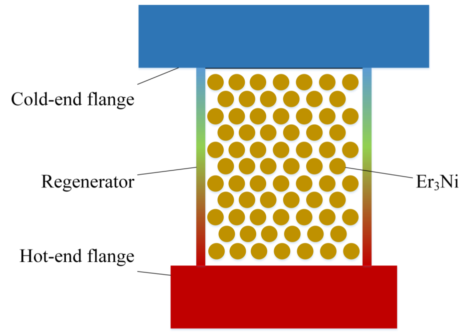


Fig.1 Schematic of magnetic material regenerator

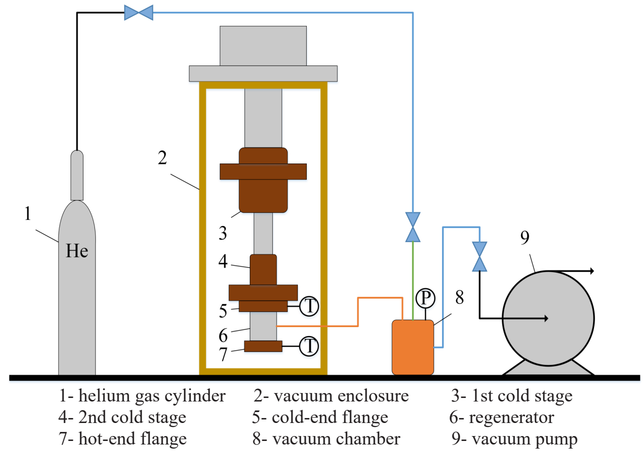
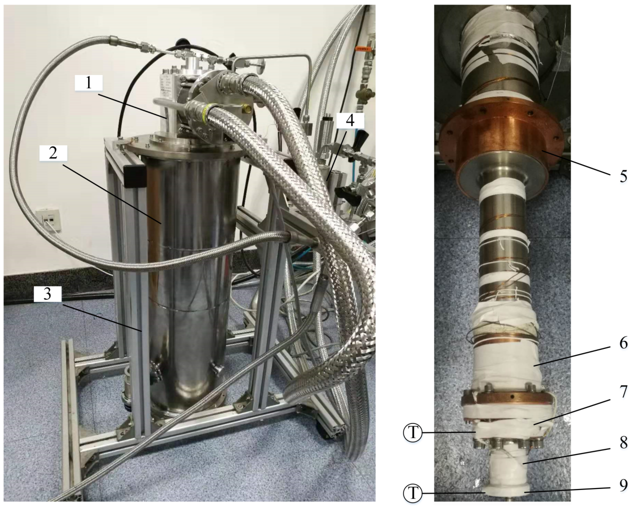


Fig.2 Schematic of apparent thermal conductivity measurement apparatus

system when using the 4 K-class GM cryocooler. The medium gas was provided by a helium gas cylinder (Fig.2), where the connected valves control the charging and discharging process, and the vacuum chamber was used for gas storage and buffering airflow. Rhodium-iron resistance thermometers calibrated (1.3 K to 300 K) by the Cryogenic Metrology Station of the Chinese Academy of Sciences were used as low-temperature sensors in the experiment. The pressure sensor (JYB-KO-H) was placed at room temperature, and the pressure range was 0~4 MPa with an accuracy of 0.2% FS. The diameter of Er_3Ni particles used in the measurement was 0.20~0.25 mm, and its porosity was maintained at about 0.359, which is consistent with the actual porosity when filling the cryocooler regenerator. The gas used in the regenerator was the actual working medium helium of cryocoolers.

$$K = \frac{(Q_t - Q_s)L}{A(T_h - T_c)} \quad (1)$$

where K is the apparent thermal conductivity in W/m·K; Q_t is the total electrical heating power in W; Q_s is heat leakage through the stainless steel wall of the regenerator in W; A is the regenerator cross-sectional area in m^2; T_h and T_c are the hot-end and cold-end temperature of the regenerator in K, respectively; L is the height of the regenerator in m.



1- GM cryocooler 2- vacuum enclosure 3- mechanical frame
4- vacuum chamber 5- 1st cold stage 6- 2nd cold stage
7- cold-end flange 8- regenerator 9- hot-end flange

Fig.3 Photo of developed apparent thermal conductivity measurement apparatus

2 Results and Discussion

2.1 Low-temperature apparent thermal conductivity of Er_3Ni particles

Fig.4 shows the apparent thermal conductivity test results of Er_3Ni particles under a vacuum of 10^{-4} Pa. The apparent thermal conductivity is 0.11~0.22 W/m·K in temperature ranges of 4~40 K, and the value increases with increasing the temperature. In order to characterize the relationship between the apparent thermal conductivity of Er_3Ni particles and the thermal conductivity of Er_3Ni material itself, the thermal conduction factor is defined [12], as shown in Eq.(2), which represents the thermal conductivity ratio of Er_3Ni particles to that of Er_3Ni material. As can be seen from Fig.4, the thermal conduction factor of Er_3Ni under vacuum decreases with increasing the temperature, and the value is 0.43 in the 4~20 K temperature range, which is significantly higher than that of stainless steel, lead, and copper in the high-temperature range. And in temperature ranges of 4~40 K, it is 0.31~0.53, corresponding to the apparent thermal conductivity of 0.11~0.22 W/m·K. This test result shows that due to the sharp changes in the physical properties of the material at low temperatures, the current methods for processing low-temperature Er_3Ni regenerators by data from other materials in the high-temperature range have significant errors, which also fully illustrates the importance of the presented work.

$$Q_m = f(1-n)\frac{A}{L}\int_{T_c}^{T_h} k\mathrm{d}T \qquad (2)$$

where Q_m is the heat conduction through Er_3Ni particles in W; f is the thermal conduction factor; n is the porosity of Er_3Ni particles; A is the cross-sectional area of the regenerator in m^2; L is the height of the regenerator in m; k is the thermal conductivity of Er_3Ni material in W/m·K; T_h and T_c are the hot-end and cold-end temperature of the regenerator in K, respectively.

Fig. 5 shows the apparent thermal conductivity of Er_3Ni particles under different helium pressures in 5~20 K temperature range. It should be noted that to minimize the effect of liquid helium during the inflation test, the cold-end temperature of the regenerator is increased from 4 K to 5 K. It can be seen that the apparent thermal conductivity of Er_3Ni particles with helium is significantly higher than the measurement value under vacuum. The mixed apparent thermal conductivity first increases with increasing the pressure and stabilizes at an average value of 3 W/m·K when the pressure reaches 1.4 MPa and above. The reason is that the volume of the regenerator restricts the actual helium molecule movement. When the mean free path of the helium molecules is greater than the actual heat transfer distance between the Er_3Ni particles, heat transfer is mainly accomplished by continuous collisions of helium molecules with particles. Therefore, the number of helium molecules increases as the pressure increases, which enhances heat transfer between particles. When the pressure increases to 1.4 MPa, the mean free path of helium molecules is much smaller than the actual heat transfer distance between Er_3Ni

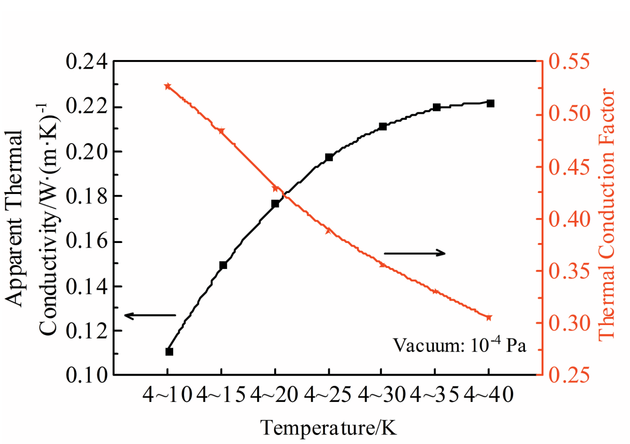


Fig.4 Apparent thermal conductivity and thermal conduction factor of Er_3Ni in different temperature ranges under vacuum

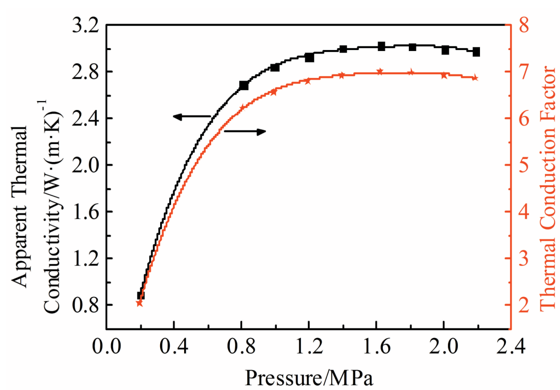


Fig.5 Apparent thermal conductivity and thermal conduction factor of Er_3Ni under different pressures in 5~20 K temperature range

particles. At this time, the heat transfer depends mainly on the constantly colliding helium molecules, during which the thermal conductivity is independent of the pressure [12]. It can also be seen from Fig.5 that the thermal conduction factor of Er_3Ni increases with increasing the pressure, and the value is finally stable at around 7 under high pressures of 1.4~2.2 MPa.

According to the above experimental results, the actual heat leakage of the regenerator was calculated based on the size of a self-developed high-frequency pulse tube cryocooler [20, 21], and the calculation results are shown in Fig.6. It can be seen that compared to the available small cooling power of cryocoolers at 4 K (the measured cooling power of high-frequency cryocoolers at 4 K is usually less than 30 mW), heat leakage between the cold and hot ends of the magnetic material regenerator is so severe. The heat leakage through Er_3Ni particles under vacuum is 8.9 mW, and the value is as high as 151 mW as the pressure is 1.4 MPa, while the test cooling power of self-developed cryocooler is only about 15 mW. Therefore, it is necessary to take measures to reduce the axial heat leakage of the magnetic material regenerator.

2.2 Apparent thermal conductivity of Er_3Ni mixed with stainless steel and nylon mesh

In order to reduce the axial heat leakage of the regenerator mentioned above, we proposed a mixed filling scheme using low thermal conductivity mesh materials and granular magnetic material Er_3Ni. The structure of the mixed regenerator is shown in Fig. 7. 635-mesh 316 L stainless steel (SS) mesh and 500-mesh nylon mesh commonly used in the actual filling of the cryocooler are selected. Both types of mesh are filled with 4 layers, each with 10 pieces. The actual porosity of Er_3Ni here is consistent with the porosity when it is individually filled (0.359)

Fig.8 demonstrates the apparent thermal conductivity test results of the regenerator after mixed filling under various pressures in the 5~20 K temperature range. It can be seen that the apparent thermal conductivity trend of mixed filling materials is consistent with that of single Er_3Ni, both of which first increase with increasing the pressure, and then stabilizes after the helium pressure increases to 1.8~2.0 MPa. However, the thermal conductivity of the mixed filling is significantly lower than that of the single filling. After mixed filling by stainless steel and nylon mesh, the apparent thermal conductivity of the mixed filler tends to a definite value of about 2.83 and 2.70 W/m·K under the pressure of 1.8~2.0 MPa, respectively. Fig.9 shows the heat leakage calculation results of the self-developed cryocooler regenerator using three different filling schemes, where

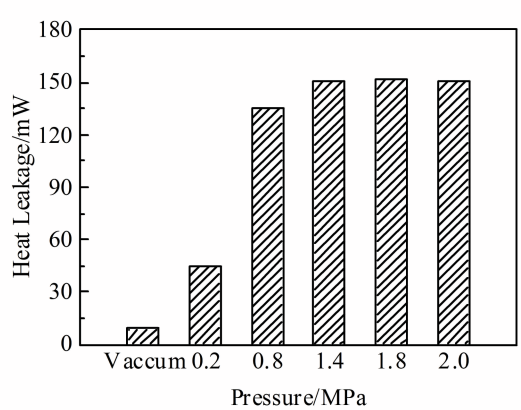


Fig.6 Axial heat leakage of Er_3Ni regenerator under different pressures

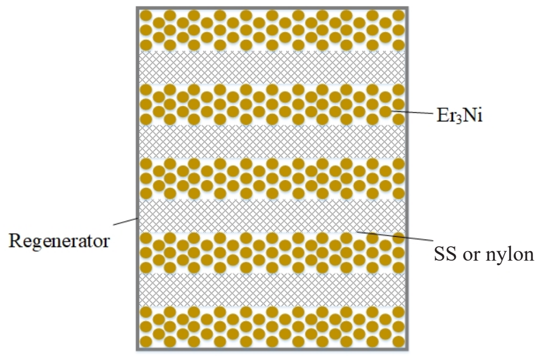


Fig.7 Schematic of filler distribution in the regenerator

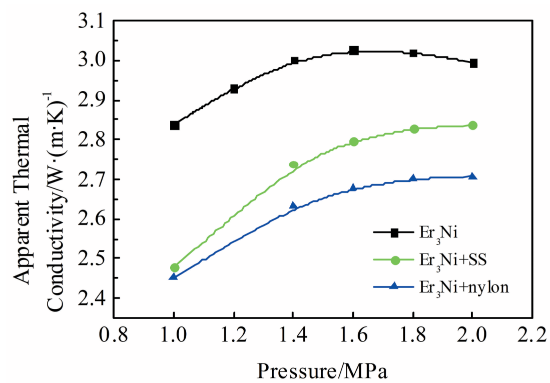


Fig.8 Apparent thermal conductivity of different filling schemes under various pressures in 5~20 K temperature range

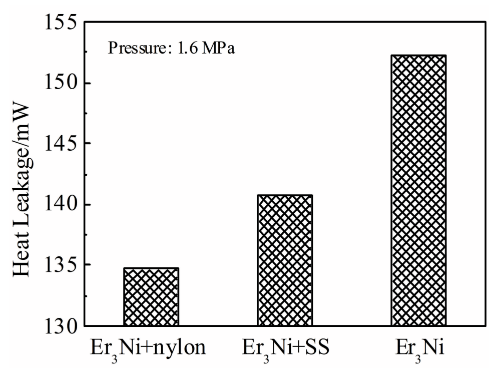


Fig.9 Effect of single filling and mixed filling on heat leakage of regenerator

heat leakage is reduced by 8% and 12% after filling Er_3Ni with stainless steel and nylon mesh, respectively. As a result, the mixed filling schemes can effectively reduce heat leakage of the regenerator, thereby improving the cooling performance of cryocoolers.

3 Conclusions

1) A low-temperature apparent thermal conductivity measurement apparatus for granular magnetic materials is developed.

2) The apparent thermal conductivity of Er_3Ni particles in temperature ranges of 4~40 K under vacuum is 0.11~0.22 W/m·K, and the corresponding thermal conduction factor is 0.31~0.53.

3) After charging helium, the apparent thermal conductivity and thermal conduction factor significantly increase with increasing the pressure and finally keep constant with an average value of 3 W/m·K and 7 under the pressure of 1.4~2.2 MPa, respectively.

4) The mixed filling scheme of Er_3Ni particles and wire mesh can significantly reduce the apparent thermal conductivity and further optimize the heat transfer performance of the regenerator. Compared to the single Er_3Ni filling scheme, the heat leakage of the self-developed cryocooler regenerator is reduced by 12% and 8% after filling nylon and stainless steel mesh into the Er_3Ni regenerator, respectively.

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Er_3Ni颗粒4~40 K温区表观热导率测量及其回热器漏热特性

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摘　要：研制了颗粒状磁性材料低温表观热导率测量装置，对Er_3Ni在4~40 K及不同氦气压力下的表观热导率进行了测量并计算了Er_3Ni热导率系数。在不同温区的测试结果表明，真空状态下，Er_3Ni颗粒表观热导率为0.11~0.22 W/m·K，对应的热导率系数为0.31~0.53；当氦气压力增大至1.4~2.2 MPa后，表观热导率趋于稳定，稳定后的平均值为3 W/m·K，对应的热导率系数为7。进一步研究了Er_3Ni型回热器不同工况下的漏热特性，提出了丝网与颗粒混合填充的方案以降低冷热两端的轴向漏热。结果表明，在Er_3Ni回热器中混合填充尼龙网和316 L不锈钢丝网后制冷性能显著提高，在1.6 MPa压力下漏热降低幅度分别高达12%和8%。

关键词：Er_3Ni；低温表观热导率；磁性材料；低温制冷机

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