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Thermal conductivity studies on activated carbon based cryopanel

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Abstract. The adsorbent temperature is one of the important parameters for pumping speed of cryosorption pump, which depends on thermal conductivity of the cryopanel. An attempt has been made to measure the thermal conductivity of the developed small size cryopanel which consist of a copper panel coated with adhesive to adhere the activated carbon adsorbent. This arrangement is similar to commercially available cryosorption pump. The thermal conductivity of the above panel has been measured with the help of cryocooler based experimental setup developed in our laboratory. The thermal conductivity of the cryopanel is further improved by mixing fine aluminium powder into the adhesive which in turn will cool the adsorbent to the lowest possible temperature. This will enhance the pumping speed of the crysorption pump. These studies on the thermal conductivity of cryopanels will be useful for the development of high performance cryosorption pumps.

1. Introduction

In an actual cryosorption pump, a metallic panel is cooled by the liquid helium flow through its built-in channels and on these panels activated carbons are adhered using a suitable adhesive based either on a plain epoxy or composite one. There is no thermal conductivity data available for this panel, since it is rather difficult to measure the temperature of carbon. In this work, an attempt has been made to estimate the thermal conductivity of this cryopanel, by making thermal conductivity measurements of a sample of copper-adhesive-carbon-adhesive-copper using an in-house developed thermal conductivity measurement system [1-3]. These results are discussed in this manuscript. The efficient pumping of helium gas using cryosorption pump not only depends on the pore sizes of activated carbon adhered onto the panel using adhesive but also depends on the temperature of the activated carbon [4, 5]. Therefore thermal conductivity of a cryopanel plays a very important role. The photographs of such panels with different adsorbing material are shown in figures 1 and 2 respectively.

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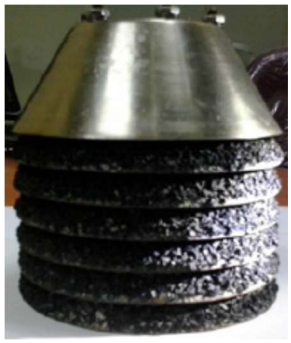


Figure 1 Panel with granule activated carbon.



figure 2 Panel with knitted carbon cloth.

2. Experimental principle

Thermal conductivity is measured by longitudinal steady state heat flow method on the basis of one dimensional Fourier heat conduction law [6-8]. A heating power Q is supplied to the heater sandwiched between two similar samples whose thermal conductivity value is to be measured. The experimental setup is standardized for thermal conductivity values by measuring the thermal conductivity of some standard known sample whose thermal conductivity data is available [1-3].

The Fourier heat conduction equation is given by,

$$\left(\frac{Q}{2}\right) = -k(T)A(\Delta T/\Delta x) \quad (1)$$

Where;

Q = heating power, W, $k(T)$ = Thermal conductivity as a function of temperature of unknown sample, $Wm^{-1}K^{-1}$, A = Cross sectional area of known sample, m^2, ΔT = Temperature gradient of known sample, K, Δx = Effective length of known sample across which temperature is measured, m.

3. Experimental setup and procedure

A Gifford-McMahon (GM) cryocooler based experimental setup has been developed to measure the thermal conductivity of various materials in the temperature range from 4.5 K to 300 K. The experimental system consists of: (a) GM cryocooler (M/s Leybold Oerlikon 1 W @ 4.2 K), (b) Intermediate heating block, (c) turbo molecular vacuum pump (Varian 301-AG), (d) DMM (Model: 2000, Keithley), (e) DC current source (Model: 6220, Keithley), (f) temperature controller (Model: 332, LakeShore), (g) silicon diode temperature sensors (Model: Si410A and DT-670), (h) temperature indicator (Model: 9308, SI) and (i) LabVIEW (Version 2013) based data acquisition system. The block diagram of the cryocooler based experimental setup is shown in figure 3. The photograph of the cryocooler based experimental setup and the cut-section view of the experimental setup are shown in figures 4 (a) and (b) respectively.

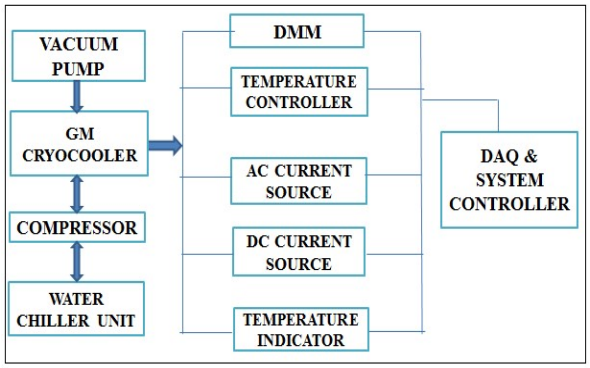
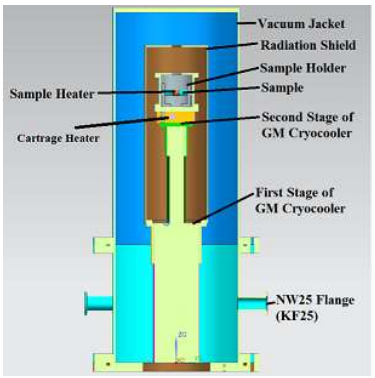


Figure 3 Block diagram of GM cryocooler based experimental setup.



(a)



(b)

Figure 4(a) Photograph of GM cryocooler setup. **Figure 4(b)** Sectional view of sample port.

The detailed arrangement of the test sample, heater and thermal link is shown in figure 5. The heater is sandwiched between the test sample and the known sample. They are held tightly in the L-shaped thermal link mounted on the 2nd stage cold head of the cryocooler. An intermediate heating block with two cartridge heaters of 70 Ω capacity each is mounted in between the sample chamber and the 2nd stage cold head of the cryocooler to maintain the sample in the temperature range of 4.5 K to 300 K. Two numbers of silicon diode temperature sensors (Si410A) have been attached to each sample and one number DT-670 temperature sensor has been attached to the intermediate heating block to measure the temperatures.

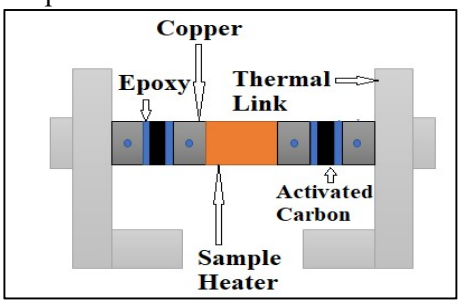


Figure 5 Detailed arrangement of the test sample, heater and the thermal link.

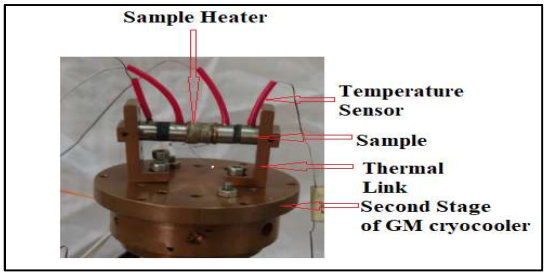


Figure 6 Photograph of the sample along with the temperature sensors.

The photograph of samples along with the temperature sensors mounted on the second stage of the GM cryocooler is shown in figure 6. The sample chamber, radiation shield and intermediate heating block have been fabricated for conducting the thermal conductivity experiments at different temperatures in the range of 4.5 K to 300 K. The sample under test is fixed to the sample chamber, which is mounted on the 2nd stage cold head of the GM cryocooler. The sample chamber is surrounded by Multi-Layer Insulation along with radiation shield to avoid radiation heat load. The whole assembly is surrounded with a vacuum jacket and the space inside the vacuum jacket is evacuated up to 1E-6 mbar with the help of turbo-molecular pump to avoid convection heat load. After achieving the desired vacuum, the cryocooler is turned on to cool the sample. The sample chamber along with sample is maintained at the desired set temperature by controlling the heating power to the cartridge heater of the intermediate heating block with the help of temperature controller (Model: 332 LakeShore, USA). When the sample is maintained at steady state temperature, the heater sandwiched between the two samples is energized. At any given base temperature of the sample, the application of the heat load increases the temperature difference (ΔT) across the temperature sensors in the axial direction of the sample. At steady state condition, the temperature difference (ΔT) is generally in the range of 0.2 K to 0.5 K. The heater power is in the range from 3 mW at 4.5 K to 20 mW at 300 K. All the necessary data are recorded through LabVIEW (Version 2013) data acquisition system.

4. Results and discussion

The thermal conductivity of sample consists of series arrangement of copper, epoxy, activated carbon, epoxy and copper is measured experimentally using GM cryocooler based thermal conductivity experimental system. The thermal conductivity of epoxy is further increased by mixing different volume fractions of filler into epoxy and measured experimentally (in the temperature range from 4.5 K to 7 K which is generally the operating range of cryosorption pump for pumping helium) using dedicated experimental setup developed in our laboratory. The thermal conductivity data at 4.5 K and 7 K is shown in figure 7. The increase in volume fraction of aluminium powder increases the thermal conductivity of epoxy but its downside is the decrease in its bonding strength as an adhesive. Therefore bonding strength studied has been performed for different volume fractions of aluminium into epoxy at 4.5 K (where bonding strength will be minimum). The bonding strength graph at 4.5 K is shown in figure 8.

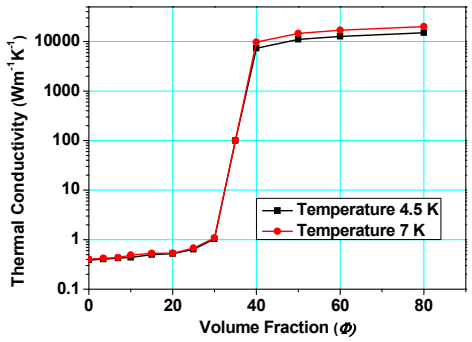


Figure 7. Variation in thermal conductivities for different volume fractions of aluminium in epoxy matrix at 4.5 K and 7 K.

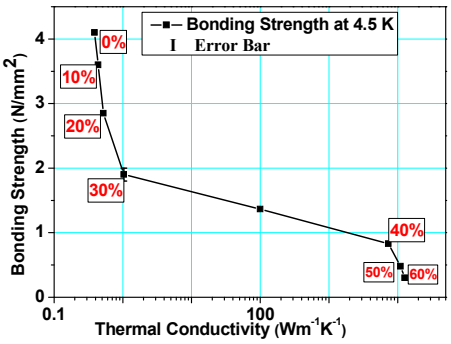


Figure 8. Bonding strengths studies of epoxy–aluminium composite at 4.5 K for different volume fractions of aluminium filler in epoxy.

From the figure 7 and 8 and considering the fabrication aspects of making the cryopanels, the 35 % is considered to be optimum. Therefore we have prepared the sample up to 35 % volume fraction and measure the thermal conductivity of sample. Figure 9 shows the thermal conductivity of sample. This thermal conductivity data is used to arrive at the thermal conductivity of activated carbon using equation 2. The thermal conductivity data of activated carbon is shown in figure 10.

$$\frac{l_s}{K_s} = \frac{l_{cu}}{K_{cu}} + \frac{l_{epal}}{K_{epal}} + \frac{l_c}{K_c} + \frac{l_{epal}}{K_{epal}} + \frac{l_{cu}}{K_{cu}} \qquad (2)$$

Where, $l_s, l_{cu}, l_{epal}, l_c$ are the effective lengths in m and $K_s, K_{cu}, k_{epal}, K_c$ are the effective thermal conductivities in $Wm^{-1}K^{-1}$ of sample, copper, epoxy/epoxy-aluminium composite and activated carbon respectively.

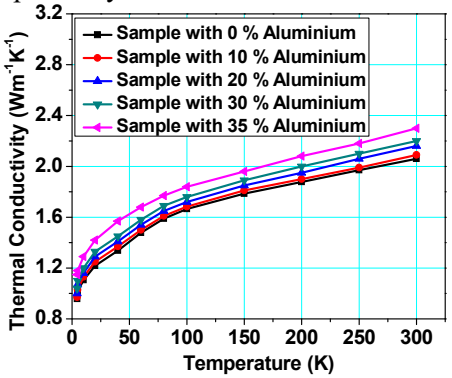


Figure 9. Thermal conductivity of sample.

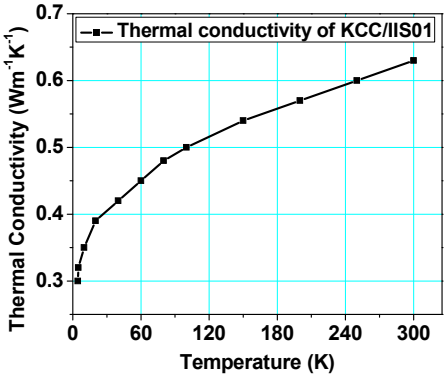


Figure 10. Thermal conductivity of Activated Carbon (KCC/IIS01).

Once the thermal conductivity data of copper, epoxy/epoxy-aluminium composite and activated carbon is at our end, we have made an attempt to theoretically predict the thermal conductivity of cryocooler based panel consists of activated carbon coated on copper base with the help of epoxy/epoxy-aluminium adhesive using equation 3. The theoretical prediction of effective thermal conductivity data of cryopanel is shown in figure 11.

$$\frac{l_{eff}}{K_{eff}} = \frac{l_{cu}}{K_{cu}} + \frac{l_{epal}}{K_{epal}} + \frac{l_c}{K_c} \quad (3)$$

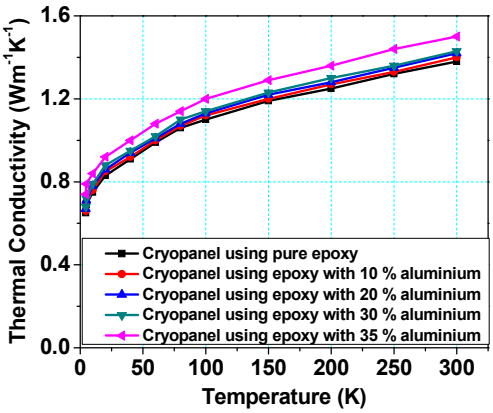


Figure 11. Theoretical prediction of thermal conductivity of cryopanel.

5. Conclusion

The thermal conductivity of activated carbon is measured in the temperature range from 4.5 K to 300 K. The thermal conductivity increases with more rate at lower temperature, this may be due to the reason that phonon are predominant factor for heat transfer at lower temperature. The thermal conductivity of activated carbon varies from 0.3 $Wm^{-1}K^{-1}$ at 4.5 K to 0.63 $Wm^{-1}K^{-1}$ at 300 K. The bonding strength studies has been performed to arrive at optimum volume fraction of aluminium powder into filler. It was found that 35 % volume fraction of aluminium into epoxy is the optimum. The thermal conductivity of the panel is also predicted theoretically. It is found that thermal conductivity of panel improves ~ 15 % if we mix 35 % volume fraction of filler, without hampering its bonding strength.

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