Experimental Investigation on Thermal Conductivity of Powder Insulation with Aluminium Opacifier and Under Evacuation by using LN$_2$Boil-off Calorimeter

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Abstract: Heat transport or entropy production is a common problem with all low temperature work. Sometimes heat transport can be undesirable and should be cut to minimum. These unwanted “heat-leaks” are costly, and the lower the temperature, the more costly it becomes to remove a given amount of heat and discharge it at ambient temperature. At very low temperatures, it becomes economical to conserve the cold using insulating material rather than to produce it because of the requirement of very large amount of energy transfer. Therefore the cryogenics vessels, transport vessel and transfer lines are insulated. Perlite powder is generally used to insulate the cryogenic region as its thermal conductivity is very low. Thermal radiation through perlite is an important heat transfer mechanism. The most effective way to minimize the effects of thermal radiation is to add metallic powders (opacifiers) to the perlite. As the proportion of opacifier is increased in the powder, the relative contribution of conduction and radiation heat transfer to apparent thermal conductivity changes. The present study attempts to obtain an optimized mixing combination of perlite powder, evacuation pressure and aluminum opacifier for reduced apparent thermal conductivity.

Keywords--- Apparent thermal conductivity, Cryogenics, Opacifier, Perlite, Boil-off Calorimeter

I. INTRODUCTION

Perlite is a volcanic siliceous rock. When crushed and heated under proper conditions, it pops like popcorn expanding to 20 or more times its original volume. Expanded Perlite is an economical insulation for cryogenic applications. It is widely used because of its low thermal conductivity, low cost, ease of handling and non-combustibility. The density of perlite powder ranges from 38 kg/m$^3$ to 50 kg/m$^3$. Grains size varies from 100 to 1600 micron. Thermal conductivity ranges from 0.0025 to 0.0129 W/m K depending upon density and particle size at different pressure of 0.8 mbar to 1×10$^{-6}$ mbar. Thermal conductivity is around 0.03 W/m K at atmospheric pressure. Because a fairly large portion of the total heat transferred through evacuated powders with one surface at room temperature and the other at cryogenic temperatures is radiant energy, one would expect that insulation performance could be improved by any method that reduces radiant heat transfer. So performance of the powder insulation can be improved by the addition of opacifiers like copper or aluminum flakes with the evacuated powders. By using optimum amount of opacifier (between 40 and 50 percentage by weight), the thermal conductivity of an evacuated powder can be reduced.

II. EXPERIMENTAL SET-UP AND DETAILS

A. Experimental set-up

The layout of the experimental set-up for determining apparent thermal conductivity is shown in Fig.1. The vent line for the nitrogen vapour from the test vessel is connected to the water saturator. The outlet of the vapour from the water saturator is connected to the flow meter and outlet from the flow meter is open to the atmosphere. The vent line for the nitrogen vapour from the guard vessels is connected to the water bubbler.

Figure 1. Photograph of experimental set-up

1. LN$_2$boil-off calorimeter 4. High vacuum pumping system
2. Water Saturator 5. Rotary pump
3. Gas flow meter 6. Diffusion pump
9. Digital temperature indicator

Nitrogen vapour after having passed through the water column in the bubbler passes out in the atmosphere. Leads to RTD sensors are taken out from the calorimeter through a feed through. A flexible hose pipe (size 25mm) connects the...
calorimeter to the vacuum system. A quick coupling (size 25mm) is used for the connection.

**B Experimental Combinations**

The experimental results were obtained for the following mixing ratio of perlite powder and opacifier,

1. 100% Perlite Powder.
2. By weight 80% Perlite powder, 20% Al powder; by volume 98.7% Perlite, 1.013% Al powder.
3. By weight 70% Perlite powder, 30% Al powder; by volume 98.26% Perlite, 1.737% Al powder.
4. By weight 60% Perlite powder, 40% Al powder; by volume 97.21% Perlite, 2.704% Al powder.
5. By weight 50% Perlite powder, 50% Al powder; by volume 96.03% Perlite, 3.96% Al powder.

The density of perlite powder and aluminium powder are respectively 48.5 kg/m³ and 1180 kg/m³. Following table shows the experimental observations.

**III. RESULTS AND DISCUSSION**

As mentioned earlier, under vacuum condition, heat transferred by radiation plays a major role. So to minimize the radiation effect, opacifier such as aluminum can be added to the perlite powder and an optimized mixing percentage of opacifier concluded for the apparent thermal conductivity of the mixture. The measured results for the 100% perlite powder are compared with the results obtained by Kropschot and Burgess and the results obtained by the previous experimental study and plotted in Fig.2. However it can be observed from Fig. 2 that the trend is similar and there is an increase in thermal conductivity with increase in interstitial pressure.

![Figure 2 Thermal conductivity of perlite under evacuation](image)

Fig.3 describes the variation of apparent thermal conductivity with interstitial pressure for different mass percentage of perlite-opacifier powder combination. As shown in fig 3 the apparent thermal conductivity of the perlite-opacifier powder combinations observed at interstitial pressure $4 \times 10^{-6}$ mbar to $1 \times 10^{-4}$ mbar. It is seen that by decreasing the interstitial pressure, the apparent thermal conductivity decreases.

![Figure 3 Thermal conductivity as a function of different weight combinations of perlite and aluminum](image)

On the other side, it can be seen that by adding opacifier (aluminum powder) percentage by weight with the perlite powder, the apparent thermal conductivity reduces up to certain limit. The Fig. 4 represents the variation in apparent thermal conductivity of different combinations of perlite powder and opacifier with respect to that for 100% perlite powder at an interstitial pressure of at $4 \times 10^{-6}$ mbar, $2 \times 10^{-5}$ mbar and $1 \times 10^{-4}$ mbar respectively. It is observed that for the particular value of interstitial pressure, by increasing the percentage of aluminum powder into the perlite powder, reduction in the apparent thermal conductivity can be observed up to a maximum of 40% aluminum powder by weight. On further increasing the percentage of aluminum powder into the perlite powder by weight leads to the increase of the apparent thermal conductivity because there will be an increase in heat transfer due to solid conduction between particles of aluminum powder.

However it can be observed from above figures that the apparent thermal conductivity decreases with an addition of the opacifier to the perlite powder. The reduction in the apparent thermal conductivity can be observed up to a
maximum of 40% aluminum powder by weight. At a mixture combination of more than 40% Al powder (by weight) the relative increase in the apparent thermal conductivity due to reduction in radiation heat transfer component is not substantial and is offset by an increase in conduction heat transfer component.

Hence we may conclude that experimentally the combination of 40% Al powder (by weight) in perlite powder is the optimum composition for lowest apparent thermal conductivity of perlite powder under evacuation.

IV. CONCLUSION

The following conclusions are drawn based on the present experimental study regarding the influence of evacuation pressure on the apparent thermal conductivity of perlite powder mixed with opacifier (aluminum powder).

For the perlite powder under evacuation, the value of the thermal conductivity is found to increase with an increase in the interstitial pressure. The apparent thermal conductivity of the perlite-opacifier mixture decreases up to a combination of 40% (by weight) of opacifier for both interstitial pressures of $4 \times 10^{-6}$ mbar and $2 \times 10^{-5}$ mbar. Thereafter the apparent thermal conductivity increased thereby indicating an increase in conduction heat transfer as compared to a reduction in radiation heat transfer component. For poor vacuum levels ($1 \times 10^{-4}$ mbar) molecular gas conduction also plays important role in increasing the apparent thermal conductivity.

V. UNCERTAINTY ANALYSIS

The temperature sensor (RTD pt 100) for measuring temperature of test vessel and ambient temperature has an uncertainty of $\pm 1\%$. The gas flow meter for measuring boil-off rate $N_2$ gas has uncertainty of $\pm 0.6\%$. The vernier caliper for measuring outer and inner diameter of cylinder of boil-off calorimeter has an uncertainty of $\pm 0.0002\%$. The measuring tape for measuring height of the outer cylinder has an uncertainty of $\pm 0.01\%$.

Therefore, the uncertainty in the apparent thermal conductivity for the present experimental study is 1.32%.

REFERENCES


