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Physics Procedia (2014) 000–000

Physics Procedia

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25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

Prediction of the Effective Thermal Conductivity of Powder Insulation

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Abstract

The powder insulation method is widely used in structure and cryogenic systems such as transportation and storage tank of cryogenic fluids. The powder insulation layer is constructed by small particle powder with light weight and some residual gas with high porosity. So far, many experiments have been carried out to test the thermal performance of various kinds of powder, including expanded perlite, glass microspheres, expanded polystyrene (EPS) and so on. However, it is still difficult to predict the thermal performance of powder insulation by calculation due to the complicated geometries, including various particle shapes, wide range of powder diameter distribution, and various pore sizes.

In this paper, the effective thermal conductivity (ETC) of powder insulation has been predicted based on an ETC prediction model of porous packed beds. The calculation methodology was applied to the insulation system with expanded perlite, glass microsphere and EPS beads at cryogenic temperature and various vacuum pressure. The calculation results were further compared with previous experimental data. Moreover, additional experimental tests were carried out at cryogenic temperature in this research. Also, the fitting equations of the deformation factor of the area-contact model are presented for various powders. The calculation results showed good agreement with the experimental results.

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014.

Keywords: powder insulation, the effective thermal conductivity, thermal performance prediction;

1. INTRODUCTION

Thermal insulation plays an important role in cryogenic application. In order to achieve and maintain a cryogenic

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Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014.

temperature, a high thermal insulation performance is needed to reduce the heat leak to the cryogenic system. Powder insulation materials have the light weight, small particle size, and low price, also they are easy to handle and do not need much maintenance. To test the thermal performance of powders, many researchers have carried out experiments to measure the effective thermal conductivity of powder insulation[1]-[7]. However, due to the irregular particle shapes, various sizes, components and densities, the prediction of the ETC is still a difficult mission [1].

In this paper, being based on the previously developed models for predicting the ETC of porous packed beds, an ETC prediction model for powder insulation is presented. With the calculation model, the thermal performance of powder insulation can be simply predicted without experimental research.

Nomenclature

A_i	surface of LN2 chamber [m^2]
A_{fs}	interface surface of powder particle and gas [m^2]
B	shape factor in area-contact model [-]
d_o	diameter of vacuum chamber [m]
d_i	diameter of LN2 chamber [m]
e^*	mass-specific extinction coefficient [m^2/kg]
h_{fg}	latent heat [J/kg]
k_{area}	effective thermal conductivity calculated by area-contact model [$W/m \cdot K$]
k_c	component of conductive heat transfer [$W/m \cdot K$]
k_{eff}	effective thermal conductivity of insulation layer [$W/m \cdot K$]
k_f	thermal conductivity of fluid [$W/m \cdot K$]
k_r	component of radiative heat transfer [$W/m \cdot K$]
k_s	thermal conductivity of solid material [$W/m \cdot K$]
k_{ss}	thermal conductivity of virtual homogeneous sphere [$W/m \cdot K$]
k_0	heat conduction by fluid in continuum regime [$W/m \cdot K$]
L_c	characteristic length [m]
$\dot{m}$	mass flow rate [kg/s]
n	effective index of refraction of the insulation layer [-]
P	pressure [torr]
r_s	radius of particle contact area [m]
$S^*_{\sqrt{A_i}}$	shape factor in conduction shape factor model [-]
T	temperature [K]
T_r	radiation temperature [K]
V_{empty}	empty volume inside a microsphere particle [m^3]
$V_{particle}$	volume of a microsphere particle [m^3]
α	deformation factor [-]
ε	emissivity [-]
ϕ	porosity [-]
λ	thermal conductivity ratio of fluid and solid [-]
ρ_{bulk}	bulk density [kg/m^3]
σ	Stefan-Boltzmann constant [$W/m^2 \cdot K^4$]

2. METHODOLOGY

In this research, we selected glass microspheres, expanded perlite, and EPS beads to predict the effective thermal conductivity of powder insulation. The effective thermal conductivity of powder insulation can be expressed as

$$k_{eff} = k_c + k_r \, , \tag{1}$$

In powder insulation, the diameter of powders are distributed from several micrometers to about 1 millimeter, and the width of insulation layer is much longer than the mean free path, which means the insulation layer can be considered as a homogeneous media. Thus, k_r is calculated as

$$k_r = 16\sigma n^2 T_r^3 \big/ 3\rho_{bulk} e^*(T_r) \,, \tag{2}$$

where

$$T_r^3 = (T_1^2 + T_2^2)(T_1 + T_2)\big/4 \,. \tag{3}$$

The mass-specific extinction coefficient of powders are different to each other. In this research, we used $e^* = 60\,m^2 kg^{-1}$, $e^* = 57\,m^2 kg^{-1}$, $e^* = 50\,m^2 kg^{-1}$ for expanded perlite [2], glass microspheres [3] and EPS beads [8] respectively.

Conductive heat transfer k_c can be calculated by one of the porous media ETC models, the area-contact model. The equation is as below (4) [9].

$$\frac{k_{Area}}{k_f} = 1 - \sqrt{1-\phi} + \frac{\sqrt{1-\phi}}{\lambda}[1 - \frac{1}{(1+\alpha B)^2}] + \frac{2\sqrt{1-\phi}}{[1-\lambda B + (1-\lambda)\alpha B]}\{\frac{(1-\lambda)(1+\alpha)B}{[1-\lambda B + (1-\lambda)\alpha B]^2}\ln\frac{1+\alpha B}{(1+\alpha)B\lambda} - \frac{B+1+2\alpha B}{2(1+\alpha B)^2} - \frac{B-1}{[1-\lambda B+(1-\lambda)\alpha B](1+\alpha B)}\} \tag{4}$$

where,

$$\lambda = k_f \big/ k_s \tag{5}$$

$$B = C[(1-\phi)\big/\phi]^m \tag{6}$$

C and m are functions of deformation factor α [9], and gas thermal conductivity k_f can be calculated by equation (7).

$$k_f = k_0 \Big/ (1 + \frac{P_{1/2}}{P}) \tag{7}$$

$P_{1/2}$ is the pressure when $k_f = k_0$. For nitrogen gas, $P_{1/2} = 230\,mbar\big/(L_c[\mu m])$ [10].

For glass microspheres, k_s cannot be applied directly to this model, because of the unique hollowness of microsphere particles. Thus, glass microspheres were modelled as a virtual homogeneous sphere to eliminate the complexity of structure. Thus, the solid conductivity of the virtual homogeneous sphere k_{ss} is calculated by equation (8) [4].

$$k_{ss} \approx 2k_s \frac{1 - \frac{V_{empty}}{V_{particle}}}{2 + \frac{V_{empty}}{V_{particle}}} \tag{8}$$

The deformation factor represents the degree of particle deformation by pressing, which reflects the crush strength of powders. The deformation factor is related to the particle diameter and bulk density. However, the deformation factors of powder insulation materials have not been reported by now. Therefore, to obtain the deformation factor of

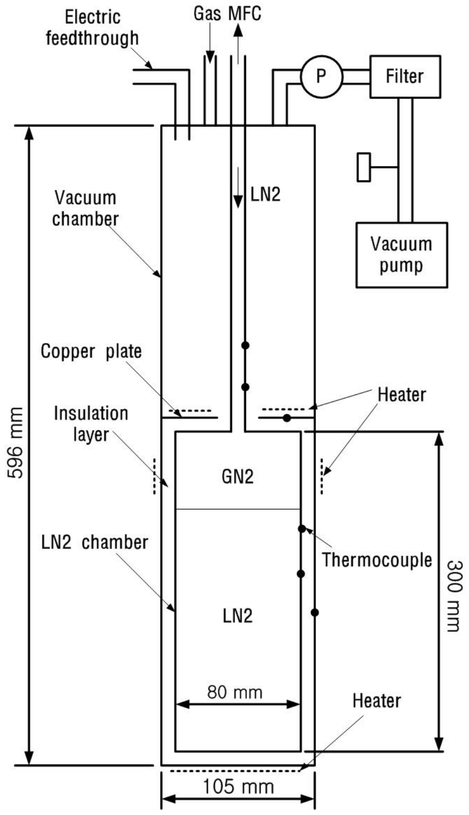

Fig. 1. Experimental apparatus for thermal insulaton

the powders, we need the experimental data of different kinds of powders. Also, the ETC of the same kind of powder in different particle sizes is necessary for comparison. In this paper, we calculated the ETC of powder insulation materials which used in the previous research, and the calculation results were compared with the experimental data of previous research to obtain the deformation factor of powders. Moreover, the experiments with glass microspheres, perlite and EPS beads were conducted for the diversity of data.

3. EXPERIMENT

The experimental apparatus is illustrated in Fig. 1. It consisted of an inner liquid nitrogen (LN2) chamber and an outer vacuum chamber. Both of them were fabricated by copper to easily develop the constant temperature of the surface. Thermocouples were attached on the wall of LN2 supply line, LN2 chamber, vacuum chamber and the copper plate above the LN2 chamber.

Powders were baked out to remove the water molecules on powder insulator particles, before filled in the thermal insulation layer. When the thermal insulation layer was evacuated, the heaters on the surface of vacuum chamber were turned on to pump out the moisture inside and increase the pumping speed. After charging LN2 into the LN2 chamber, the mass flow rate of vaporized nitrogen gas was measured under various pressure conditions. The pressure of thermal insulation layer was controlled by the residual gas nitrogen inside. The effective thermal conductivity was obtained by equation (9) [11].

$$k_{eff} = \dot{m} h_{fg} \Big/ \left(S^*_{\sqrt{A_i}} \cdot \sqrt{A_i} \cdot \Delta T \right) \tag{9}$$

Table 1. Characteristics of powder insulation materials.

			Glass microspheres		
	Apparent density (kg/m^3)	Bulk density (kg/m^3)	Average particle size (μm)	Porosity (-)	Remarks
Warwyk [4]	390	168	95	0.57	
Kim [1]	125	73	65	0.42	3M K1 type
This research	200	108	55	0.46	3M K20 type
			Expanded perlite		
Fesmire [5]		115	200	0.885	
Adams [6]		140	190	0.860	
Kropschot [7]		55	599	0.945	
		98	-	0.902	
		136	-	0.864	
		150	178	0.850	
This research		61	517	0.939	
			EPS beads		
This research		35	1300	0.965	

Where, the shape factor $S^*_{\sqrt{A_i}}$ is calculated by equation (10).

$$S^*_{\sqrt{A_i}} = \frac{2\sqrt{\pi}}{\{1 + (2/\sqrt{6}[(\frac{d_o}{d_i})^3 - 1])\}^{1/3} - 1} + \frac{3.1915 + 2.7726(\frac{h_i}{d_i})^{0.76}}{\sqrt{1 + 2\frac{h_i}{d_i}}} \tag{10}$$

4. RESULT

Table 1 shows the characteristics of powder insulation materials used in this research. These powders have various particle sizes and bulk densities, which influence the thermal performance of powders. Fig. 2 shows the comparison of experimental data and calculation results of perlite by Fesmire [5] and of glass microspheres by Kim [1]. When $\alpha = 0$, k_{Area} well matched the experimental results under the pressure above 10^{-1} torr. However, in the pressure below 10^{-1} torr, the components of radiative heat transfer and heat transfer by area contact of particles become significant and cannot be ignored. Therefore, k_r and α of particles must be considered additionally to improve the calculation method. We can notice that the calculation well matched the experimental data under the whole vacuum conditions with a certain value of deformation factor α.

Fig. 3 shows the experimental data by this research. As we can see, EPS beads showed the best thermal performance

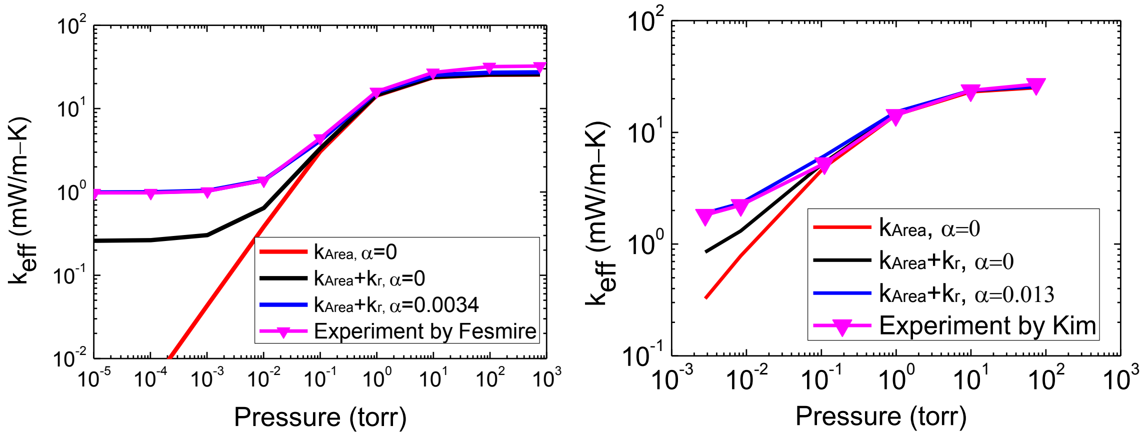

Fig. 2. Comparison of the calculation results and the experimental data for expanded perlite by Fesmire [5] (left) and for glass microspheres by Kim [1] (right)

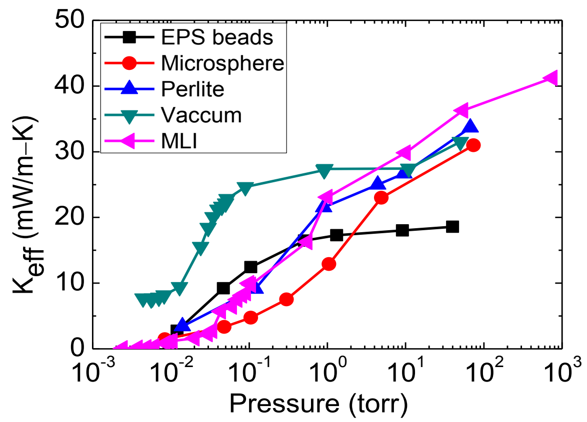

Fig. 3. The effective thermal conductivity of various insulation methods

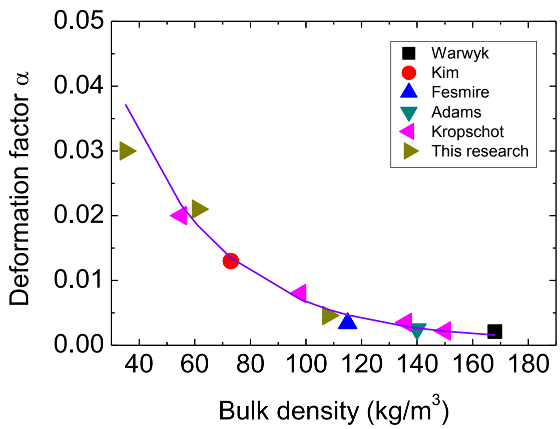

Fig. 4. The deformation factor of powder insulation materials in various bulk density

at pressure above 2 torr. In a soft vacuum condition, conduction heat transfer between fluid and solid particle is dominant, and the small solid conductivity k_s of EPS beads is the main reason which caused a low ETC in this pressure range. However, the ETC of glass microspheres was lower than other powder insulators at the pressure below 2 torr. Because microsphere particles are very small, which can suppress the heat transfer by fluid effectively. The ETC of 10-layer multi-layer insulation (MLI) was smaller than powder insulation at the pressure below 10^{-2} torr.

The deformation factor of the powder in Table 1 is shown in Fig. 4 as a function of bulk density. The deformation factor decreases with the increase of bulk density. The fitting equation of the deformation factor is as equation (11).

$$\alpha = \exp(-2.4 - 2.7\times10^{-2}\rho_{bulk} + 7.2\times10^{-6}\rho_{bulk}^{\ 2}) \tag{11}$$

The effective thermal conductivity of powder insulation can be predicted by the calculation model proposed in this paper with this empirical formula of deformation factor.

5. CONCLUSION

In this research paper, experiments were conducted by glass microspheres, expanded perlite and EPS beads to test the thermal performance of powder insulation materials. Also, the thermal performance of vacuum insulation and multi-layer insulation were examined in the same experimental apparatus to be compared with powder insulation. Otherwise, the ETC of powders with various specifications were calculated by the effective thermal conductivity calculation model presented in this research. Then, the deformation factor of powder in area-contact model was obtained through the comparison process of the experimental data and the calculation model, and an empirical correlation of the deformation factor in area-contact model was presented as a function of bulk density, which is available to predict the ETC of expanded perlite, glass microspheres and EPS beads. However, the deformation factors of powder insulation materials other than expanded perlite, glass microspheres and EPS beads are necessary to predict the ETC of them.

Acknowledgements

This research is supported by a grant from Space Core Technology Development Program of National Research Foundation of Korea (NRF-2013-042033) funded by Ministry of Science, ICT & Future planning (MSIP).

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