Effects of Vacuum Pressure and Vacuum Insulation Thickness in Free Molecular Heat Transfer

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1. Introduction

CNS(Cold Neutron Source) moderator cell will contain 22K liquid hydrogen very low temperature fluid. It is surrounded by vacuum vessel as an insulation to reduce heat transfer from ambient.

Vacuum insulation is widely used in cryogenic system. In general, convective and conductive heat transfer ,except radiation, between low temperature surface and high temperature surface can be prevented when vacuum pressure is lower than 10^{-3} Torr. But there is another heat transfer mechanism by free molecular flow, which is closely connected with vacuum pressure and vacuum insulation thickness(distance between cold and hot surface).

In this study, to find out required vacuum pressure for vacuum insulation design, heat transfer rate with vacuum pressure is estimated using simple geometry. Distance between cold and hot surface as a vacuum insulation thickness is studied, too.

2. Flow regime classification with vacuum pressure

Flow regime is classified into continuum flow, mixed flow and free molecular flow by vacuum pressure[1].

• Continuum flow	$Kn < 0.01$
• Mixed flow	$0.01 < Kn < 0.3$
• Free molecular flow	$Kn > 0.3$

Kn, called as the Knusen number, is defined as

$$Kn = \lambda / L \qquad (1)$$

where λ is the mean-free-path closely related to the viscosity and vacuum pressure.

$$\lambda = \frac{\mu}{P}\sqrt{\frac{\pi RT}{2}} \qquad (2)$$

μ : viscosity of gas (kg/m-sec)
P : absolute pressure of gas (Pa)
R : gas constant (J/kg-K)
T : absolute temperature of gas (K)

The characteristic length is defined as

$$L = 4V / A \qquad (3)$$

3. Results and Discussions

The heat transfer by free molecular is expressed as Eqn. (4)[2,3], where ΔT can be obtained by Eqn. (5)

$$Q / A = k_{air} \frac{T_1 - T_2 - 2\Delta T}{L} \qquad (4)$$

$$\Delta T = \frac{2-a}{a}\,\frac{2\gamma}{\gamma+1}\,\frac{\lambda}{\Pr}\,\frac{T_1 - T_2 - 2\Delta T}{L} \qquad (5)$$

a : accommodation factor
γ : $= c_p/c_v = 1.4$,
λ : mean free path (m)
L : characteristic length (m)
Pr : Prandtl number 0.7 for air at 300K

Accommodation factor means how thermal equilibrium between gas molecular and surface reaches, which depends on a kind of gas and surface temperature. For the air, accommodation factor is 0.8-0.9 at 300K, 1 under 78K.

There is an alternative equation to express free molecular heat transfer[1,4,5] as follows:

$$Q / A = F_a G P (T_1 - T_2) \qquad (6)$$

where P is absolute pressure, G can be obtained by

$$G = \frac{\gamma+1}{\gamma-1}\sqrt{\frac{R}{8\pi T}} \qquad (7)$$

Free molecular heat transfer between two parallel infinite plates with distance 1m can be calculated by Eqn. (4) and (6), assuming variables as shown in following table.

	Plate 1	Plate 2
Temp.	300K	22K
ε	0.12	0.16
a	0.85	1

Heat flux variation between two parallel plates with vacuum pressure is shown in Fig. 1. Obtained values from two equations are almost same at very low vacuum pressure under 1mPa (≈7.5×10^{-6} Torr). Free molecular

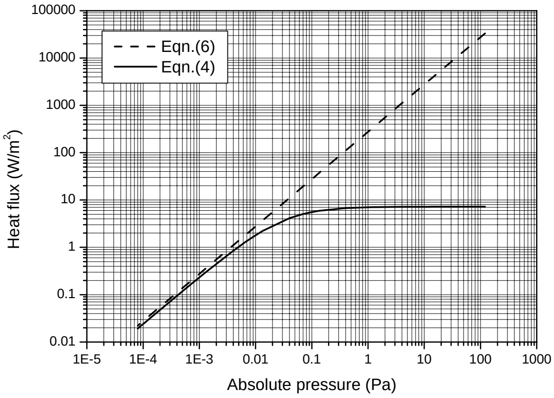

Figure 1. Comparison of Eqn(4) and Eqn(6)

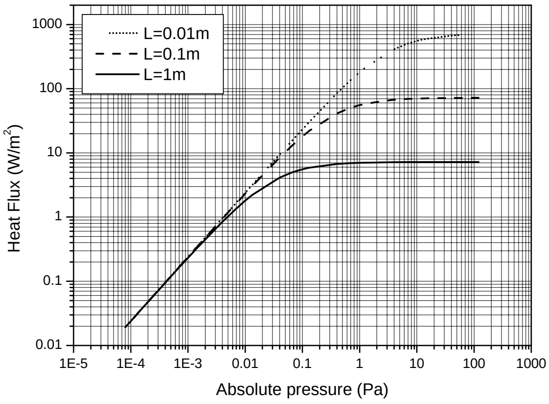

Figure 2. Effect of vacuum insulation thickness and vacuum pressure

heat transfer from eqn. (4) increases proportional to pressure until 0.01Pa, and then converges on constant value that approaches heat transfer rate by pure conduction through the air. Although free molecular heat transfer don't exceed it, heat transfer rate obtained by Eqn.(6) continuously increase with pressure. From this results, It can be noted that Eqn. (6) can be used for very low pressure under 1 mPa.

The influence of vacuum insulation thickness (distance between two parallel plates) and vacuum pressure is shown in Fig.2. As the distance is shorter, heat transfer rate by free molecular flow reaches more higher. This can be explained with thermal resistance.

All graph lines come together in one at low pressure under 1mPa (≈7.5×10^{-6} Torr). It can be said that heat transfer by free molecular does not vary with distance between hot and cold surfaces at low pressure 1mPa.

To find out distance between hot and cold surfaces where heat transfer rate by free molecular begin decreases for given vacuum pressure, heat transfer rate is calculated with changing of distance between hot and cold surface as shown in Fig. 3. Knusen number is used to normalize the effect of distance. Increasing of Knusen number means decreasing of distance (vacuum insulation thickness). Figure 3 shows that a distance corresponding to under Knusen number 10 is required to reduce free molecular heat transfer by vacuum insulation thickness. From this results, it seems that critical vacuum insulation thickness where begins decreasing of free molecular heat transfer is a distance corresponding to Knusen number 10.

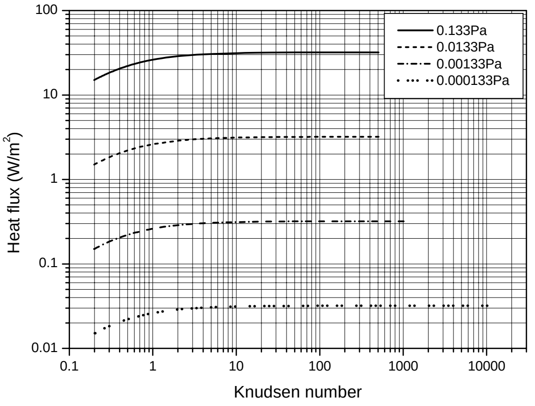

Figure 3. Critical vacuum insulation thickness

4. Conclusion

From the above discussions, a summary of results in this study is as follows

1. As vacuum pressure is lowered, the free molecular hat transfer decreases.
2. The free molecular heat transfer is influenced by only vacuum pressure when the vacuum pressure reaches 1×10^{-3} Pa(≈7.5×10^{-6} Torr)
3. A distance corresponding to Kn = 10 is critical thickness for vacuum insulation.

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