

Composite aerogel insulation for cryogenic liquid storage

Kyeongho Kim¹, Hyungmook Kang², Soojin Shin², In Hwan Oh³, Changhee Son¹, Yun Hyung Cho⁴, Yongchan Kim¹, and Sarng Woo Kang²

¹ Department of Mechanical Engineering, Korea University, Anam-dong, Seongbuk-gu, Seoul 136-713, Republic of Korea

² Center of Urban Energy Research, Korea Institute of Science and Technology, 5, Hwarang-ro 14-gil, Seongbuk-gu, Seoul 02792, Republic of Korea

³ Green City Technology Institute, Korea Institute of Science and Technology, 5, Hwarang-ro 14-gil, Seongbuk-gu, Seoul 02792, Republic of Korea

⁴ Mechanical and Biomedical Engineering, Kangwon National University, Hyoja 2-dong, Chuncheon-si, Kangwon-do 200-701, Republic of Korea

libra@kist.re.kr

Abstract. High porosity materials such as aerogel known as a good insulator in a vacuum range ($10^{-3} \sim 1$ Torr) was widely used to storage and to transport cryogenic fluids. It is necessary to be investigated the performance of aerogel insulations for cryogenic liquid storage in soft vacuum range to atmospheric pressure. A one-dimensional insulating experimental apparatus was designed and fabricated to consist of a cold mass tank, a heat absorber and an annular vacuum space with 5-layer (each 10 mm thickness) of the aerogel insulation materials. Aerogel blanket for cryogenic (used maximum temperature is 400K), aerogel blanket for normal temperature (used maximum temperature is 923K), and combination of the two kinds of aerogel blankets were 5-layer laminated between the cryogenic liquid wall and the ambient wall in vacuum space. Also, 1-D effective thermal conductivities of the insulation materials were evaluated by measuring boil-off rate from liquid nitrogen and liquid argon. In this study, the effective thermal conductivities and the temperature-thickness profiles of the two kinds of insulators and the layered combination of the two different aerogel blankets were presented.

Nomenclature

Q	Heat transfer rate from the ambient environment into the apparatus, W
k	Thermal conductivity, mW/m·K
k_e	Effective thermal conductivity, mW/m·K
V_{STP}	Volumetric flow rate at STP, m ³ /s
ρ_{STP}	Density of gas at STP, kg/m ³
$\dot{m}$	Mass flow rate of gas extracted from the apparatus, kg/s
h_{fg}	Heat of vaporization at saturated condition, J/g
L	Axial length of insulation materials, m
A	Heat transfer area, m ²
P	Pressure, Torr
T	Temperature, K



1. Introduction

Thermal insulation plays a significant role in cryogenic systems. So it specifically provides control and safety aspects for storage and transport of cryogenic fluids. However, the control and safety of insulation systems are often overlooked [1]. Such aspects could involve mechanical or vibration loads, requirements for maintenance, and ascent pressure environments. Therefore, the successful insulation systems must be lightweight and be considered with compatibility, mechanical requirements, and an outgassing issue [2].

Normally, the thermal insulation of working cryogenic systems combines several insulation technologies of vacuum insulation, Multi-Layer Insulation (MLI), and Vapor-Cooled Shield (VCS). Especially, MLI for radiation insulation is known as the best insulation under High Vacuum (HV) from $<10^{-6}$ to 10^{-3} Torr. However, MLI is not practical for use in vacuum level above 10^{-3} Torr. While aerogel blanket is fully hydrophobic and well-suited for the open ambient environment [3].

The requirement of promising insulation systems is economical insulation for efficient and low-cost systems rather than superinsulation [4]. That is, the costs must justify the systems. Generally, in manufacturing a bulk storage container, heating, vacuum pumping, testing, and other steps for High Vacuum (HV) are costly. But the insulation materials occupy only a small fraction of the costs. Thus, in evaluating the whole costs, the fabrication and maintenance of the cryogenic system is more economical under Soft Vacuum (SV) from 10^{-2} to 10 Torr than High Vacuum (HV).

In this study, the one-dimensional insulation experimental apparatus was fabricated to compare and investigate thermal characteristics of two kinds of aerogel blankets and a layered combination of the materials under liquid nitrogen and liquid argon environment.

2. Materials and specifications

Aspen Aerogels' flexible blankets such as Cryogel Z and Pyrogel XT-E were used as shown Fig. 1. The performance of data for the aerogel blankets are summarized in Table 1 [5-6]. These materials have no corrosive effects on steel including stress corrosion cracking in austenitic stainless steel [7]. In addition, there is typically no an outgassing issue with the aerogel materials. Thus, the hydrophobic porous insulation materials are easily used for fabricating of various cryogenic applications.

The test cases of the aerogel blankets and specifications are listed in Table 2. The two kinds of the aerogel insulation blankets consist of 5-layer each and a combination of the insulators was composed of 3-layer Cryogel Z and 2-layer Pyrogel XT-E. Prior to testing, each insulator was heated at 320K and evacuated to achieve an initial vacuum level condition of 10^{-2} Torr.



Figure 1. Cryogel Z (left) and Pyrogel XT-E (right) of Aspen Aerogels, Inc.

Table 1. Performance data for aerogel blankets (NA = Not Application)

Type	Cryogel Z	Pyrogel XT-E
Used maximum temperature, °C	125	650
Mean temperature, °C	Thermal conductivity [mW/m·K]	
-129	14	NA
-73.3	15	NA
-17.8	16	NA
0	NA	20
23.9	17	NA
93.3	19	NA
100	NA	23
200	NA	28
400	NA	46
600	NA	89
Water vapor sorption, weight %	≤5 %	≤5 %

Table 2. Specification of test materials

No.	Material system	No. of layers	Total thickness, mm	Outside diameter, mm
1	Cryogel Z	5	50	370
2	Pyrogel XT-E	5	50	370
3	Cryogel Z + Pyrogel XT-E	3 + 2	50	370

3. Experimental method

3.1. Experimental design

A cylindrical insulation test apparatus was designed to take the one-dimensional axial direction heat flow through an insulation material system between CBT (Cold Boundary Temperature) and WBT (Warm Boundary Temperature) as shown Fig. 2. In addition, since the purpose of the study is to investigate the thermal performance of the porous insulation materials with various vacuum pressures, the apparatus was fabricated with considering characteristics of evaporating cryogenic liquid and vacuum insulation. The rate of the heat transfer, Q , through the insulation system into the cold mass tank is directly proportional to the flow rate of cryogenic liquid boil-off as shown Eq. (1). The flow rate is measured by a mass flow meter (FMA-1620A-I, OMEGA) connected a data acquisition system (GL820, GRAPTEC Co.).

$$Q = V_{STP} \rho_{STP} h_{fg} \quad (1)$$

where, V_{STP} is the volumetric flow rate at STP, ρ_{STP} is density of gas at STP and h_{fg} the heat of vaporization at saturated condition.

Generally, Fourier's law shows a function of pressure and temperature in Eq. (2).

$$Q = -k(P, T) A \frac{dT}{dx} \quad (2)$$

where, Q is the axial input heat rate from ambient environment into the apparatus, k is the thermal conductivity, P is pressure, T is the temperature, and A is the heat transfer area.

However, the insulation materials having porous structure are used to improve the thermal performance under the evacuated environment. Therefore, effective thermal conductivity, k_e , can be expressed as the sum of solid conduction, k_{sc} , gas conduction, k_{gc} , convection, k_{cv} , in the porous structure, and radiation, k_r , as shown Eq. (3) [8].

$$k_e(P, T) = k_{sc} + k_{gc} + k_{cv} + k_r \quad (3)$$

The effective thermal conductivity is determined from Fourier's law for heat conduction through the one-dimensional axial direction as Eq. (4).

$$k_e(\bar{T})_p = \frac{\dot{m} h_{fg} L}{A \Delta T} \quad (4)$$

where, $\bar{T}$ is the mean temperature at steady-state, $\dot{m}$ is the mass flow rate of gas extracted from the apparatus, and L is the axial length of insulation materials.

The standard temperature and pressure (STP) are 25°C (298K) and 101.3 kPa (7.6×10^2 Torr), respectively.

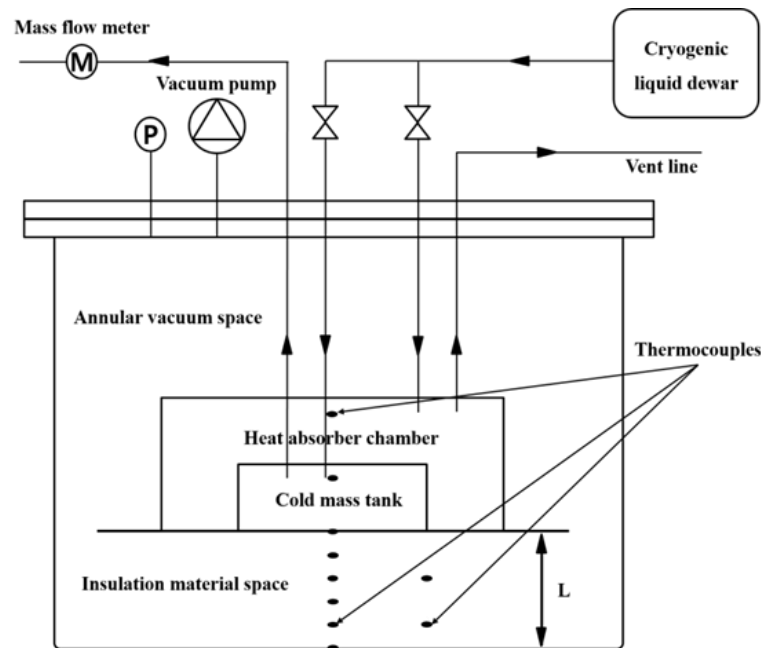


Figure 2. A simplified schematic diagram of the axial cryogenic insulation thermal performance test apparatus

3.2. Experimental apparatus

The apparatus consists of four parts, a cold mass tank, a heat absorber chamber, an annular vacuum space, and an insulation material container as shown in Fig. 2. The cold mass tank (O.D. 120 mm, height 50 mm, and volume 0.57 L) is charged with cryogenic liquid such as liquid nitrogen or liquid argon to keep CBT, temperature of top of layered aerogel blankets. The amount of evaporating gas is measured by a mass flow meter (FMA-1620A-I, OMEGA). Also, the cold mass tank is surrounded by the heat absorber chamber (O.D. 200 mm, height 110 mm, and volume 2.9 L) charged with the cryogenic liquid to protect the cryogenic liquid in the cold mass tank from radial and down-directional heat flow. The heat absorber chamber is surrounded by the annular vacuum space (O.D. 400 mm, height 610 mm, and volume 77 L) including the insulation material container (O.D. 400 mm, height 50

mm, and volume 6.3 L). The annular vacuum space and the insulation material container were evacuated by a mechanical vacuum pump (W2V40, WOOSUNG AUTOMA Co.) and a turbo molecular pump (TMP, NEXT 400 D, Edwards). In addition, the vacuum pressure was measured by the convection vacuum gauge (275i, Kurt J. Lesker Co.).

Two E-type thermocouples were installed in each part such as the cold mass tank and the heat absorber chamber. Also, eight E-type thermocouples were placed among each layer of the aerogel blankets to obtain temperature-thickness profiles as shown Fig. 2.

3.3. Experimental details

After installing the aerogel blanket for test as shown in Fig. 3, the annular vacuum space and the insulation material container involving the porous insulator were evacuated by the mechanical pump and the turbo molecular pump to reach the soft vacuum environment (10^{-2} to 10^1 Torr). Because the liquid nitrogen boil-off method was used, the cold mass tank and the heat absorber chamber were charged by 20 ~ 25 L (depending on the vacuum pressure) to cool down the experimental apparatus containing the insulation materials for over 5 hours. When the apparatus reach steady-state, each layered aerogel blanket has kept a little temperature variation for over an hour.

The process mentioned above was repeatedly carried out in the case of 10^{-2} , 10^{-1} , 10^0 , 10^1 , 10^2 , and 7.6×10^2 Torr.



Figure 3. Basic installation of aerogel blankets under the cold mass tank and the heat absorber chamber; the bottom of the apparatus (left), the front of the apparatus (right)

4. Results and discussion

4.1. Temperature-thickness profiles of insulation materials

Layered temperature profiles as a function of the blankets' thickness for the different cold vacuum pressures are presented in Fig. 4-7. Fig. 4-6 are under the liquid nitrogen environment and Fig. 7 is under liquid argon environment. Similar temperature profiles for the three kinds of the material systems are observed and curvature of the profiles increases with the vacuum level. Because these temperature-thickness profiles as a function of Cold Vacuum Pressure (CVP) are affected by not quantity of heat transfer, but the deviation of the thermal conductivity according to the temperature ranges. That is, the porous materials have billions of interstitial spaces and those spaces, along with the nanoparticles, grab the air molecules. So they determine the amount of gas conductive and convective heat transfer.

Therefore, the temperature between CBT and WBT approach the equilibrium. And then the curvature of the temperature profiles at the steady-state is determined by the deviation of the effective thermal conductivity under each vacuum pressure.

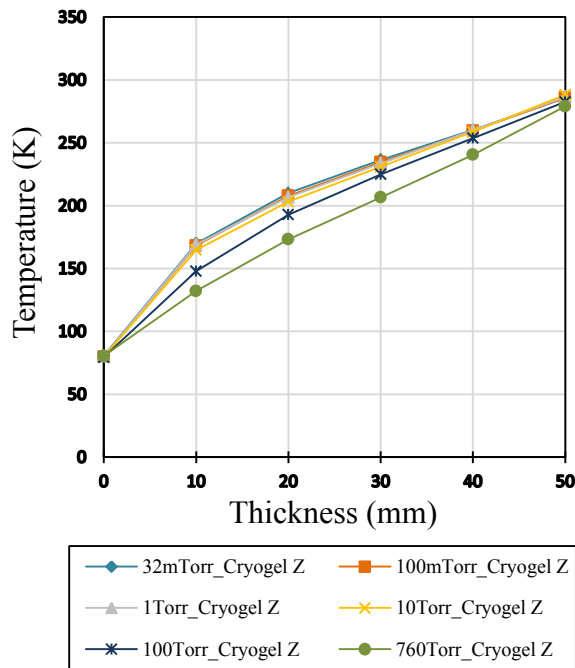


Figure 4. Temperature-thickness profile for 5-layer Cryogel Z under the liquid nitrogen environment; residual gas is nitrogen.

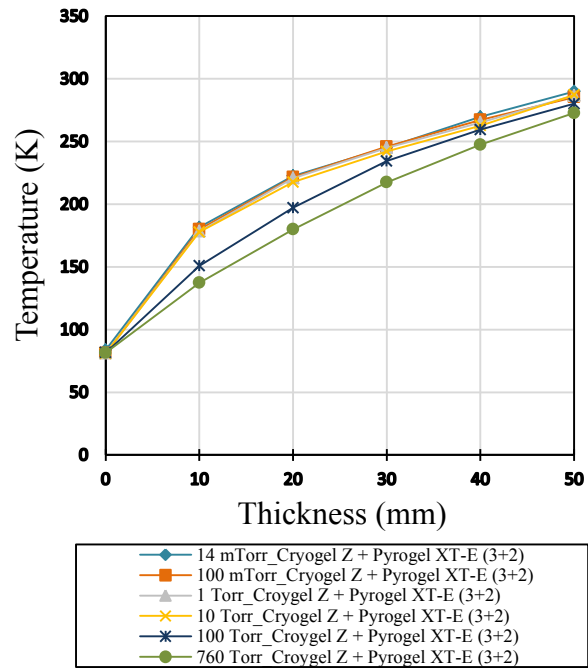


Figure 5. Temperature-thickness profile for 3-layer Cryogel Z + 2-layer Pyrogel XT-E under the liquid nitrogen environment; residual gas is nitrogen.

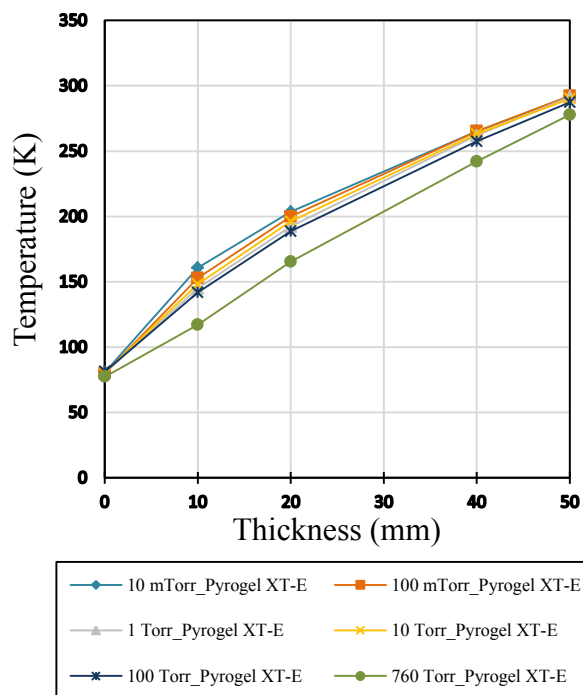


Figure 6. Temperature-thickness profile for 5-layer Pyrogel XT-E under the liquid nitrogen environment; residual gas is nitrogen.

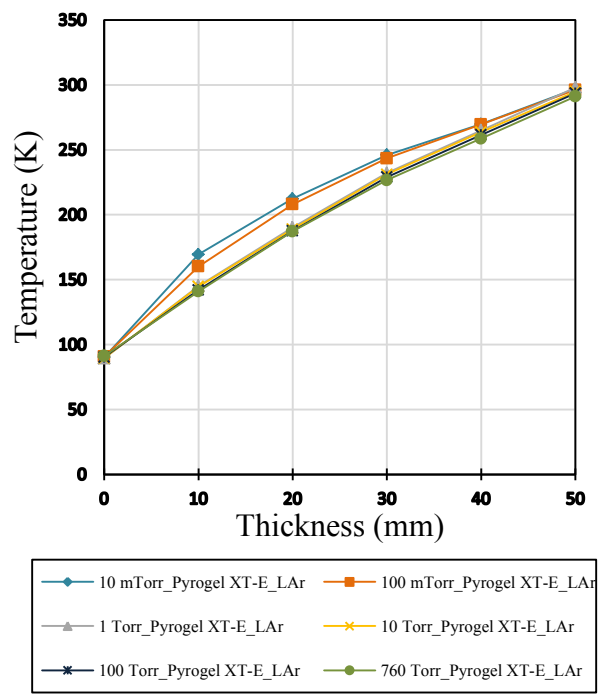


Figure 7. Temperature-thickness profile for 5-layer Pyrogel XT-E under the liquid argon environment; residual gas is nitrogen.

4.2. Effective thermal conductivity with Cold Vacuum Pressure (CVP)

Fig. 8 presented the variation of the effective thermal conductivity with cold vacuum pressure for the aerogel blankets. The k -values, the effective thermal conductivities, rise moderately from soft vacuum to no vacuum as the gas in the porous aerogel materials begins to dominate the heat transfer. Therefore, as the cold vacuum pressure diminishes, the k -values decrease due to reduced conductive and convective heat transfer in the porous structures.

In addition, the k -values of Pyrogel XT-E under the liquid argon environment are higher than that under the liquid nitrogen environment. The reason is that the effective thermal conductivity is affected by the mean temperature between CBT and WBT.

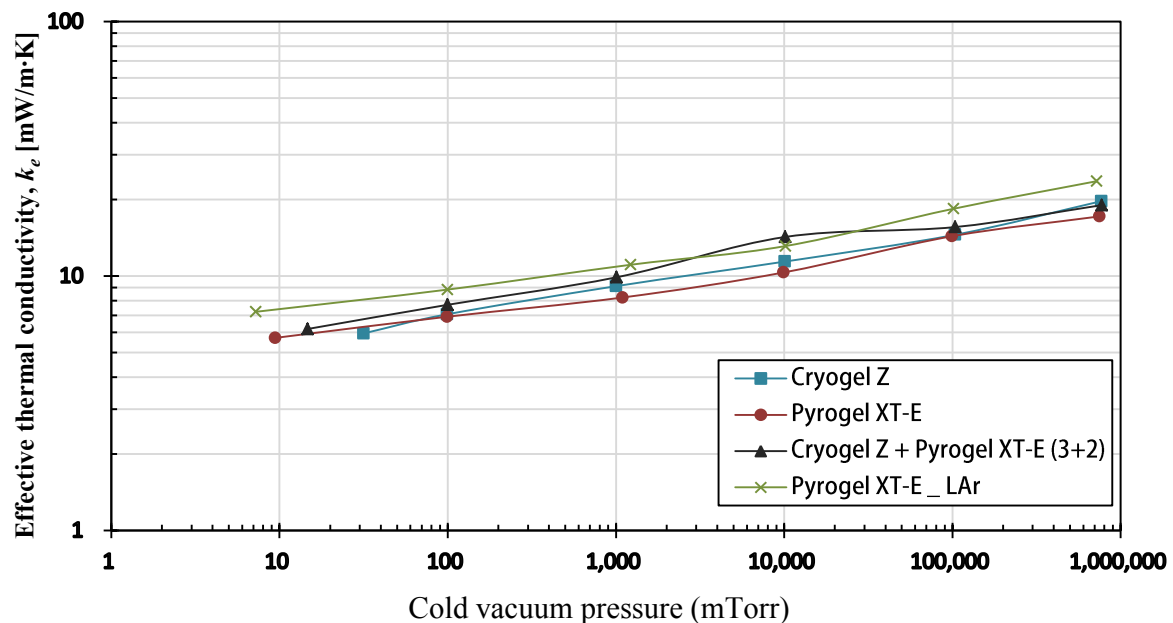


Figure 8. Variation of effective thermal conductivity for aerogel blanket insulation materials; residual gas is nitrogen.

5. Conclusions

Cryogenic thermal performance test of the Aspen Aerogels' flexible blankets such as Cryogel Z and Pyrogel XT-E was successfully completed. In this study, the effective thermal conductivities of each aerogel system were similar according to the cold vacuum pressure. The temperature profiles of the aerogel materials near the cold body are steep at the higher vacuum environment. However, the temperature profile of Pyrogel XT-E is gradual. It means that the porosity of Cryogel Z is the larger thermal resistance at the higher vacuum pressure. That is, Cryogel Z is getting better the thermal performance than Pyrogel XT-E under the soft vacuum environment. Thus, the results of this experimental study will provide new possibilities for thermal insulation systems under the soft vacuum and the no vacuum environment. As mentioned above, most of the technologies will require, in a number of cases, more efficient systems. Therefore, this study is targeted for low-cost and intermediate performance uses.

In the future, the experimental apparatus will be improved in order to calculate the accurate effective thermal conductivity of the hydrophobic porous insulation materials under the high vacuum environment. It is promised that the next study can provide the data for the high thermal performance applications.

6. Acknowledgement

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