Application of Silica Aerogel as Cryogenic Insulation

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Abstract—**The work deals with the study on the evaluation of silica aerogel blanket for cryogenic applications in space launch vehicles. An experimental investigation has been done to compare the thermal conductivities, thermal resistance of insulation of aerogel based insulations with foam insulations by simulating cryogenic conditions at room temperature and pressure. The study evaluates thermal parameters on the basis of insulation thicknesses and cryogen evaporation kinetics. Separate mathematical models have been formulated on the basis of the variation with thickness to compare the effectiveness of aerogel based cryogenic insulations.**

Index Terms—**Thermal conductivity, Thermal resistance of insulation, Cryogenic insulation, Insulation thickness.**

ABBREVIATIONS AND ACRONYMS

LN_2	Liquid Nitrogen
PUR	Polyurethane Rigid Foam
PUF	Same as PUR
Q	Heat leak (W)
λ	Heat of Vaporization of LN2 = 199.3 J/g
$\dot{m}$	Boil off rate of LN_2 (g/s)
$\mathcal{T}$	Time interval = 600s
Δx	Thickness of insulation (m)
Ti	Temperature at inner surface of insulation (K)
To	Temperature at outer surface of insulation (K)
k	Thermal Conductivity (W/m K)
k_a	Apparent thermal Conductivity (W/m K)
A_i	Inner area of insulation (m^2)
A_m	Logarithmic mean area of insulation (m^2)
A_o	Outer area of insulation (m^2)
R_T	Thermal resistance of insulation (K/W)
r_1	Outer radius of vessel (m)
r_2	Outer radius of insulation = $r_1 + \Delta x$
h	Height of bottle (m)

I. INTRODUCTION

Heat leak into a cryogenic fluid is costly and undesirable because of the large amount of work required in achieving the cryogenic temperature so storage vessels or tanks containing cryogenic fluids should be provided with an insulation that will have a very low rate of heat transmission from ambient atmosphere due to the large temperature difference. Conventional cryogenic vacuum insulation systems require a hard vacuum typically less than 1 micron Hg at 0^oC to reduce gas conduction or convection. The hard vacuum required is expensive to produce, requiring long pump out times at elevated temperature which increases the production cost of vacuum insulated equipments. The hard vacuum must be maintained throughout the useful life of the equipment which may range from 15 to 20 years and it can be seen that despite all precautions, the pressure in the vacuum space rises inevitably causing a dramatic performance loss. One alternative is to use foam insulation however they have much higher heat leak comparatively. Precaution must be taken to weatherseal the foam insulations else they get degraded rapidly. Insulation systems that perform well at temperatures above cryogenic temperature usually do not perform well at cryogenic temperatures which are below freezing point of water as most of the insulations have very low internal vapor pressure, which creates high potential for atmospheric moisture to enter the system and impair the insulation quality. So such insulation systems must provided with auxiliary coatings or devices to prevent its loss of performance considerably. Accordingly, a suitable cryogenic insulation system is requirement which is reliable over its lifetime, cheaper to fabricate, has a high performance and is relatively insensitive to vacuum loss comparatively. For such problems, *silica aerogel* can be thought of as a suitable alternative for cryogenic applications.

Samuel Stephens Kistler (1930s) first produced silica aerogels by formulating the idea of replacing the liquid phase by a gas with only a slight shrinkage of the gel which was a tedious and time consuming procedures, and as such there was no follow-up interest in the field of aerogels until 1968 when rediscovery of aerogels took place by a team of researchers headed by Professor S J Teichner at the University Claude, Bernard, Lyon, France. Application of aerogels for thermal insulation were studied by Hrubesh [9], Smith et al. [12]. Deng Z, Wang J et al. (1998) compared the strength of thermal insulation based on silicon dioxide aerogels. Matos J R, Kruk, M Mercuri et al. (2002) analyzed the cage structure of organic aerogels structure and analyses their effect on thermal properties. Yan Chang-hai, Meng Song-he, Liu Guo- qian et al. (2006) modeled and performed a heat transfer analysis on thickness of fibrous insulations of metallic thermal protection system during the re-entry of spacecrafts into the atmosphere. J E Fesmire (2006) experimented on space launch vehicle devices using aerogel blanket insulations [6]. Sheng Chen, Yu Yun, Yu Yang et al. (2012) proposed silica aerogel based multi layer insulation materials to be used in TPS of payload in rockets [8].

II. Experimentation

Silica aerogel blanket was readily available in markets in sizes according to the requirement manufactured by Aspen & Co. The Al. vessel of diameter 100mm and length 225 mm was well cleaned and neatly polished and silica aerogel blanket was bonded around the vessel using RTV silicone adhesive on the surface. The thickness of the blanket was 5 mm. Two or three layers of the blanket were bonded over the bottle surface depending on the required thickness of the aerogel insulation. The silica aerogel insulated bottle was connected to digital temperature measurement equipment through T type thermocouples, attached to the metal surface of the bottle, inter-space between the layers and over the surface of the outermost insulation layer as shown in fig.1. The amount of cryogen evaporated was monitored by recording weight of cryogen filled container at regular time intervals. During experimentation, the data from thermocouples and weighing balance were recorded during a time gap of 10 minutes. LN_2 was refilled to the bottle for every 250g evaporated with the same quantity. The experimentation procedure were repeated for 5, 10, 15 mm thickness of aerogel blanket while the same procedure were also repeated for 5, 10, 15 mm thickness of PUR insulation. PUR was formed by mixing required proportions of raw materials or chemicals [5]. The mixture was finely blended using a suitable high speed stirrer and the mixed chemicals were poured into a cylindrical mould in which the Al. bottle was kept and PUR formed by rising (flowability) from the bottom and formed around the vessel inside the mould. After the foam was hardened, vessel with insulation were hammered out of the mould without breaking the foam and the surface was finished to the required thickness of insulation using a suitable emery paper and a knife. The uncertainty in measuring the thermal conductivity, apparent thermal conductivity and thermal resistance of insulation were found to be 6%, 5% and 7% respectively. The temperature profile around the different insulation thicknesses for aerogel as well as PUR is shown in figure 2.

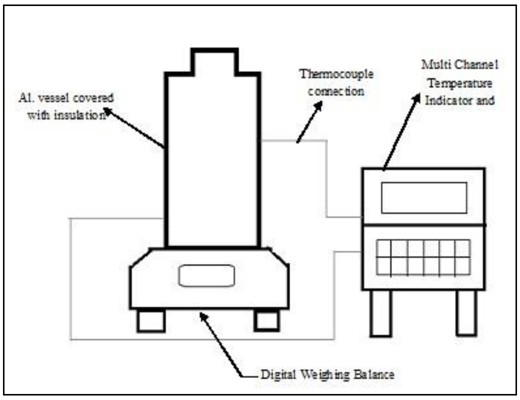

Figure 1. Experimental Setup.

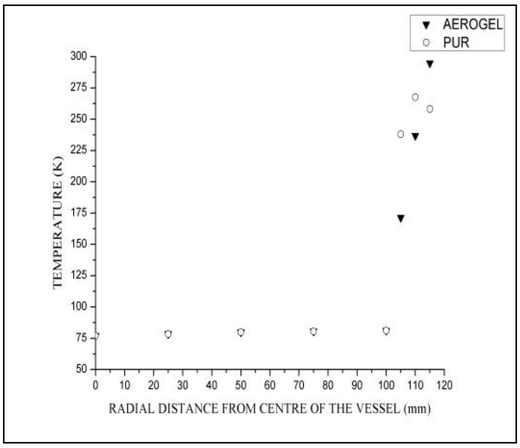

Figure 2. Temperature Profile around Insulation varying with thickness.

III. Results And Discussions

Thermal parameters to be calculated for aerogel and PUR insulations for varying thickness included, thermal conductivity, apparent thermal conductivity and thermal resistance of insulation respectively. The equations concerned for calculations are given below.

$$k = (Q \text{ x } \Delta x)/(A_i \text{ x } (T_o - T_i)). \quad (1)$$

$$Q = \lambda \text{ x } (\dot{m}/\mathcal{T}). \quad (2)$$

$$k_a = (Q \text{ x } \Delta x)/(A_m \text{ x } (T_o - T_i)). \quad (3)$$

$$A_m = (A_o - A_i)/ \ln (A_o/A_i). \quad (4)$$

$$R_T = (\ln(r_2/r_1))/(2\pi \text{ x } k \text{ x } h). \quad (5)$$

Figure.2 gives the details regarding the temperature profile around the different insulation with variation in thickness, which indicates that the temperature around the outer surface of insulation for PUR is below 300K due to ice formation around PUR surface which shows proves the effectiveness of aerogel insulation compared to PUR. The boil off rate of LN_2 varies from 0.187 to 0.104 grams per second as thickness of aerogel insulation is increased from 5 to 15 milli meter, while it varies from 0.28 to 0.18 grams per second in case of PUR.

Aerogel insulations having 10mm thickness has LN_2 boil off rate of approx. 80 grams per ten minutes which is within the allowable limit for cryogenic insulation without auxiliary coatings. On comparing the thermal conductivity of insulation, it was found that the thermal conductivity of aerogel insulation increased from 11 to 16 milli watt per metre per Kelvin due to the presence of unavoidable air resistance at normal conditions while that of PUR increased from 20 to 32 watt per metre per Kelvin, which was high comparatively and it necessitates the requirement of vapor coatings and increase in insulation thickness for PUR even at normal room conditions. To validate the above results, apparent thermal conductivity was calculated which also indicated the same variation as in figures 3 and 4 respectively.

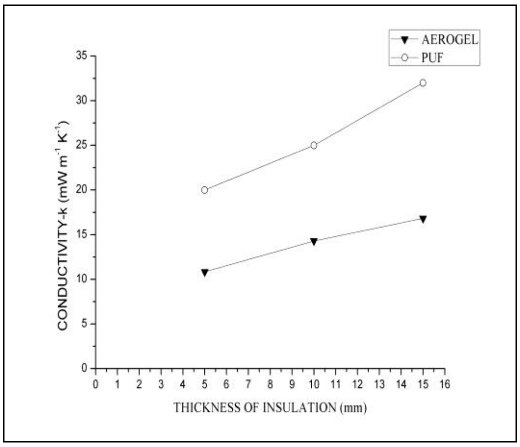

Figure 3. Variation of thermal conductivity.

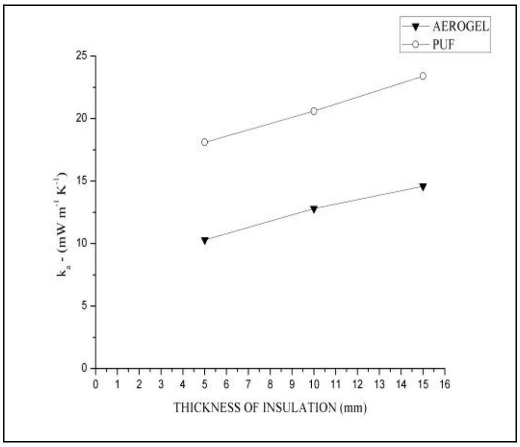

Figure 4. Variation of apparent thermal conductivity.

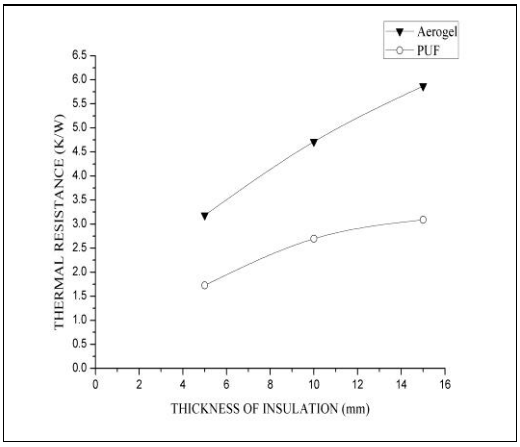

Figure 5. Variation of thermal resistance.

Now similarly the variation in thermal resistance of insulation for different thicknesses of the two insulation were calculated which showed that even though conductivity of aerogel based insulation increased with increase in thickness, the thermal resistance of insulation increases to about twice on increasing thickness from 5 to 10mm, which showed the effectiveness of aerogel based cryogenic insulation at normal conditions compared to PUR as indicated in figure 5.

Inorder to validate the above results and to find the variation of thermal conductivity and thermal resistance of insulation, a mathematical model were modeled for each insulation separately for a particular parameter variation as indicated in figures 6 and 7 respectively.

The figure.6 indicated that without any aid of auxiliary coatings, the thermal conductivity of aerogel based insulation increased from 11 to 25 milli watt per metre per Kelvin and were low comparatively, which showed its effectiveness even at normal conditions to store $LN_{2.}$ Figure 7 indicated the variation thermal resistance of insulation for both insulation using a suitable parabolic mathematical models or equations, which also indicated that aerogel blankets are more effective upto 15mm thickness and effectiveness were much higher compared to PUR.

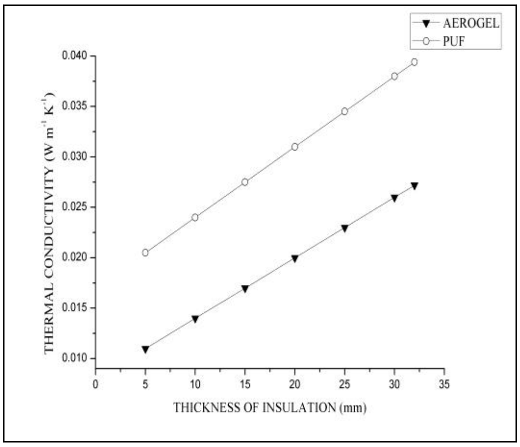

Figure 6. Variation of thermal conductivity using mathematical models.

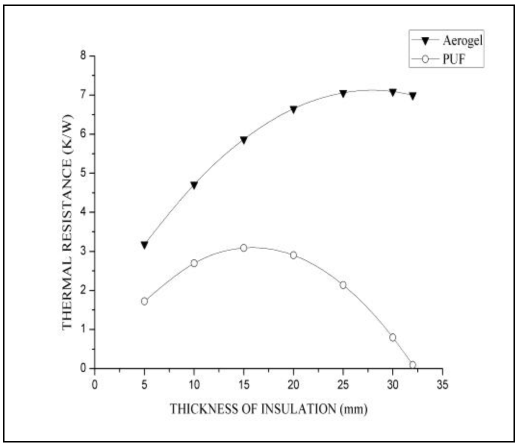

Figure 7. Variation of thermal resistance of insulation using mathematical models.

IV. Conclusions

The above results show that aerogel blankets are far superior to PUR insulations. Even with 10 mm thickness for PUR, the exterior most temperature is subzero thereby causing copious ice formation. With increase in thickness, thermal conductivity slightly increases and thermal resistance of insulation steadily increases for aerogel blankets. The data regarding thermal conductivity and thermal resistance of insulation for silica aerogel blankets shows that they are at least three times better than PUR under similar conditions.

Acknowledgment

The authors wish to thank the HPTF and EPS division of VSSC, ISRO for their valuable insight, support and guidance throughout the experimental work for making the research possible.

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