Aerogel-Based Insulation Materials for Cryogenic Applications

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Abstract. Many different aerogel-based materials are now being used in thermal insulation systems for cryogenic applications. These materials include flexible composite blankets, bulk-fill particles, and polymer composites in both evacuated and non-evacuated environments. In ambient environments, aerogels provide superior thermal performance compared to conventional polymeric foam and cellular glass insulations while offering unique advantages in solving problems with weathering, moisture, and mechanical damage. Aerogels are also used as spacer materials in multilayer insulation systems. These layered systems provide combined structural-thermal capability for cryogenic systems in either vacuum-jacketed or externally-applied insulation designs. Test data (effective thermal conductivity) include a wide range of both commercial and experimental aerogel materials. Testing was performed using laboratory cryostats and standard methods for boundary temperatures 293 K and 78 K. Examples of aerogel-based insulation systems are given for both evacuated and non-evacuated applications.

1. Introduction
Thermal insulation systems for cryogenic applications span a wide range of requirements and call for demanding levels of performance. Aerogels and their composites continue to be developed to take advantage of highly tailorable processing techniques that enable specialized end products and unique thermo-physical properties attributed to their nano-porous internal networks. Aerogel materials have become commercially available in three categories: flexible composite blankets, bulk-fill particles, and layered composite systems. Examples of field applications include liquefied natural gas (111 K), liquid oxygen (90 K), liquid nitrogen (77 K), cryo-compressed hydrogen (~40 K), and liquid hydrogen (20 K).

2. Materials and Insulation Systems
Six different aerogel materials were tested for cryogenic-vacuum thermal performance. The aerogel blanket materials are composite materials that include a fiber reinforcement material in the production process. Two systems are layered composite insulation (LCI) systems of radiation shield layers in combination with aerogel composite blanket materials. System G1-191 is a layered composite of pairs of ultra-low density (ULD) aerogel blanket and double-aluminized Mylar film. System A193 is a layered composite of pairs of aerogel composite paper (0.7 mm thick) and double-aluminized Mylar film. The aerogel materials/systems tested, along with their basic physical properties, are summarized in Table 1.

Additional insulation materials/systems were tested for comparison [1]. The descriptions of these additional test specimens are given in Table 2. These materials include “vacuum only” and a closed-cell
spray-on foam [2] on one end of the spectrum of thermal performance followed by the glass bubbles system [3] and a baseline of multilayer insulation (MLI) on the other [4].

Table 1. Physical properties of aerogel-based test specimens.

| Cryostat Test Series | Test Specimen | No. of Layers | Total Thickness* (mm) | Density* (kg/m³) |
|----------------------|---------------|---------------|-----------------------|------------------|
| C100 A108            | ¹Bulk-fill aerogel beads | 1 | 25 | 80 |
| C100 A111            | ²Pyrogel® aerogel blanket (black) | 6 | 18 | 125 |
| C100 A194            | ²Cyrogel® aerogel blanket | 2 | 20 | 130 |
| C500 G2-109          | ²Spaceloft® Subsea (grey) | 4 | 20 | 152 |
| C500 G1-190          | ³ULD® aerogel blanket white | 8 | 23 | 55 |
| C500 G2-113          | ³ULD® melamine flexible aerogel grey | 8 | 21 | 65 |
| C500 G1-191          | ³ULD® Aerogel MLI layered composite | 8 | 23 | 52 |
| C100 A193            | Aerogel MLI layered composite (0.7-mm aerogel paper) | 7 | 5 | 91 |

*As tested  ¹Ultra-Low Density (ULD)  ²Cabot Corp. (manufacturer)  ³Aspen Aerogels, Inc. (manufacturer)

Table 2. Physical properties of additional insulation test specimens for comparison.

| Cryostat Test Series | Test Specimen | No. of Layers | Total Thickness* (mm) | Density* (kg/m³) |
|----------------------|---------------|---------------|-----------------------|------------------|
| C100 A114            | Vacuum Only (black surfaces) | 1 | 25 | n/a |
| C500 G1-157          | SOFI BX-265 (polyiso foam) | 1 | 25 | 42 |
| C100 A102            | Glass Bubbles K1 | 1 | 25 | 65 |
| C100 various         | Kaganer Line (MLI Baseline); average of 26 different MLI test specimens | From 10 to 80 | ~22 typical | ~50 typical |

*As tested.

Limitations in using MLI systems are summarized as follows: 1) high vacuum is required for operation (and in the first place, it is not possible to vacuum-jacket all hardware), 2) not all hardware can be suitably wrapped or properly covered, and 3) localized compression will ruin the thermal performance. MLI cannot withstand mechanical loading. Compared to the no load condition for six different MLI systems tested (average heat flux of 0.6 W/m²), a mere 0.7 kPa (0.1 psi) causes ~15x increase in heat flux, a small 7-kPa load causes an ~40x increase, and a modest 70-kPa load causes >100x increase in heat flux [5].

Compared to MLI, bulk-fill, or foam material types, aerogel-based systems may be advantageous depending on the vacuum/pressure environment. Other key factors include: physical design of system; installation build process; and operational requirements. For non-vacuum applications, an alternative to closed-cell foam is the layered composite extreme (LCX) system which takes advantage of the unique nano-porous, compressible, and hydrophobic properties of aerogel blanket material [6]. The breathable LCX system, an MLI for the ambient-air environment, has been proven on operational LH2 systems (20 K). Aerogel blanket materials such as the Pyrogel® provide high temperature capability to 923 K (1200 °F) where fire protection might be needed for cryofuel systems.

3. Experimental Method and Apparatus

Two cryostat test instruments were used for absolute thermal performance measurements. Both are steady-state boiloff calorimeters using liquid nitrogen. Cryostat-100 has a vertical cylindrical cold mass assembly that is 1-m tall by 167-mm diameter while the Cryostat-500 has a horizontal flat plate cold mass assembly of 204-mm diameter [8-9]. The cold and warm boundary temperatures for all tests are 78 K and 293 K, respectively. The effective thermal conductivity (k, in mW/m-K) and heat flux (q in W/m²) are calculated for the standard ΔT of 215 K. The test methodology follows the guidance of ASTM C1774, Annex A1 and Annex A3, respectively [10]. For high vacuum tests, each test specimen was heated and evacuated according to standard laboratory procedures.
Three additional temperature sensors (Type E, 30 gage thermocouples) are placed within the specimen at specific intervals through the thickness from the cold side to the warm side. Because the heat flow rate through the test specimen is constant for all layers, intermediate thermal conductivity values ($\lambda$) can be calculated and reported with the mean temperature ($T_m$) for each layer. In this way, a single test yields nine $\lambda$ points for determining the temperature dependence of heat transmission through a test specimen operating between the large $\Delta T$.

4. Cryogenic-Vacuum Test Results

The cryostat test results for all test series are presented in Figure 1. Included for comparison are the additional materials/systems as discussed. For all tests, the boundary temperatures are approximately 293 K and 78 K and the residual gas in nitrogen.

In higher vacuum, the lowest $k_e$ systems are the MLI baseline and layered composites of aerogel/MLI. The data for glass bubbles, dominated by gas conduction heat transfer, shows the transition from free-molecular to continuum heat transfer at ~50 millitorr. In the soft vacuum region up to ambient pressure, all aerogel materials are superior. The two layered composites (A193 and G1-191) are examples of combining the advantages of two different material systems (aerogel and MLI) for applications requiring tolerance for vacuum degradation and/or mechanical loading.

The results for the six aerogel materials are given in Figure 2 for detailed examination. In high vacuum, the ULD aerogel and Spaceloft Subsea Gray gave the lowest $k_e$. Through the moderate vacuum (from 50 to 1,000 millitorr) and soft vacuum (from 1,000 to 50,000 millitorr) ranges is where some significant differences appear according to the characteristics of the aerogel on the nanoscopic level, the fiber matrix (if any) and physical arrangement on the microscopic level, and the interstitial spaces (if any) on the macroscopic level. Even with this simplistic analytical view, the differences can at least be somewhat resolved by considering the four modes of heat transfer (solid conduction, radiation, gas conduction, and convection) are all in play for this region of CVP.

Additional test data points were taken in all cases to verify the unique shapes of the data for each aerogel material. For example, the aerogel beads specimen has more free interstitial space for gas conduction and convection to occur while the ULD aerogel specimen has the finest pore size and hence lowest gaseous conduction. For ambient pressure conditions, the two ULD aerogels show the highest $k_e$ while the twice heavier Cryogel is superior. Detailed data sets for the Cryogel material, including different gas environments, are previously reported [11].

Plots of the layer temperature distributions were also produced for all layered test specimens. The key distinction is the progression of inflections in the curves where the steepest inflection always occurs at the first layer (coldest layer) and under higher vacuum conditions.

5. Thermal Analysis and Discussion

The intermediate or interlayer temperature sensors used in the cryostat testing provide additional data to determine the temperature dependence of thermal conductivity within the two prescribed boundary temperatures. The use of three intermediate temperature sensors creates four layers, numbered from one to four, from the cold side. Equations (1) through (4) give the basic nomenclature:

\[
Q = k_e * A_e * \Delta T / \Delta x \quad \text{Fourier equation} \quad (1)
\]
\[
q = Q / A_e \quad \text{constant} \quad (2)
\]
\[
q = q_1 = q_2 = q_3 = q_4 = \lambda_4 * \Delta T_4 / \Delta x_4 \quad \text{and so forth} \quad (3)
\]
\[
T_m = (T_{\text{colder}} + T_{\text{warmer}}) / 2 \quad \text{or} \quad T_{m4} = (T_{c4} + T_{w4}) / 2 \quad \text{and so forth} \quad (4)
\]

The $q$ is constant for a steady-state heat flow rate and therefore the $q$ through each layer is constant. Because the $\Delta T$ and $\Delta x$ for each layer are known, the $\lambda$ for each layer can be calculated and reported for the corresponding $T_m$.

Often needed is an estimate of an insulation system thermal performance for specific boundary temperatures. Test data for MLI under high vacuum (<10^-5 torr) provide a preliminary way of estimating
the increases in heat transmission for WBT up to 350 K. Given in Table 3 are the increases in heat flux, on a percentage basis, for an average of 12 different MLI systems from a baseline WBT of 293 K. Likewise, Table 4 shows the reductions in heat flux for an MLI system with decreasing cold boundary temperatures from a 78 K baseline.

From baseline heat flux ($q_{\text{base}}$) test data at the standard boundary temperatures of 293 K and 78 K, a first-order estimation of the thermal performance for a specific layered system design is calculated using a WBT factor ($b_w$) and a CBT factor ($b_c$) as follows:

$$q_{\text{design}} = b_c \times b_w \times q_{\text{base}}$$

For example, the heat flux estimate for a system operating at boundary temperatures of 325 K / 20 K is approximately the same thermal performance as the baseline of 293 K / 78 K ($q_{\text{design}}=1.32\times0.79\times q_{\text{base}} = 1.04\times q_{\text{base}}$. The theoretical heat flux is proportional to the $\Delta T$ (and $T^4$ for the radiation portion), but the more important and influential factor is the materials’ heat transmission characteristics that occur at the progressively lower temperatures combined with the likely improvement of the level of vacuum.

Table 3. Increase in heat flux for increasing WBT (for MLI system with constant CBT = 78 K) [4].

| WBT (K) | $\Delta T$% increase, $\Delta T$ | % increase, $q$ | factor $b_w$ |
|---------|---------------------------------|----------------|--------------|
| 293     | 215 baseline                    | baseline       | 1.00         |
| 305     | 227 6                          | 14             | 1.14         |
| 325     | 247 15                          | 32             | 1.32         |
| 350     | 272 27                          | 46             | 1.46         |

Table 4. Decrease in heat flux for decreasing CBT (for MLI system with constant WBT = 300 K) [5].

| CBT (K) | $\Delta T$% decrease, $\Delta T$ | % decrease, $q$ | factor $b_c$ |
|---------|---------------------------------|----------------|--------------|
| 76      | 224 baseline                    | baseline       | 1.00         |
| 40      | 260 16                          | 14             | 0.86         |
| 20      | 280 25                          | 21             | 0.79         |
| 4       | 296 32                          | 33             | 0.67         |

Figure 1. Variation of $k_e$ with CVP for aerogels compared to other cryogenic insulation systems.
6. Conclusion
Cryogenic-vacuum thermal performance of a number of different aerogel-based thermal insulation systems in comparison with other cryogenic insulation systems is provided for a variety of applications, including both vacuum and non-vacuum designs. Aerogels include blanket type, bulk-fill type, and layered composites including radiation shield layers. Future aerogel materials under development will likely lead to further advances to enable new cryogenic applications and multi-functional systems. However, a number of aerogel materials are widely commercially available today, proven for cryogenic use in both vacuum and non-vacuum environments at temperatures from 4 K to 400 K.

7. References
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