Thermal Conductivity of Aerogel Insulation for Cryogenic Applications

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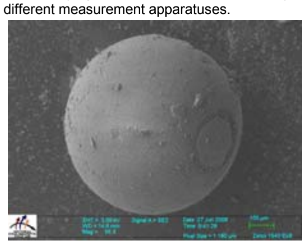
ABSTRACT:

Building on prior research by Barrios et al on the thermal conductivity of aerogel beads, this study was performed to incorporate modifications to the original research to quantify thermal conductivity values at different pressures and temperatures. Research was performed using a measuring device located inside of a vacuum-insulated cryostat, consisting of two concentric cylinders [Barrios]. Aerogel beads fill the annular space between the cylinders. The outer cylinder is cooled by a single stage Gifford-McMahon cryocooler, and the inner cylinder is connected to a heater. This setup is used to create a 10 K temperature difference across the insulation. Values for the aerogel beads' bulk effective thermal conductivity (k_{eff}) were calculated based on the temperature difference and heating power using Fourier's law of heat conduction. Data were collected at three different average temperatures (30 K, 50 K, and 70K) at pressures incrementing by powers of ten from 1 mTorr up to 100 Torr. Difficulties in achieving the lowest temperatures prevented data collection at all points, but the data that were collected reinforce previous work. Thermal conductivity values ranged from ~0.0019 W/m-K to ~0.0128 W/m-K.

INTRODUCTION:

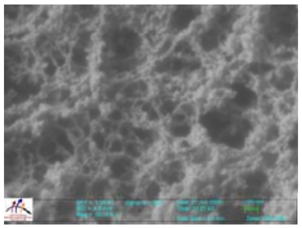
Thermal insulation is critical for cryogenic applications to ensure that required low temperatures (ranging from 90 K for liquid oxygen to 4.2 K for liquid helium, for example) are maintained. NASA is currently sponsoring research of densified liquid hydrogen and oxygen, as potential spacecraft propellants. This creates a demand for storage containers for these materials with the most effective insulation. For many cryogenic systems, multi-layered insulation (MLI) is the insulation of choice. However, MLI requires a high vacuum for optimal effectiveness, prompting a search for more efficient insulating materials at different vacuum levels. Powder insulations have shown promise at soft vacuums, and have a structural advantage in that they are far simpler to install and maintain.

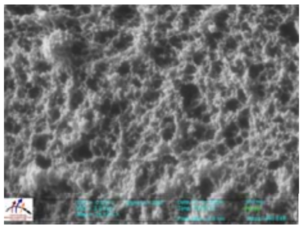
Previous studies have been done of various powder insulations, such as glass microspheres and aerogel beads. This study looks at Nanogel® aerogel beads, manufactured by Cabot Corporation. Aerogel beads are made of a highly porous silicate sol-gel that is dried in such a way (often supercritical drying, but new methods have been developed as well) so as to preserve the complex nanostructure of the material. The beads are formed by spraying during the drying process. While known for their impressive thermal properties, research has begun only recently on quantifying values for thermal conductivity at different vacuum and temperature levels, using different measurement apparatuses.



Nanogel® Aerogel Beads imaged using a Zeiss 1540 XB Field Emission Scanning Electron Microscope, at 95x (top left), 50,000x (bottom left), and 24,520x (bottom right).

Particle size range	≈ 1.0 mm
Pore diameter	≈ 20 nm
Porosity	> 90%
Bulk density	90-100 kg/m2
Thermal conductivity	0.018 W/m-K at 25° C



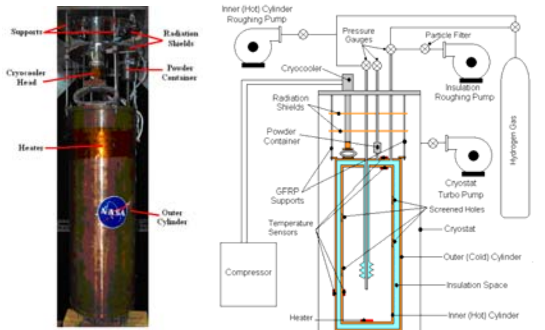


Rettelbach et al used regular and opacified aerogel powder between 10 K and 275 K in a guarded hot plate apparatus. Nayak and Tien used glass microspheres between 80 K and 300 K in a concentric sphere apparatus. Fesmire et al examined aerogel beads, glass microspheres, and perlite at temperatures between 77 K and 300 K in a boiloff calorimeter apparatus. Previous research by Barrios et al looked into both glass microspheres and aerogel beads, at temperatures of 30 K, 50 K, and 70 K. Changes have been made to his measurement apparatus to improve temperature control and vacuum seal. This updated apparatus was used in this study to build upon that previous research.

This project will collect further data on aerogel beads. The bulk effective thermal conductivity of the aerogel beads at varying temperatures and pressures will be calculated. Steady state measurements were taken at average temperatures ranging from 30 K to 180 K, at pressures of 100 Torr, 10 Torr, 1 Torr, .1 Torr, .01 Torr, and .001 Torr of hydrogen gas. Since liquid hydrogen tank insulation is one of the proposed applications for aerogels, the various pressures are achieved by the addition or evacuation of hydrogen gas, as any leaks from the tank into the insulated space would be hydrogen. The results from these trials will then be compared to prior findings. Also, the aerogel beads were examined in the microscopy lab and images were generated using an SEM to provide better insight about the material's nanostructure and resulting physical properties.

EXPERIMENTAL METHOD:

The measurement apparatus was developed by Barrios et al. It consists of two concentric copper cylinders. The annular space between the two cylinders and the inner space of the inner cylinder are not completely sealed from each other; small screens in the side of the inner cylinder allow for gas to flow between the two spaces to facilitate evacuation and equalize the pressure. The twelve ¼" screened holes are arranged in four staggered rows of three (six columns of two). The annular space is filled with aerogel beads. The inner cylinder is attached to a heater and the outer cylinder is thermally attached to the coldhead of a Gifford-McMahon single-stage cryocooler, providing a temperature gradient across the insulating material. The cylinders are inside a vacuum insulated cryostat, with liquid nitrogen insulation levels maintained by a solenoid valve. The vacuum space is under constant evacuation using a turbo pump. A Lakeshore 340 Temperature Controller controls the temperatures. Pressures are read from MKS pressure gauges at the top of both the annular space and the inner space, using 1000, 100, and 1 Torr gauges, depending on the trial. The cylinders were purged with hydrogen gas. LabView software collects data on the temperatures (K) and heater output (V) every 10 minutes. Cooldown of the apparatus took place with the cylinders filled with hydrogen at atmospheric pressure, and to achieve the various pressures, hydrogen was evacuated or added as needed. After temperature changes, 48 hours elapsed before data were taken. Upon reaching desired pressures, data were collected for at least 24 hours, and later analyzed for steady state regions. Steady state data were used to calculate the bulk effective thermal conductivity, using Fourier's law of heat conduction. Data were collected at three temperature ranges: 25K-35K (average 30K), 45K-55K (average 50K), 65-75K (average 70K); and six pressures: 100 Torr, 10 Torr, 1 Torr, 100 mTorr, 10 mTorr, 1 mTorr.



Measurement Apparatus

RESULTS AND ANALYSIS:

The data collected by LabView were used in the equation derived by Barrios et al to calculate the bulk effective thermal conductivity (k_{eff}) for each data point, based on steady state data.

$$k_{eff} = \frac{q_T}{(T_H - T_C)\left[\left(\frac{2\pi h}{\ln\left(\frac{r_C}{r_H}\right)}\right)+\left(\frac{2\pi r_H^{\,2}}{t}\right)\right]}$$

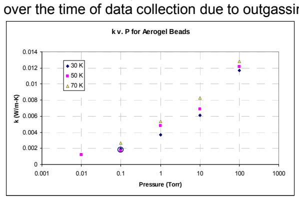
q_t	Total heat flow	(variable)
T_H	Temperature of outer cylinder	(variable)
T_C	Temperature of inner cylinder	(variable)
h	Height of outer cylinder	0.5779 m
t	Insulation thickness between ends	0.0127 m
r_H	Outer cylinder radius	0.09685 m
r_C	Inner cylinder radius	0.08415 m

Thermal Conductivity v. Pressure

k v. P for Aerogel Beads

•Shows the expected relationships between thermal conductivity and pressure, and thermal conductivity and temperature; *k* increases as pressure increases, and *k* is higher at higher temperatures.

•Previous trials attributed error to a temperature gradient through the outer cylinder; however, temperature checks found a negligible difference in temperature at different points of the outer cylinder. Error in these trials can be attributed to fluctuations in pressure over the time of data collection due to outgassing from the aerogel beads or perhaps a very small, slow leak in the system.

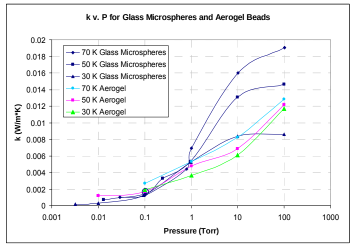


•k_{eff} ranges from a low of ~0.0019 W/m-K at ~0.01 Torr to a high of ~0.0128 W/m-K at ~100 Torr.

•Data point for 30 K, 0.1 Torr (circled) has an unexpectedly high *k* value, based on trends from the rest of the data

•Data for 70 K, .01 Torr produced unexpected *k* value (0.00112 W/m-K); pressure during data collection rose from 0.8 mTorr to 40.1 mTorr in 24 hrs, resulting in a low value for .01 Torr (no .001 Torr data available for comparison)

k v. P for Glass Microspheres and Aerogel Beads (with hydrogen residual gas)

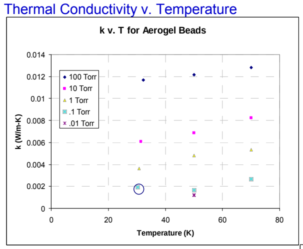


•Compares data from these trials with previous work by Barrios on glass microspheres (dark blue). Data fall within the same range of values, although there is less variation with temperature in aerogel beads.

•Data at the extreme ends of the graph for aerogel beads are needed to confirm the expected s-curve graph for thermal conductivity; glass microsphere values level off above 10 Torr, while aerogel beads continue to increase above 100 Torr

•Aerogel beads would be a better insulation choice at softer vacuums and above 30 K than the glass microspheres, if aerogel *k* values do not continue to increase after 100 Torr; glass microspheres seem to perform better at higher vacuums, although more data on aerogel beads are required for these low pressures.

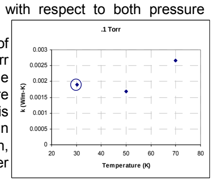
Thermal Conductivity v. Temperature



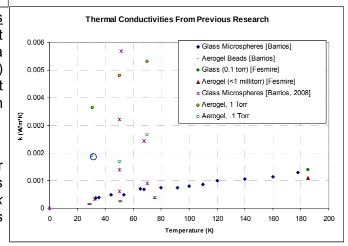
k v. T for Aerogel Beads

•Further demonstration of the thermal conductivity trends, increasing with respect to both pressure and temperature.

•The deviation of the 30 K, 0.1 Torr data point from the trend is more evident in this graph; as seen in the 0.1 Torr graph, the value is higher than expected.



Thermal Conductivities From Previous Research - Data for 1 Torr and .1 Torr (errant 30 K point included) graphed alongside data from previous research by Barrios (with He) and Fesmire, reinforcing the conclusion that data fall within an acceptable range with an expected trend.



CONCLUSION:

Thermal conductivity values calculated for aerogel beads are consistent with previous findings and suggests a general trend for *k* values versus temperature and residual gas pressure. This experiment has provided *k* values for aerogel beads at low temperatures (30 K, 50 K, and 70 K) and soft vacuums (0.1 Torr to 100 Torr), ranging from ~0.0019 W/m-K to ~0.0128 W/m-K. Difficulties in achieving low pressures precluded data collection at 0.001 and 0.01 Torr for all temperature ranges. Future work needs to be done to facilitate reaching these pressures (perhaps improving vacuum seals or evacuation methods) and collecting data there. A method for controlling gas addition and evacuation to achieve steadier pressures may also prove beneficial. Data collection at pressures between 100 Torr and atmospheric are also needed for clarification of aerogel bead thermal behavior.

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