

G-Plus Report to Owens Corning

Thermal Conductivity Measurements of Fiberglass

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Introduction

Fiberglass made by Owens Corning is being used in noise reduction of automobile exhaust system. Specifically, the glass fibers are packed inside the muffler to achieve the desired acoustic effect. A secondary benefit of the fibers is to serve as a thermal insulation. Because of this insulating property, the glass fibers can serve to reduce the temperature of the muffler shell. This in turn reduces the need for heat shields around mufflers and reduces the amount of exterior temperature accelerated corrosion of the muffler shell, especially in the winter “salt belts” where large amounts of salt are placed on highways to minimize the safety impact of snow and ice. In addition, for some applications the use of the fiberglass could allow the use of lighter weight carbon based polymer composite materials in place of steel for muffler shells. However, in order to properly design exhaust systems without heat shields or to take advantage of new materials, the thermal conductivity of the fiberglass material at operating temperatures (for some applications above 750° C) must be known.

We selected two types of Owens Corning glass fibers, 17 μm and 24 μm in diameter, for this study. There are some room temperature thermal conductivity data for the fiberglass, but high temperature data are not available. Based on the thermal radiation model, thermal conductivity should increase rapidly at high temperature, providing less thermal insulation. In addition, thermal conductivity depends on packing density of the glass fibers. We will study the effect of packing density on thermal conductivity. Another issue is that the glass fiber conducts heat better along the fiber, while the conduction across the fibers is poor, because thermal conduction from one fiber to another has to go through an interface with thermal resistance. In fiberglass, most fibers are not in good contact with the surrounding fibers, thus, most heat transfer is dependent on the thermal radiation effect.

Among the many methods of measuring thermal conductivity, only a few can be used for glass fibers. The traditional heat flow meter is used in testing thermal insulations near room temperature. At higher temperatures this method cannot be used due to material and instrument limitations. Our plan is to use a transient plane source (TPS) method to measure thermal conductivity directly. The advantage of the TPS method is that measurements can be taken at over 700° C, and covers the temperature of the automobile exhausts. The following is a report for the G-Plus project conducted at ORNL to apply the TPS method to characterizing the thermal conductivity of two types of fiberglass and also the effect of packing density.

Experimental

Thermal conductivity of the glass fibers was measured using a Hot Disk Thermal Constants Analyzer. A picture of the system is shown in Figure 1. A Keithly Source meter was used to provide constant heating of the sample. It is also used to measure the temperature of the sensor-sample interface. The Hot Disk sensor is a flat, thin, double-spiral nickel wire sandwiched between two mica sheets. For routine Hot Disk tests, the sensor is placed between two identical hockey-puck samples (typically 2” in diameter and



Figure 1. Hot Disk Thermal Constants Analyzer measures temperature change at the interface as a function of time.

1” thick). During the measurement, the mica sensor acts as both heater and temperature sensor. This technique has been used to measure thermal conductivities of solids, liquids, sands and powders. In this study we extend the measurements to loosely packed glass fibers.

A typical test for glass fiber uses 0.1-watt constant-power heating for 20 seconds. The sensor temperature is recorded as a function of time. Thermal conductivity is calculated directly from the experimental data. Detailed theory and experimental descriptions of the Hot Disk technique can be found in references [1-3].

The high temperature tests were conducted inside a Blue M furnace as shown in Figure 2. The glass fibers were loosely packed inside a bucket. The bottom of the container was filled up with fiber first. Then the mica sensor was placed on top. The same amount of glass fibers was filled on top of the sensor. The final assembly is shown in Figure 3.

In order to perform high temperature measurements, special contacts were made from stainless steel. Four high temperature wires with insulation were connected to the mica sensor using SS contacts. A rectangular mica sheet with four screw holes was used as the support for the sensor and wires. The four wires were connected to the contacts as shown in Figure 4. The mica sensor can delaminate due to high temperature exposure; therefore, the sensor has to be replaced after a 600° C measurement. A heavy plate was placed on top of the sample to achieve higher packing density. The wires were fed through an opening of the furnace. Figure 5 shows the sample and wires inside the furnace.



Figure 2. Blue M furnace used for high temperature tests.



Figure 3. The glass fibers are packed inside a bucket. The Hot Disk sensor is placed in the middle of the sample using shielded high temperature wire.



Figure 4. A close-up view of the mica sensor with high temperature contacts and wires.



Figure 5. Inside the Blue M furnace, the glass fibers are inside the container.

For each fiberglass, room temperature measurements were made outside the furnace. Different pressures were added to the glass fibers to study the effect of packing density. At high temperature, thermal conductivities were measured up to 700° C. Each fiber was tested for loose packing. One extra set of tests was performed with high packing density up to 700° C.

Results and Discussions:

The testing container has a diameter of 11.25” and height of 13.5”. The 24 μm fibers were tested first. The total weight of the fibers used was 466 g. The loose packing has a density of 0.032 g/cm³. Five thermal conductivity measurements were conducted at room temperature. Then a glass plate was put on top of the fibers. The density was 0.048 g/cm³. A heavy block was put on top of the glass plate bringing the density to 0.095 g/cm³. The density was calculated using the total weight of the fiberglass, W, and the volume, V. The volume was calculated from the area of the container, A, and the average height of the fiberglass, h.

$$\rho = W/(Ah) = W/(\pi r^2 h) \quad (1)$$

The room temperature thermal conductivity values of the three densities are shown in Table 1. As shown in Figure 6, the density calculation is only an estimate of the actual pack density. When weight was added to the fiberglass, the volume above the sensor compacted more than the volume below the sensor. This was because of the four high temperature wires were bent to hold the sensor in place (as shown in Figure 3). The tension from the wires prevented the sensor from sinking under the weight. Under loose packing condition, the weight of the sensor and the wires made contact below and

Table 1. Thermal conductivity of 24 μm glass fibers at room temperature

Density	0.032 g/cm ³	0.048 g/cm ³	0.095 g/cm ³
Test 1	0.021	0.024	0.026
Test 2	0.023	0.022	0.026
Test 3	0.022	0.023	0.029
Test 4	0.023	0.023	0.025
Test 5	0.022	0.023	0.025
Average	0.0222	0.023	0.0262

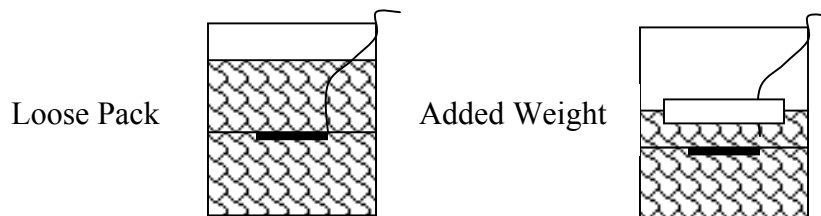


Figure 6. Illustration of the non-uniform density change with added weight.

above uneven, and these non-uniform conditions for need to be considered in data analysis.

Thermal conductivity increased slightly as a function of density. For high temperature tests, the loose packing density 0.032g/cm^3 was used. Since the Blue M furnace must be operated above 400°C (for heating element protection). The high temperature tests started from 400°C and ended at 700°C . Because the background noise increased at higher temperature, the testing power was increased from 0.2W at 400°C to 0.6W at 700°C . Figure 7 is the thermal conductivity vs temperature plot of the $24\ \mu\text{m}$ glass fibers.

The scatter at higher temperatures is due to signal noise. At 400°C , thermal conductivity increased to over 0.100W/mK . This is mainly due to a radiation contribution to the overall conductivity. The value is close to the Owens Corning estimates. Above 500°C , the data showed increased scatter. This is mainly due to background noise. An additional cause maybe that an average of 2 hours of “soak” was used between each temperature above 500°C . The 500°C value, which seemed higher, was probably because of a longer soaking time (> 3 hours). The fiberglass was fused together after 700°C tests. The adhesive between the mica sheets of the sensor also become ineffective at high temperatures. This may also contribute to the scattering of data above 500°C since there was not much pressure from the fiberglass holding the sheets together.

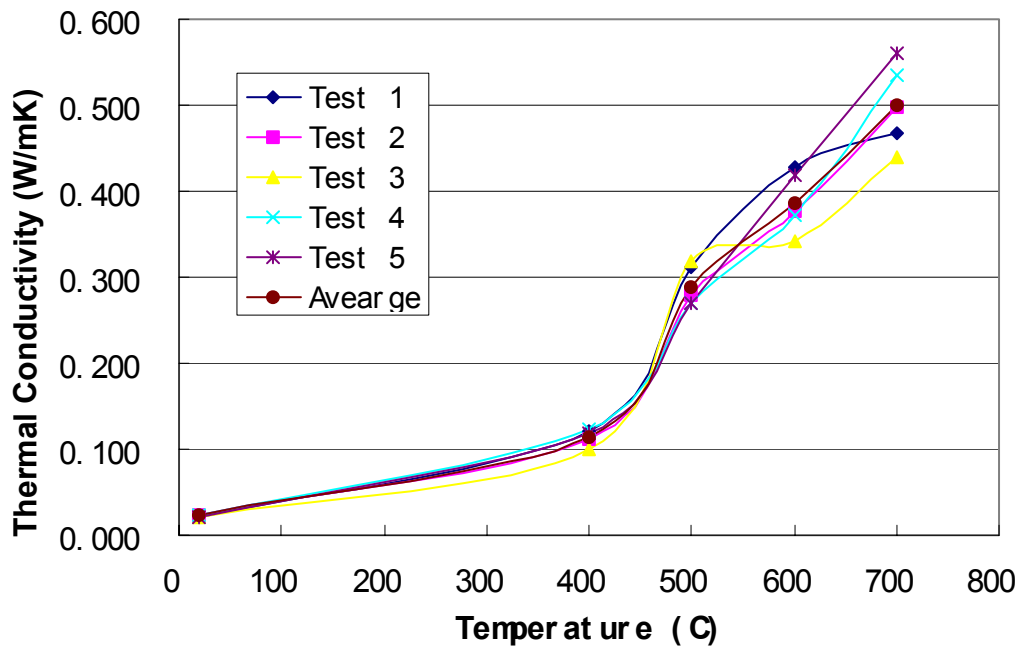


Figure 7. Thermal conductivity vs. temperature plot of $24\ \mu\text{m}$ glass fibers.

The same tests were conducted on a second type of glass fiber with a diameter of 17 μm . A new set of electrical contacts and a new mica sensor were used for this test. The total weight of the fiber was 314.3 g. The three density levels at room temperature were: 0.020 g/cm^3 , 0.043 g/cm^3 and 0.077 g/cm^3 . Thermal conductivity under the three densities is shown in Table 2. The density change was more noticeable as more pressure was applied. The low-density condition was used for high temperature tests. As shown in Figure 8, the thermal conductivity increased in the same manner as the 24- μm fibers. The electrical contacts were lost at 600° C due to mica sensor damaged limiting data. Only data up to 500° C are plotted. The temperature dependency is similar to the 24- μm fibers. Note the 500° C data showed less scatter. This was because the soak time between each temperature was limited to around 45 to 60 minutes. This time period was long enough to assure temperature equilibrium, while minimizing the high temperature damage to the sensor.

Table 2. Thermal conductivity of 17 μm glass fiber at three packing densities.

Density	0.020 g/cm^3	0.043 g/cm^3	0.077 g/cm^3
Test 1	0.019	0.018	0.023
Test 2	0.018	0.018	0.024
Test 3	0.019	0.019	0.029
Test 4	0.018	0.020	0.024
Test 5	0.018	0.019	0.024
Average	0.0184	0.0188	0.0248

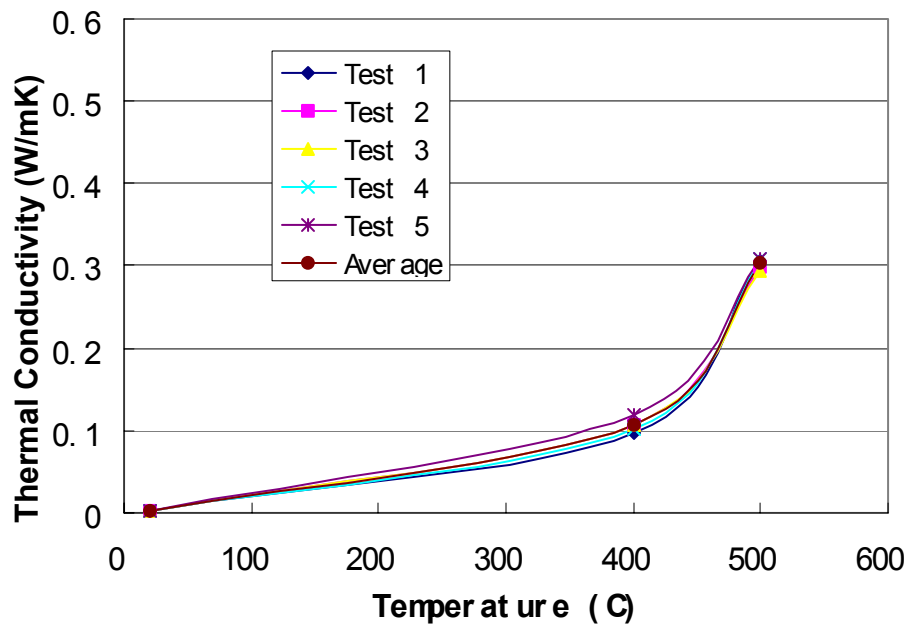


Figure 8. Thermal conductivity vs temperature plot of 17 μm glass fiber

A second round of tests were conducted using the 17 μm glass fiber. The total weight of the fiber was 248.5 g. With no weight added to the top the density was 0.015 g/cm^3 . When a ceramic plate was used the density became 0.027 g/cm^3 . Under these two conditions the thermal conductivity at room temperature is shown in Table 3. The ceramic plate was left inside the container for high temperature tests. As shown in Figure 9, thermal conductivity of the high packing density glass fiber increase faster than the low density one. The data scatter at high temperatures were limited by <60 minutes soaking time.

Table 3. Thermal conductivity of 17 μm glass fibers (test No.2)

Density	0.015 g/cm^3	0.027 g/cm^3
Test 1	0.019	0.020
Test 2	0.018	0.020
Test 3	0.020	0.021
Test 4	0.019	0.021
Test 5	0.019	0.020
Average	0.019	0.020

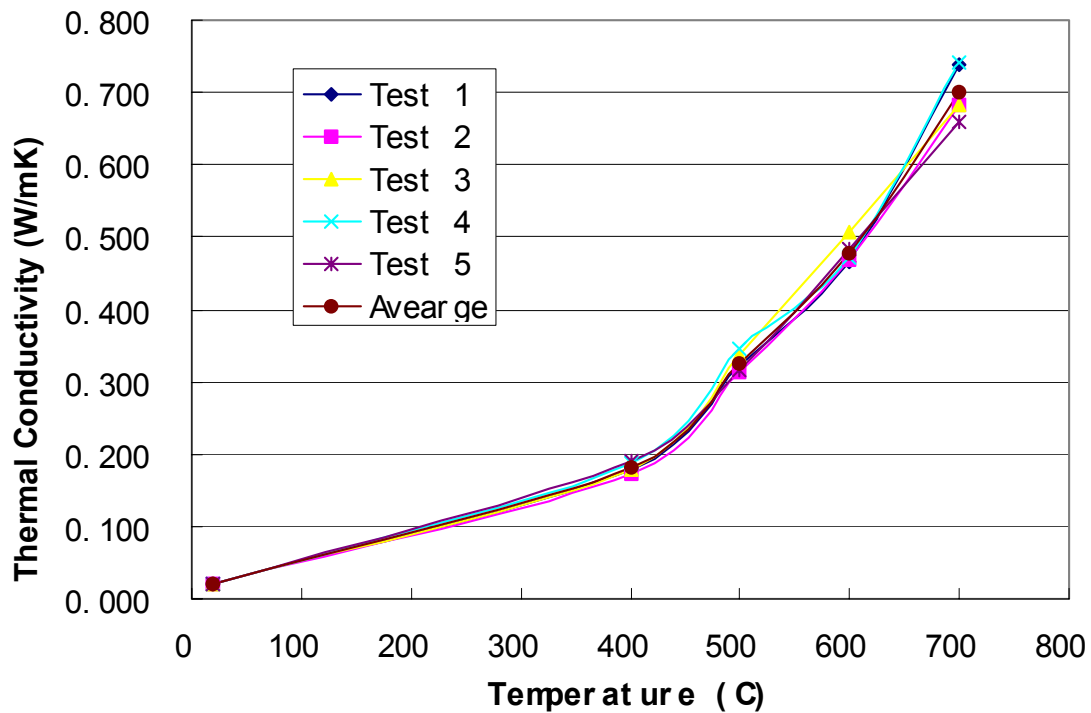


Figure 9. Thermal conductivity vs temperature plot of high-density 17 μm glass fibers.

Potential Problems with Hot Disk Technique

The Hot Disk technique assumes the materials being tested are homogeneous solids. In the case of fibreglass insulation, this assumption is not true. The data obtained from the Hot Disk method need to be verified by other techniques. We chose the Heat Flow Meter system at ORNL. This system is dedicated to thermal conductivity measurements of thermal insulations and a large amount of insulation can be measured. We tested the 24 μm fibreglass.

Testing Using Heat Flow Meter

Thermal conductivity measurements were performed on Owens-Corning's muffler insulation using a heat flow meter apparatus (ASTM C 518). The apparatus has plates that are two feet square, with an 8 inch square heat flow meter in each plate. About 4.5 pounds of the insulation were loaded into the apparatus, and measurements were made at thickness of 4.0, 2.0, and 1.39 inches (the last being the smallest thickness that the apparatus could achieve with this specimen). Measurements were made over mean temperatures from 40°F to 120°F using a temperature difference of 40°F between plates. The results are given in Table 4, in the order in which the measurements were made. No hysteresis was observed during the cooling and heating cycle. The conversion of thermal conductivity unit in Table 4 is $\text{Btu in./h ft}^2\text{°F} = 0.1442 \text{ W/mK}$. The English unit was not converted in all the plots because this is the standard used in the thermal insulation industry.

Figure 10 shows the thermal conductivity versus mean temperature for the runs at the three densities converted into SI unit. Note that we could not easily isolate the metered area, so the densities reported are the overall average densities of the specimen. These thermal conductivities are generally in line with expectations for fiberglass insulation materials. Note the thermal conductivity values are significantly higher than the values shown in Table 1. We believe the sample volume made a big difference in these two techniques. Although we used the largest sensor available to the Hot Disk system, the sampling volume was still small. Moreover, the fibers in contact with the Hot Disk sensor were not homogeneous. All these factors could not be taken into account during calculation. Since most of the temperature rise was at the Hot Disk sensor/fiber interface, the local effective density could be higher than the entire volume.

Figure 11 shows the thermal conductivity versus density at room temperature. The curve through the data is a least squares fit to the form:

$$k = 0.179 + b\rho + c/\rho \quad (2)$$

The first term is the thermal conductivity of still air at 75°F, the second term represents solid conduction through the glass fibers, and the third term represents radiation. The "b" coefficient is 0.00405, which is very reasonable based on experience with other types of fiberglass insulation.

Figure 12 shows the radiative contribution to the thermal conductivity calculated by subtracting the thermal conductivity of air and the solid conduction term from the total conductivity. The thermal conductivity of air over this temperature range is given by $k = 0.179 + 0.0002933*(T-75)$. A power law fit gives a nearly T^3 variation for the radiative contribution. This is the variation that would be expected for a gray medium (note, for normal fiberglass building insulation, we have observed variations that are more like $T^{3.5}$ due to non-gray characteristics).

Putting this together gives a model for the thermal conductivity as:

$$k = k_{\text{air}} + 0.04\rho + (4\sigma T^3 L) / (0.75\alpha\rho L + 2/\varepsilon - 1) \quad (3)$$

where k = thermal conductivity, Btu in./h ft²°F

k_{air} = thermal conductivity of still air, Btu in./h ft²°F

ρ = density, lb/ft³

σ = Stefan-Boltzmann constant, 1.714×10^{-9} Btu/hft²°R⁴

T = absolute temperature, °R

L = specimen thickness, in.

α = opacity, ft³/lb in.

ε = emissivity of boundary surfaces

We should note that Equations 2 and 3 look different, but they are equivalent for the way the tests were conducted. The tests were conducted by compacting a given amount of insulation, so that the quantity ρL (and hence the denominator) in Equation 3 is a constant. Because of this, the last term in Equation 3 is proportional to L , or equivalently, to $1/\rho$ as in Equation 2. Equation 3 assumes that the thermal conductivity of glass and the opacity are independent of temperature.

Using an emissivity of 0.9 and the four thermal conductivity values from Figure 11 at 75°F gives opacities that are very consistent at 3.08 to 3.20 ft³/lbin., with an average of 3.1 ft³/lbin. (Note, fiberglass batt building insulation has opacities that are around 20 ft³/lbin., no doubt mostly because of the finer fiber diameter).

Equation 3 can be used to estimate the thermal conductivity at higher temperatures for a range of densities and specimen thickness. Figure 13 shows calculated curves for three densities at a thickness of 4 inches. The thermal conductivity of air was calculated from a more accurate equation than the linear relationship given above for temperatures near room temperature. Note that Figure 13 uses good physics, but extrapolates well beyond the range of data, and is intended only for a check against high temperature data obtained using the hot disk method. In particular, as noted above, the solid conductivity term and the opacity are assumed to be independent of temperature. The calculated value at 500° C is similar to the Hot Disk result at the same temperature. However, the Hot Disk system did not show the same sensitivity as the Heat Flow Meter. To use the Hot Disk results in insulation materials, similar calibrations are needed. At the present time the Hot Disk system, although it can reach high temperatures, does not have calibrated data to back the accuracy of the measurements.

Table 4. Thermal Conductivity of Owens-Corning Muffler Insulation

Temperature, ° F	Thermal Conductivity, Btu in./h ft ² °F			
	Run 1	Run 3	Run 4	Run 5
75	0.321	0.317	0.271	0.262
40	-	0.284	0.249	0.243
50	-	0.293	0.255	0.248
60	-	0.303	0.261	0.254
75	-	0.317	0.270	0.262
90	-	0.332	0.280	0.270
105	-	0.347	0.290	0.278
120	-	0.363	0.299	0.286
75	-	0.318	0.271	0.262

Note: Run 1: L = 4.000 in., $\rho = 3.38 \text{ lb/ft}^3$
 Run 2 was aborted
 Run 3: L = 4.000 in., $\rho = 3.38 \text{ lb/ft}^3$
 Run 4: L = 2.002 in., $\rho = 6.76 \text{ lb/ft}^3$
 Run 5: L = 1.388 in., $\rho = 9.75 \text{ lb/ft}^3$

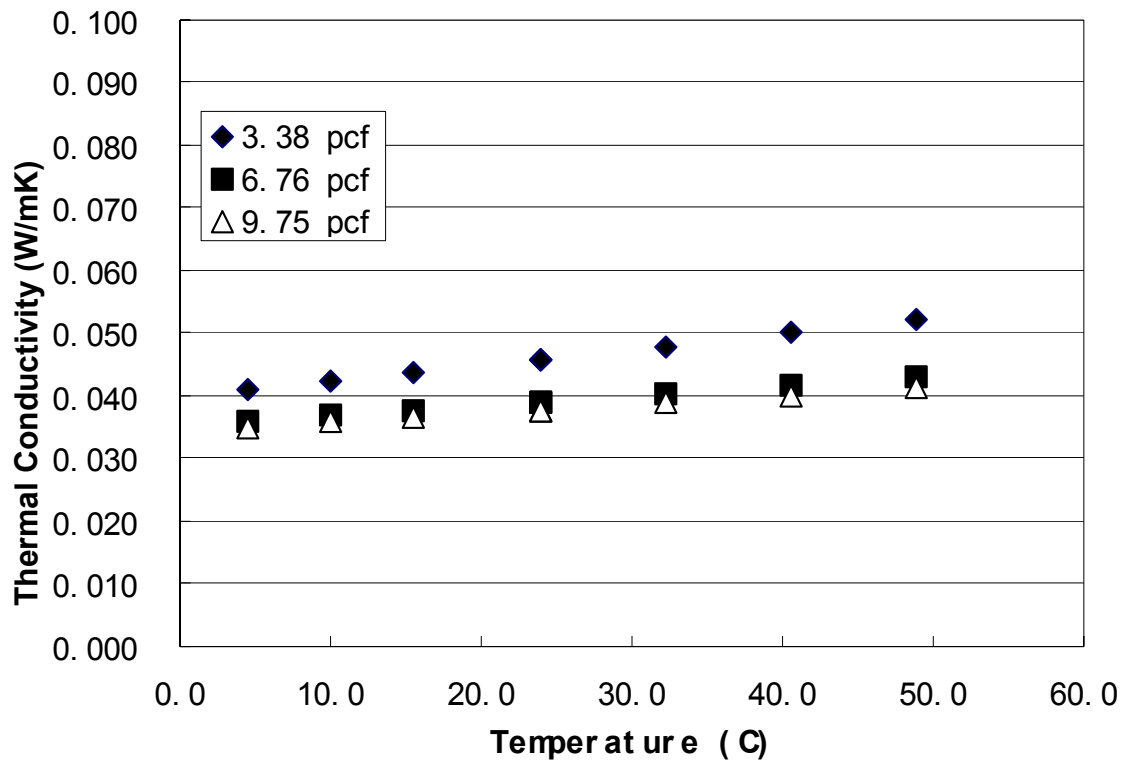


Figure 10. Thermal conductivity of 24 μm fibers from RT to 50 C.

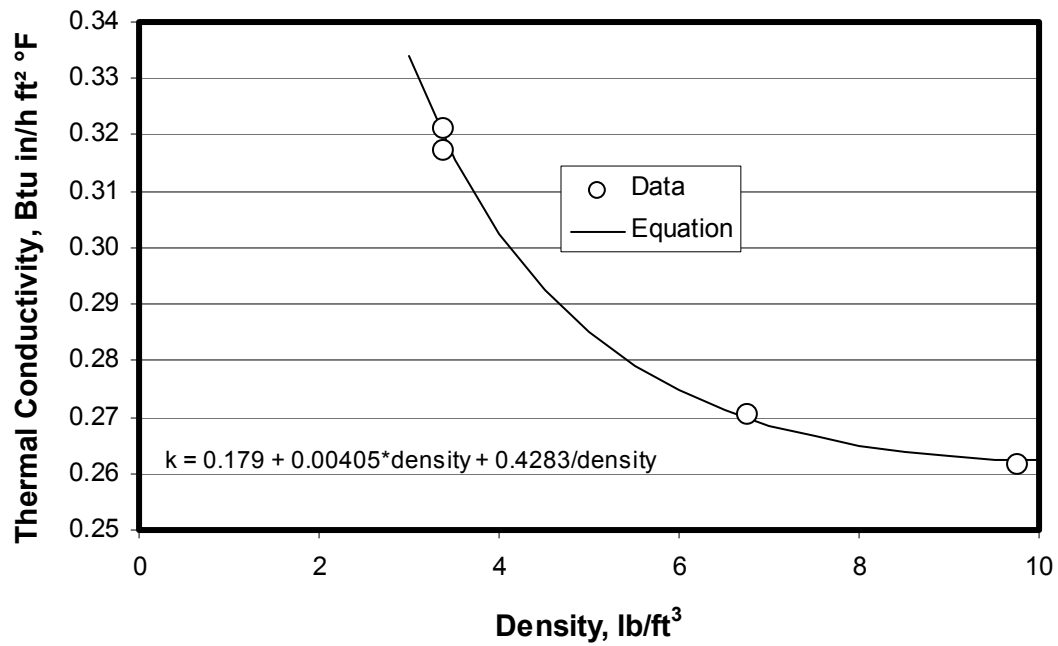


Figure 11. Thermal conductivity as a function of density. 1 Btu in./h ft²°F = 0.1442 W/mK

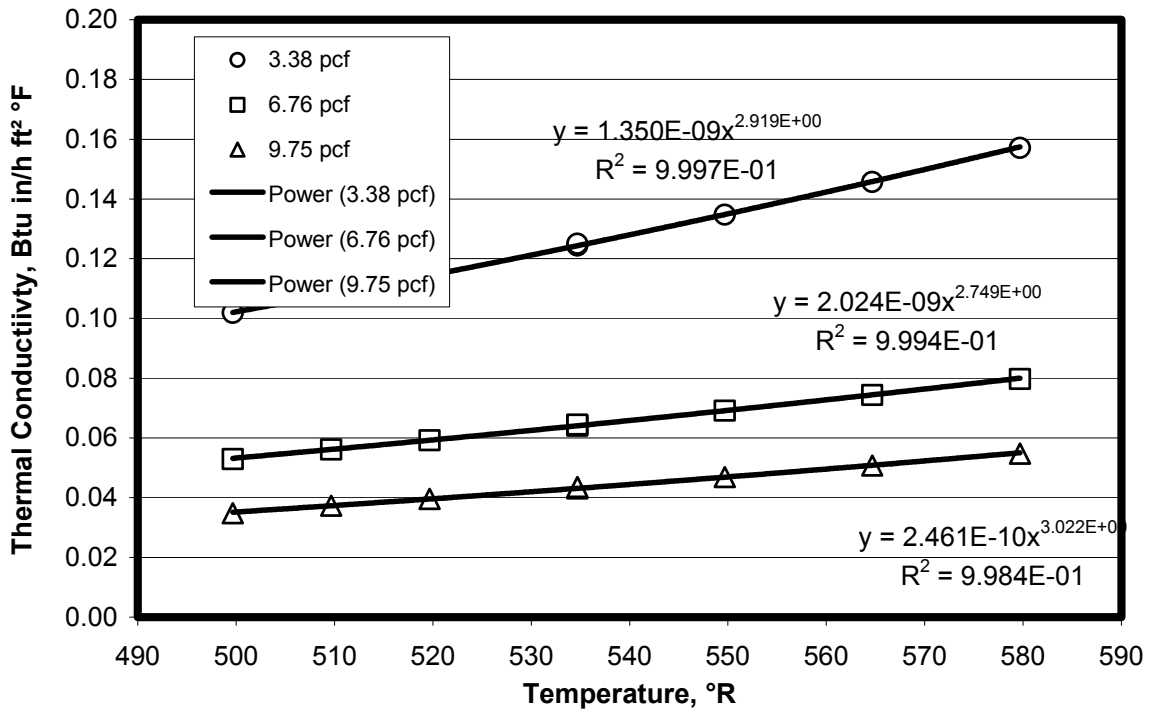


Figure 12. Radiative contribution to thermal conductivity. ($^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$),
 $1 \text{ Btu in./h ft}^2\text{ }^{\circ}\text{F} = 0.1442 \text{ W/mK}$

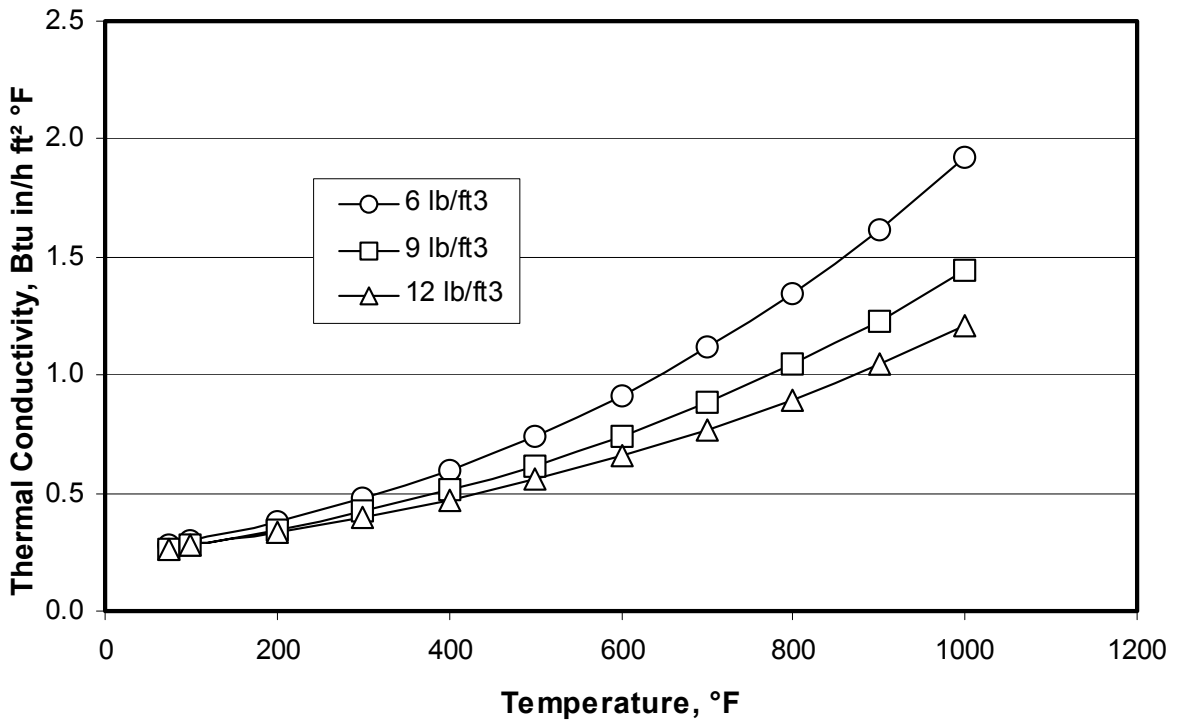


Figure 13. Calculated thermal conductivity. $1 \text{ Btu in./h ft}^2\text{ }^{\circ}\text{F} = 0.1442 \text{ W/mK}$

Summary:

Thermal conductivity of Owens Corning glass fibers were tested from room temperature to 700° C using the Hot Disk system. The general trend shows a significant increase of thermal conductivity as a function of temperature. This effect is mainly due to radiation contribution. At room temperature the effect of increased packing density only showed small a effect on the thermal conductivity. A more sensitive Heat Flow Meter system was used to measure thermal conductivities at lower temperatures. The results showed a lowering of thermal conductivity with increasing densities. The low temperature data fits and physical laws were used to extrapolate and estimate the high temperature thermal conductivity. The results showed that the Hot Disk technique needs more calibration to be used reliably for measurements of thermal insulations.

Acknowledgement:

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