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Measurements and Analysis of Thermal Conductivity of Insulating Material

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ABSTRACT

Thermal insulation is one of the major requirements for various aero space components in different aero structure. Ceramic materials having low thermal conductivity are pervasive as a thermal insulation for elevated temperature environment. In our project an experimental study has been carried out for evaluation of thermal conductivity of ceramic materials (Alumina and ceramic based porous insulating materials) from room temperature to 1100°C using hot wire thermal conductivity measurement equipment. A correlation has been developed for effect of temperature on thermal conductivity of above two materials. Thermal conductivity increases with increasing temperature for both ceramic and ceramic based porous insulating materials (CBPIM). Evaluation of thermal conductivity value at elevated temperatures defines the use of these materials for various aerospace/industrial applications as a thermal barrier.

A ceramic may be defined as a product manufactured by the mixture of inorganic and non- metallic materials under controlled environment of temperature and pressure. Ceramic materials are brittle, hard, strong in compression, weak in shearing and tension. An important type of ceramic product is those known as refractories, used because of their ability to withstand high temperatures without loosening its strength significantly. Ceramic products can be divided into those at normal temperatures and those used at high temperatures. Ceramic materials are well suited for thermal insulation due to their low thermal conductivity at room temperature as well as elevated temperatures. The measurement of thermal conductivity of ceramic materials at room temperature and elevated temperatures is essential to be used as a thermal insulation barrier for different structural application.

This study can also contributes in study of heat dissipation factor as it includes one of important areas of the development of light weight housing for various electronics components/chips in airborne/ground platforms.

Thermal insulation properties depend upon several factors. The most prominent of which include thermal conductivity, surface emissivity, insulation thickness, density and specific heat capacity. In our project , measurement of thermal conductivity of Alumina(Porous- standard reference sample supplied by M/S Anter corporation, USA) and ceramic based porous insulating materials (CBPIM) has been carried out in the temperature range of 50°C to 1100°C on M/S Anter Unitherm model 3141 apparatus(Hot Wire Thermal* Conductivity *Measuring System) as per ASTM C-1113. Effect of increasing temperature on thermal conductivity of Alumina and (CBPIM) has been analyzed.

INTRODUCTION:

Energy conservation is becoming increasingly important, and as a consequence, the enhancement of the thermal efficiency of industrial furnaces used in the production of steel and in other industries is becoming essential. Heat loss through furnace walls can be effectively reduced by lowering the thermal conductivity of the refractoriness and the heat insulating materials used for lining the inside of the furnaces.

While there has been an increased awareness of the importance of accurately calculating the thermal conductivity of refractory and heat-insulating materials for furnace design, these values fluctuate considerably depending on the method and the measurement conditions.1–4) In this regard, the method of stationary heat flow and the hot wire method have been used for determining the thermal conductivity of heat-insulating bricks under JIS R 2616.

However, the Standardization Committee of the Technical Association of refractories, Japan, has promoted the expansion of the application of these methods to more heat-conductive refractory materials, such as oxide systems. As a result, in 2007 the hot wire method was defined in the JIS system (R2251-1) as a method for measuring the thermal conductivity of refractories in the range of 10W/mK and lower.

In performing measurements with the hot wire method, there are certain assumptions in using the theoretical equations related to the process of calculating the relevant thermal conductivity. One of the assumptions is that the specimen size is regarded as infinite during the measurement.

This suggests that it is necessary to finish the measurements before the heat flow from the hot wire reaches the outer surfaces of the specimen. The time required for the heat flow to reach the specimen surface depends on the thermal diffusivity, the specific heat capacity and the thermal conductivity of the material, where the specimen size is of particular importance in the application of the hot wire method to materials with high thermal conductivity.

Aiming at expanding the field use of the hot wire method for determining the thermal conductivity of not only heat-insulating bricks, but also other types of refractory materials, Haupin reported that materials with higher conductivity require proportionally larger specimens. Hayashi studied and defined the minimum specimen size required for accurately determining the value of the thermal conductivity.

Moreover, according to Van der Held and VanDrunen, materials with higher conductivity require proportionally larger specimens. They point out that thermal diffusivity affects the shape of the curve in plotting the temperature against the log of the time. More specifically, the first part of the plot is curved and gradually becomes linear with time until the size of the specimen becomes a factor, which is the point where the relation ceases to be linear again. Hence, they limited the analysis to the linear portion of the plot and obtained an equation for the thermal conductivity.

Another necessary condition for measuring the thermal conductivity with the hot wire method is that the temperature of the specimen should be uniform in the material and should be maintained at a predefined level.

Although this is possible when the heating furnace used for the measurement is sufficiently larger than the specimen, if, for example, two conventional bricks as specified in JIS R 2101 are used to form a specimen set, a very large furnace will be required. Otherwise, if a small furnace is used, a sophisticated temperature control system will be required to maintain a uniform temperature in the furnace, and the heating equipment will likely be complex and expensive.

Experimental Work: In this experimental study, Alumina (Porous) and ceramic based porous insulating materials (CBPIM) has been taken as a material for evaluation of thermal conductivity in the temperature range of 50°C to 1100°C. Both these materials have been selected in brick form (Two samples of each material of size 230mm x 115mm x 80mm).
The composition of CBPIM is as follows:
Amorphous Silica: 78%
Alumina: 11%
Metal Oxides (TiO_2, Al_2O_3, ZrO_2) & Glass Filaments: 4%
Binder: 2%
Density: 0.35 gm/cc, Porosity: 85%
CBPIM is in micro-porous structure to minimize the transmission of heat over a large temperature range.

APPARATUS USED:
Anter 3141 computerized Hot Wire Thermal Conductivity Measuring system. This is based on ASTM C-1113. The hot wire method is a standard transient dynamic techniques based on the measurement of the temperature rise in a defined distance from a linear heat source (hot wire) embedded in the test material. The procedure is employed to determine the thermal conductivity of non – carboneous, dielectric refractory materials. It uses a platinum alloy wire as the hot wire , with two small platinum alloy voltage taps welded to the hot wire : these measures the voltage during a test . This wire system is called harness assembly. The furnace of the apparatus consist of an insulated cavity with six numbers of bar heating elements that surround the sample area. The rate at which the wire heats up after power is applied to it depends upon the ability of the sample material to conduct the heat away. The temperature of the wire is determined from its resistance and known temperature coefficient.

TEST PROCEDURE:
Two sample (Each of size230mm×115mm×80mm) of same material are used for evaluation of thermal conductivity. There is one groove created centrally along the length of the lower sample having the size of 0.09mm wide and 0.08mm depth to inert the hot wire and to avoid the floating of the wire in the groove. After insertion of the hot wire in the groove made on lower sample, powder of sample's has to be pored over the wire in the groove in such a way to fill groove completely and in this manner the heat conduction will not be affected. Second sample is placed on the top of lower sample making exact face to face contact and care being taken to ensure the placing of hot wire in the groove. Once this is

seated properly, check the voltage taps wires not to be in contact with the heating elements. Ensure the upper sample is firmly seated and does not "rock" on the wire. Now the samples are loaded and ready to begin testing.

TESTING PARAMETERS as per ASTM C-1113 are given as:
- 9.0 Hours of dwell at each set point before the testing is conducted.
- 1.5 Hours of dwell between tests at each set point.
- 3 test conducted at each set point.

Programming as per above testing parameters has been carried out on the apparatus window based window software for alumina(porous) and ceramic based porous insulating materials (CBPIM) sample separately. Thermal conductivity of Alumina and PIM were evaluated at 50°C, 100°C, 200°C, 400°C, 600°C, 800°C, 1000°C and 1100°C. Effect of increasing temperature on thermal conductivity of Alumina and CBPIM has been analyzed.

Sample analysis after exposure from ambient to 1100^{O}C
- Weight loss - ve 3% (approx)
- Density + ve 33% (approx.)
- Shrinkage in dimension - ve 10 to 11% (approx.)

UNITHERM™ MODEL 3141 THERMAL CONDUCTIVITY MEASURING SYSTEM

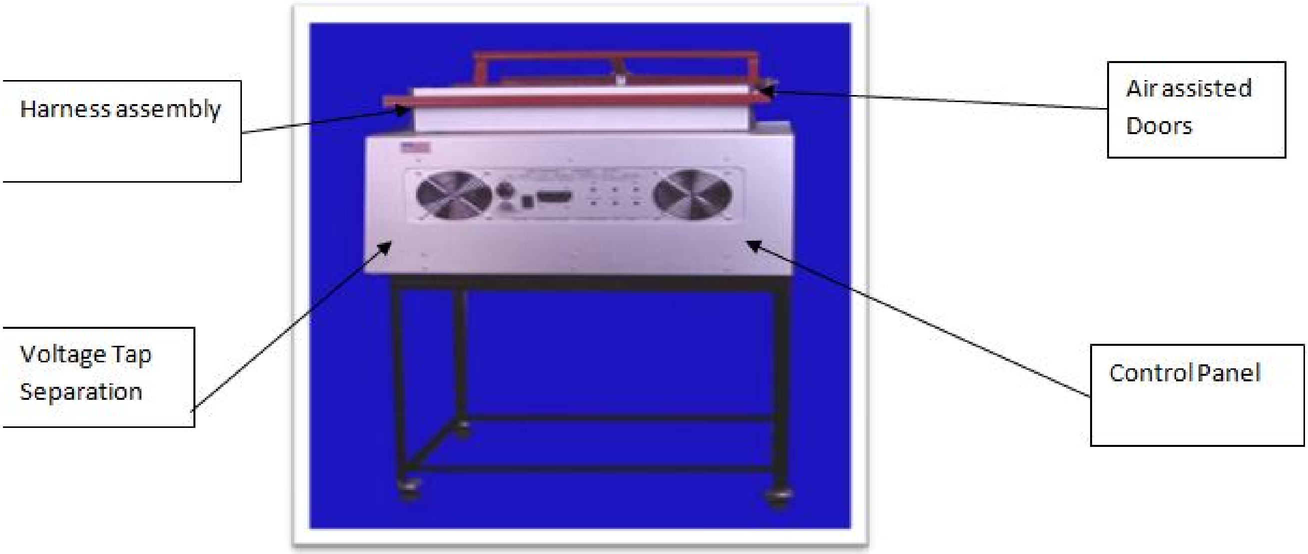

Figure 1: Unitherm Model 3141 Thermal Conductivity Measuring System

A line source, in this case a very fine platinum alloy wire, is embedded in one face of the bottom sample block and covered another block of the same size and identical material. The rate at with which this wire heats up after power is applied to it depends on the ability of the surrounding material to conduct the heat away. The temperature of the wire is determined from its resistance and known temperature coefficient. An additional thermocouple is used for verification. The Unitherm^{TM} Model 3141 is produced with several refinements, such as independent temperature verification (reducing the resistance thermometry to a differential measurement), and fully automated temperature cycling with multiple test sequences at selected temperatures, among others. The physical execution of the device has taken into consideration the ease of operation, economy with precious metal wire, and a high rate of testing. To allow improved time economy, the device is available with multiple furnaces, so one furnace may be heating while another is cooling or several samples may be tested in parallel. Sample preparation and loading, has been greatly simplified. It is recommended under Ambient to 1400°C or 1500°C conditions. It has the following features:
- Fully-automated Windows^{TM} - based operation and data analysis.
- Hot-wire method (ASTM C1113 & ISO 8894*) can be tested.
- Easy loading furnace with accurate uniform heating.
- Air assisted doors opens and closes automatically.
- Ideal for refractories and insulators

UNITHERM^{TM} Model 3141 Thermal Conductivity Measuring System uses a time-proven hot-wire method to determine the thermal conductivity of mod- erate to low conductivity dielectric* materials, such as fibrous panel insulators, fire bricks, etc. The size and shape of the sample is historically that of a standard fire brick with an equal companion piece used for thermal symmetry. A powder testing container is also available.

The hot-wire method is an absolute one in that it does not require a known material for reference. The specimen, shaped as a rectangular slab, is placed in the center of a uniformly heated furnace. A central line-source heater is placed in the axis of the sample.

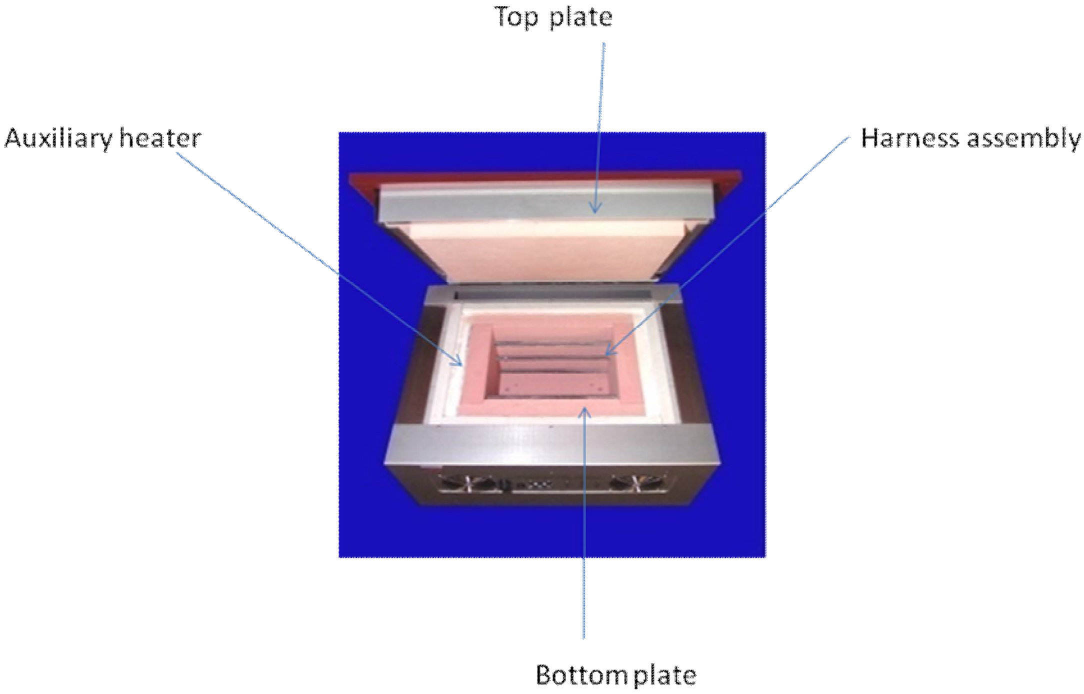

Figure 2: Furnace with uniform heating Air assisted door opens and closes automatically

OPERATION is fully automated, including the highly complex data analysis process that has made this method very difficult to use in the past. All control routines and calculations are performed by a personal computer, utilizing Windows^{TM} software that requires absolutely no programming knowledge on the part of the operator. The results are provided in a variety of tables and charts selected by user.
The Unitherm^{TM} line of instruments features fully computerized systems and is designed to measure the various thermo physical properties of solids. All instruments in this family of devices employ a standard serial interface to the control computer, and multiple unit operation is standard.
An extensive tutorial is supplied with each instrument to allow self-teaching of the operation. On-line help screens are available in every phase of the program.

Results & Discussions: Thermal conductivity of Alumina (Porous) and CBPIM were measured at above mentioned temperatures by continuously running the apparatus for 96 hours duration. Since there was sudden jump in value of thermal conductivity of CBPIM was observed from 1000°C to 1100°C temperature, Fresh test were conducted at 1025°C, 1050°C and 1075°C temperature for CBPIM.

Thermal conductivity of Alumina (Porous) standard brick is 0.30 W/m°K at 50°C and it increases to value of 0.410 at 1100°C. This increase in thermal conductivity follows a polynomial fit of second order. There is no change in physical properties of Alumina (porous) brick observed after the test. The presence of porosity has the greatest effect in lowering the value of thermal conductivity of any solid. Pores primarily decrease the net section area through which heat can be transported by phonons and reduction in thermal conductivity depends on not only the volume fraction of the pores but also their spatial distribution.
Thermal conductivity of CBPIM is 0.018 W/m°K at 50°C and it increase almost linearly to the value of 0.065 W/m°K at 900°C. Above 900°C temperature, the increase in thermal conductivity of MTIM follows a second order growth and it increases to the value of 2.20 W/m°K at 1100°C. This increase in between 900 to 1100°C temperature is due to fusion of silica, which reduces the micro porosity of the material and hence in turn sharply increases the thermal conductivity.

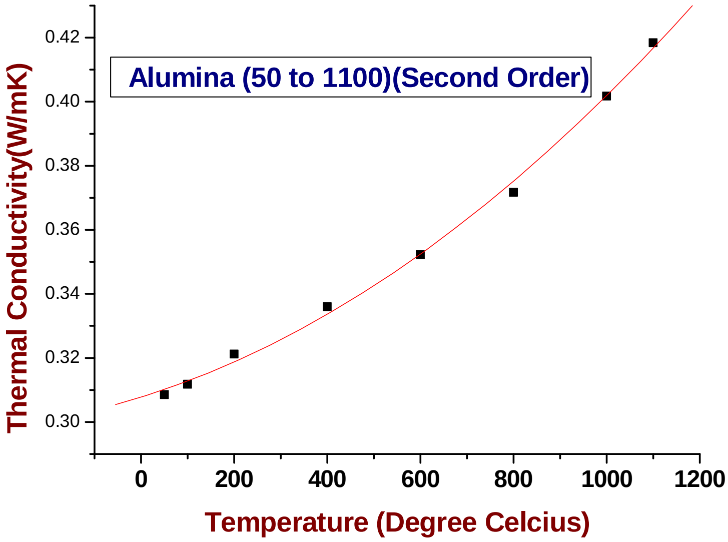

Figure:3 Thermal conductivity of Alumina porous - reference test sample

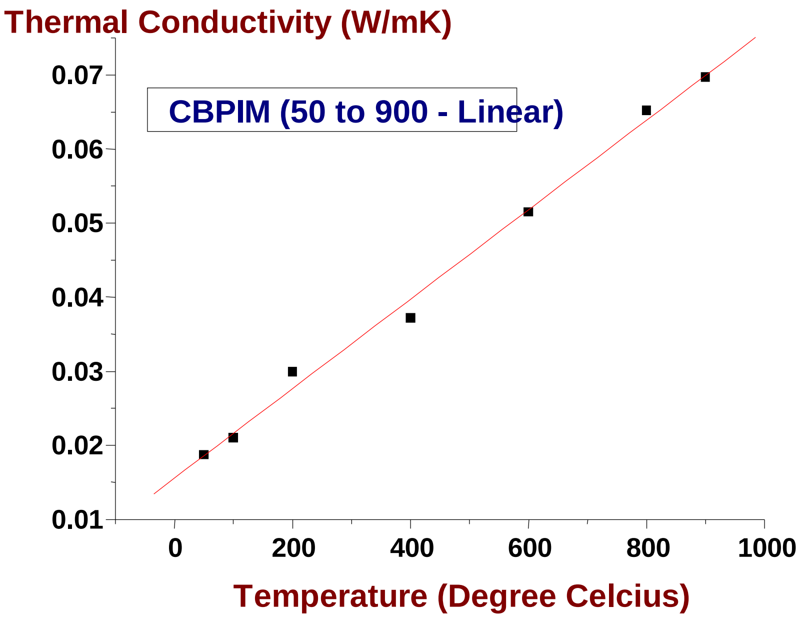

Figure 4: Thermal conductivity of CBPIM

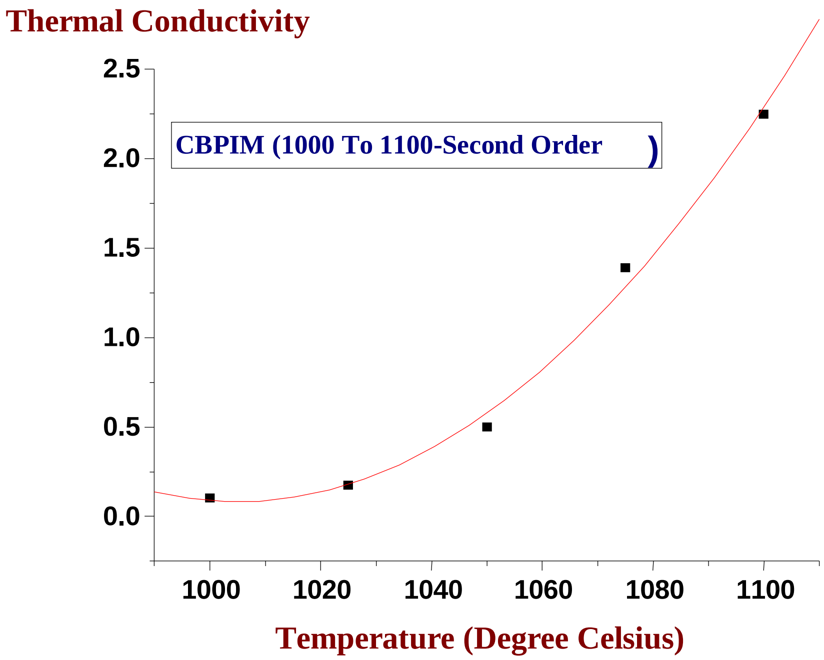

Figure 5: Thermal conductivity of CBPIM (1000° C to 1100°C-Second Order)

Applications: Alumina (porous) and CBPIM are used as thermal barrier for different applications which includes automotive exhaust heat shield, commercial fire protection, aerospace heat shielding, high temperature pipe insulation, refractory material in furnace, Boiler and high temperature furnace door lining, thermal insulation in industrial oven etc.

CONCLUSION

In this experimental study, it is clear that thermal insulation property of CBPIM is maintained up-to 900°C temperature because increase in thermal conductivity at this temperature is only to the value of 0.0697 W/m°K. From 900°C to 1100°C temperature, there is an increase of 3.125% in thermal conductivity value. Also the CBPIM loses its micro porous structure and weight. Hence it limits the use of CBPIM up to temperature of 900°C as a thermal insulating material. Also the change in thermal conductivity of CBPIM follows a linear behavior up to 900°C and after that it follows second order polynomial growth. For Alumina porous brick, the increase in thermal conductivity follows a second order growth and there is no change in the material up-to 1100°C temperature.

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