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Design and Development of IoT Based Apparatus for Measuring Thermal Conductivity of Insulating Slabs

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Abstract

Thermal conductivity is the amount of heat that can be passed through or conducted by any material. Evaluating the thermal conductivity of insulators is critical for many applications. The available thermal conductivity apparatuses are expensive, time-consuming, and tedious to operate. With the advent of nanotechnology, there is a tremendous increase in the research and development of new insulating materials to be used for various applications. So, there is an urgent need to develop a portable, simple, and cost-effective apparatus that can be used in research laboratories to measure the thermal conductivity of newly developed insulating materials. In this regard, a portable and cost-effective thermal conductivity apparatus has been indigenously developed in the laboratory. The apparatus has been used to measure the thermal conductivity of insulating slabs. The values obtained from the apparatus have been verified with known material and found to be in broad agreement with the value available in the literature. The results obtained have been deployed onto the cloud in real-time using the Internet of Things platform. A plot of the thermal conductivity of the insulating slab at different temperatures has been displayed in the cloud. It can be concluded that the developed apparatus can be used to measure the thermal conductivity of any insulating slab with reasonable accuracy. Furthermore, this apparatus gives the same accuracy for measuring the thermal conductivity of metals as long as their dimensions are known, such as metallic bars or slabs. The thermal conductivity of the metals is compared to the standard values and this can determine their purity and if composites such as nanomaterials have been added. It is very useful for the mining industry as well, to measure the thermal conductivity of metals and assess their purity.

Keywords: *Electrical Conductivity, Insulators, Thermal Conductivity, Protection, Apparatus, Iot, Metals, Mining*

1.0 Introduction

With recent advancements in nanotechnology, there is a phenomenal increase in research and development activities in material science[1,2]. This has led to a whole new set of nano-composites being developed and used[3,4]. These nanocomposites exhibit altogether different properties as compared to the base materials. To test the properties of these novel materials, there is a need to develop cost-effective, easy-to-use equipment at the laboratory level. Thermal Conductivity is one such property that needs continuous testing and improvement.

Thermal conductivity is the amount of heat that can be passed through or conducted by any material. In the case of insulators, the lower the thermal conductivity, the better the quality of the insulator. The thermal conductivity given by Fourier's law states that the rate at which heat is transferred through a material is proportional to the negative of the temperature gradient and is also proportional to the area through which the

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heat flows. It follows the equation: $q = -k.\nabla T$ (5) where ∇T refers to the temperature gradient, q denotes the thermal flux or heat flux, and k refers to the thermal conductivity of the sample under test[6,7]. Typical values of thermal conductivity for materials currently utilized in the thermal insulation industry for insulators such as rigid polyurethane foam, mineral wool, expanded polystyrene foam, and extruded polystyrene foam are in the range of 20-40 mW m^{-1} K^{-1} [8].

For measuring the thermal conductivity of insulating materials, researchers have used many methods in the past. The methods fall under two brackets – transient and steady-state[9]. The steady-state methods often take a long time and are tedious whereas the transient states are restricted to only certain dimensions of the materials and are not very accurate[5,6,9].

Insulators and composites are developed every day in research laboratories. The insulator and composite samples prepared in these laboratories are primarily in the form of powder or slab. Measuring the thermal conductivity of insulators is quite complicated more so in the case of insulating slabs. For insulating slabs, the temperature needs to be monitored and continuously recorded at different points on the slab. This requirement further complicates the process. So there is a need to have a sophisticated data acquisition system that can monitor temperature from different temperature sensors placed at different points on the slab and record it on a real-time basis.

In the present work, a simple, portable, and cost-effective thermal conductivity apparatus has been developed in the laboratory. The apparatus has been put in use to measure the thermal conductivity of available insulating slabs. The methodology used to develop the equipment is discussed in the next section.

2.0 Methods and Materials

The design and development of the equipment was carried out in two Phases. In the first phase, the electrical circuit design was carried out and the required components were procured. In the second phase, the mechanical design of the equipment was carried out using Fusion360 software and was then fabricated in the laboratory. The Design and development methodology are discussed in the subsequent sections.

2.1 Specification of Electronic Components Used

The following components were needed to develop the apparatus for measuring the thermal conductivity of insulator slabs:

2.1.1 Atmega 328-p Microcontroller Series

The Atmega 328-p microcontroller series is a single-chip microcontroller whose operating voltage varies from 1.8V-5V, depending on the type and application. It has 32 GPIO pins, a 10-bit A/D converter, and 3 timers and counters. It has serial and UART communication protocols to enable communication with other devices.
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2.1.2 ESP 8266 Wi-Fi Module

This is also known as Node-MCU, a Wi-fi module, with TCP/IP protocol to establish the connection between the device and the internet.

2.1.3 PZEM004-T Module

It is an energy meter that can be interfaced with any microcontroller to convert the AC power values into DC to be fed into the microcontroller. It uses a current transformer and can measure voltage up to 260V, with a power factor measuring range of 0-1 and an operating frequency 45-65Hz. It can measure the Voltage, Current, Power, Frequency, Energy, and Power Factors.

2.1.4 DS18B20 Digital Thermocouples

It is a digital temperature sensor that can measure temperatures from -55 to 125 degrees Celsius, with an accuracy of +/-5 degrees Celsius. Operating voltage 3.3V-5V.

2.1.5 Nichrome Wire 230V, 1000W

The nichrome wire is used to carry the current on the insulator slab producing heat. It has a diameter of 0.90 mm +/-0.025 mm and Resistance per meter: 1.71 Ohms (+/-20%) at 20 degrees Celsius.

2.2 Mechanical Construction

The insulator slab is set up on a stand as shown in Figure 1. The equipment designed is in broad agreement with ASTM C518 standard[10]. The product essentially consists of a box of dimensions 70cm x 40cm x 45 cm, mimicking a standard microwave. The sample is placed on the stand in the box and the band heater (wires of nichrome) are wound together in a very close manner throughout the material to conduct the heat that is passed through them via an electrical supply as shown in Figures 1 and 2. The wires are placed throughout the length of the material on the surface of the sample that is to be tested and the supply is provided from the line. The wires are placed on another insulating sheet which is placed on the surface of the insulator so that there is no degradation of the material in question through any breakdowns. The wires can be adjusted and insulation tape is also wrapped around the corners and the breadth of the material so that no heat is lost due to radiation[11]. The only heat that is measured is the heat due to conduction[12]. Figure 3 is a pictorial representation of the insulator slab to be tested on a stand that is placed inside the box.

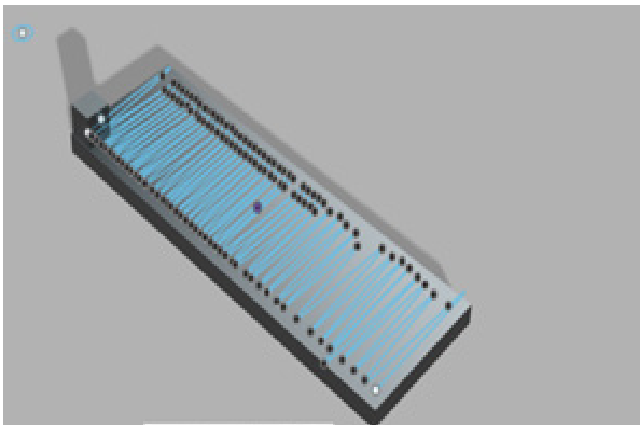

Figure 1. Image of insulator slab and placement of wire.

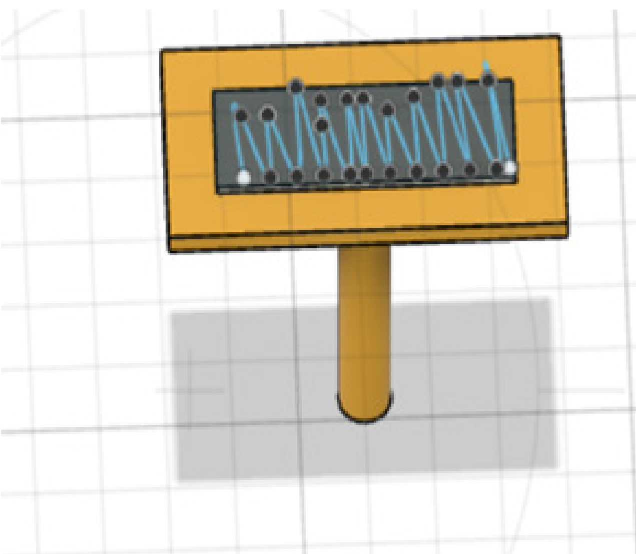

Figure 2. Placement of band heating wires on sample.

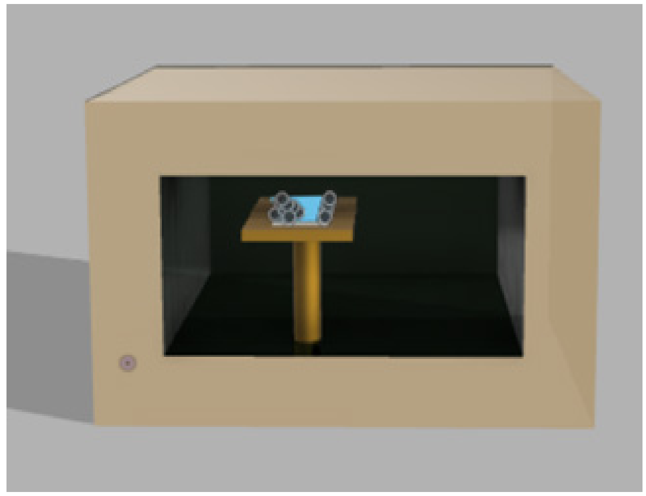

Figure 3. Image of insulator slab to be tested on a stand in the box.

Figure 4 indicates the flowchart representation of the methodology of implementation. The electronic apparatus consisting of a microcontroller, and PZEM module are soldered onto a printed circuit board. The entire electronic circuit is covered in the form of a box. Once the wires are placed, the temperature difference is measured using thermocouples, by placing them on the top surface (the hot surface) and the bottom (the lower surface, which is considered the cold surface). These temperature differences are measured by the microcontroller whose GPIO pins are connected to the thermocouples. ATmega328P microcontroller is used in the apparatus. Digital thermocouples are used to ensure ease in coding the microcontroller.

The readings are recorded and the supply is varied using autotransformers which generate different voltages as per the requirement and the thermal conductivity is calculated.

The method is quick and easy to implement and provides accurate readings. The ThingSpeak platform is used for IoT (Internet of Things) to store the data on the

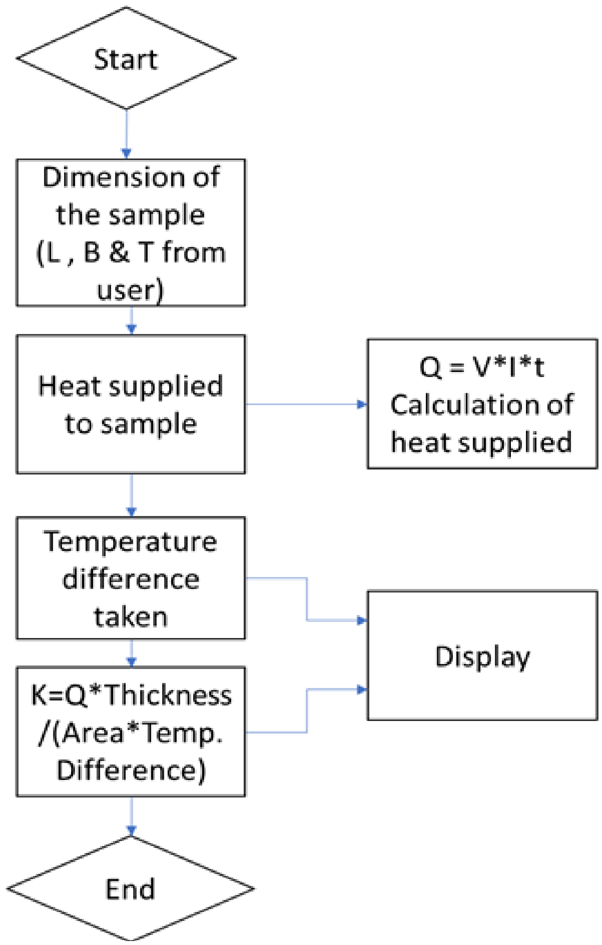

Figure 4. Flowchart indicating the methodology of implementation.

cloud and the user can view the data and plots from time to time as per the requirement.

The method is restricted only to slabs, as their dimensions must be known for calculation purposes. The dimensions were calculated using vernier calipers and measurements can be taken accordingly. The essential principle is that the heat generated due to electricity is recorded as voltage magnitudes by the microcontroller and the thermal conductivity values are calculated using the formula:

Q= K*A*dT/dx (1)

Where Q is the heat generated, K is the thermal conductivity,

A is the Area of the insulating slab

X is the thickness of the material and dT is the temperature difference between the cold and hot surface.

The metallic wire gets heated on the application of voltage and causes a rise in thermal current. When the current is set up, heat is generated as well, leading to a difference in temperature between the upper and the lower surface. The thermocouples are used to measure the temperatures at the top and the bottom. The temperature difference is recorded. The heat developed is taken as

V*I*t (2)

Where,

V= voltage supplied

I= current developed

t= time taken to reach the steady state

These values are recorded from the PZEM module and the time taken is measured using the microcontroller. After taking the values, for different temperatures, K (thermal conductivity) is plotted vs. temperatures, and the plot is obtained using IoT on an interactive dashboard. The protocol used in this case is HTTP to connect the hardware to the cloud. ThingSpeak also uses MATLAB for the analysis of waveforms and graphs and the graphs for each result have been plotted on ThingSpeak using MATLAB format.

3.0 Results

The thermal conductivity apparatus has been used to measure the thermal conductivity of silicon and ceramic slabs. The results have discussed the subsections.

3.1 Results for Silicon Rubber Slabs

Table 1 represents the results obtained for the thermal conductivity of Silicone rubber for temperatures varying

Table 1. Thermal conductivity vs temperature for silicone rubber slab of dimensions 15 x 15 x 0.6 cm

Thermal Conductivity (W/mK)	Temperature (Kelvin)
0.182	300
0.174	325
0.162	350
0.155	375
0.148	400
0.143	425
0.131	450

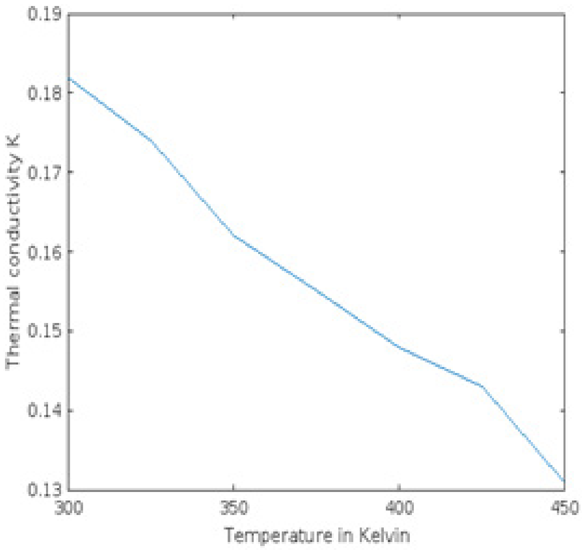

Figure 5. Thermal conductivity vs temperature plot on IoT dashboard.

from 300K to 450K. The thermal conductivity values were found to be 0.182 W/mK for 300 K while reducing to 0.131W/mK for 450 Kelvin. It can also be seen from Figure 5 that the thermal conductivity decreases with an increase in temperature.

3.2 Results for Ceramic Slab

Table 2 represents the results obtained for the thermal conductivity of Ceramic slab temperatures ranging from 300K to 450K. The thermal conductivity values were found to be 0.045 W/mK for 300 K while reducing

Table 2. Thermal conductivity vs temperature for a ceramic slab of dimensions 15 x 5 x 0.6 cm

Thermal Conductivity (W/mK)	Temperature (Kelvin)
0.045	300
0.043	325
0.041	350
0.038	375
0.034	400
0.031	425
0.028	450

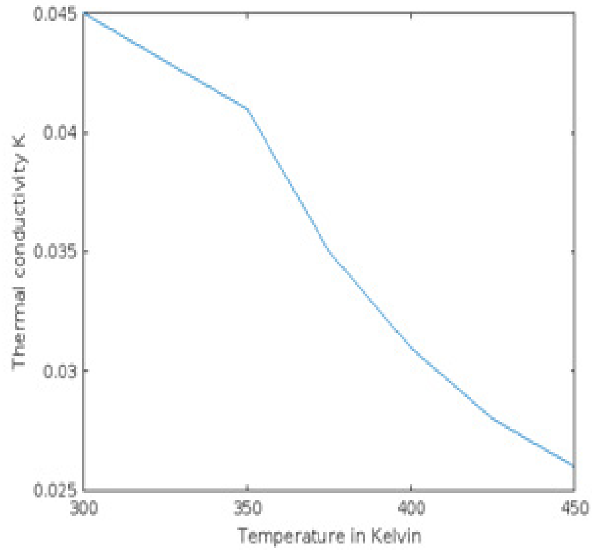

Figure 6. Temperature vs thermal conductivity plot for ceramic slab using IoT dashboard.

to 0.028W/mK for 450 Kelvin. It can also be seen from Figure 6 that the thermal conductivity decreases with an increase in temperature.

3.3 Result for a Ceramic Slab with Surface Irregularities and Cracks

Table 3 represents the results obtained for the thermal conductivity of the Ceramic slab with surface irregularities for temperatures ranging from 300K to 450K. The thermal conductivity values were found to be 0.049W/mK for

Table 3. Thermal conductivity for a ceramic slab of dimensions 15 x 5 x 0.75 cm with surface irregularities

Thermal Conductivity (W/mK)	Temperature (Kelvin)
0.0492	300
0.0521	325
0.056	350
0.067	375
0.078	400
0.082	425
0.088	450

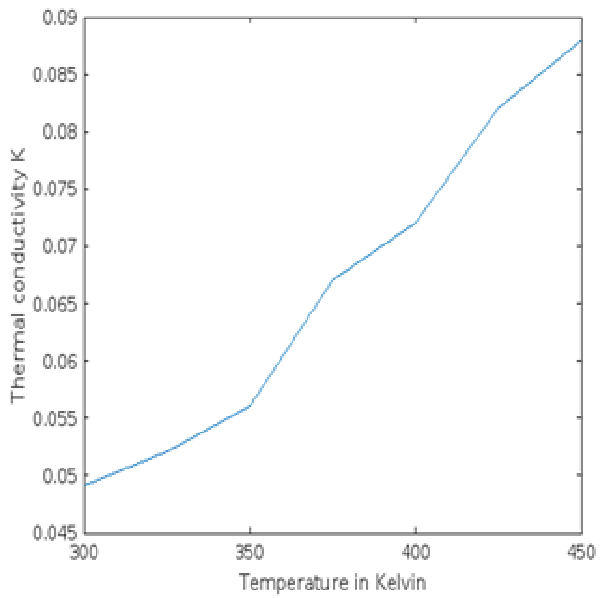

Figure 7. Temperature vs thermal conductivity plot for a ceramic slab with surface irregularities and cracks.

300K while reducing to 0.088W/mK for 450 Kelvin. It can also be seen from Figure 7 that the thermal conductivity decreases with an increase in temperature.

4.0 Discussions on the Results

The overall behavior of the thermal conductivity of the insulators tested concerning temperature is plotted and the temperature difference curves are plotted as well which highlights the accuracy of the evaluated values as well as the behavior. The use of IoT simplifies the need to aggregate data and analyze them separately and the data points are obtained as arrays which are plotted by ThingSpeak in conjunction with MATLAB. The thermal conductivity of the silicone rubber and ceramic slab without defects had values very similar to the expected values from the literature, of 0.18W/mK as compared to the expected was 0.2W/mK[13,14] and the behavior was linearly decreasing as expected. However, when faults such as surface irregularities and minute cracks were present on the faulty slab, the insulator mimicked a conductor, whose thermal conductivity increased with temperature. Hence, conclusions were drawn that the slab had lost its insulating properties, which lead to the error when compared to the expected value of 0.034 W/mK[14].

5.0 Conclusions

A portable thermal conductivity apparatus was developed and put into use to check the thermal conductivity of different materials. Provisions were made to continuously monitor the results and deploy it onto the cloud platform for data visualisation and analytics. The results obtained were compared with that of the values available in the literature. There are quite a few inferences that have been drawn both with regard to the performance of the equipment and the results obtained which are summarised below:

- The overall cost of the equipment is reduced significantly reduced while maintaining reasonable accuracy.
- The time taken for the measurement was quite less and more samples could be measured for the same amount of time.
- The average time for measurement of thermal conductivity per temperature reading was around 5 minutes.
- Accuracy was not compromised and different slabs with faults and erosions can also be measured for future analysis, to determine how surface irregularities and cracks, etc can affect the insulator properties.
- The error was approximately 2-5 % for normal insulators and the faulty insulator showed a deviation of 20% from its expected value.
- The behavior of conductivity in the insulator was such that it reduced linearly with an increase in temperature, which corresponded to an increase in temperature difference, as the cold surface temperature was taken to be room temperature (300K)
- Cracks and irregularities on the surface depicted a faulty nature of the insulator material, which resulted in more conductivity, as corroborated by other research as well.

It can be concluded that the developed apparatus can be used to measure the thermal conductivity of any insulating slab with reasonable accuracy.

In addition, the researchers related to mining industry and metallurgy can use the apparatus and obtain equal accuracy in the measurement of thermal conductivity. The presence of minerals can be assessed with the thermal conductivity of the metals and insulators that are measured by the said apparatus.

From the results and analysed research, even the presence of minerals can be assessed by comparing the measured values of thermal conductivity of a metallic bar or slab as there will be no chemical reaction aside from the generation of heat current, so conductivity of minerals can also be assessed which is extremely beneficial for the development of petrochemistry and mining industry.

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