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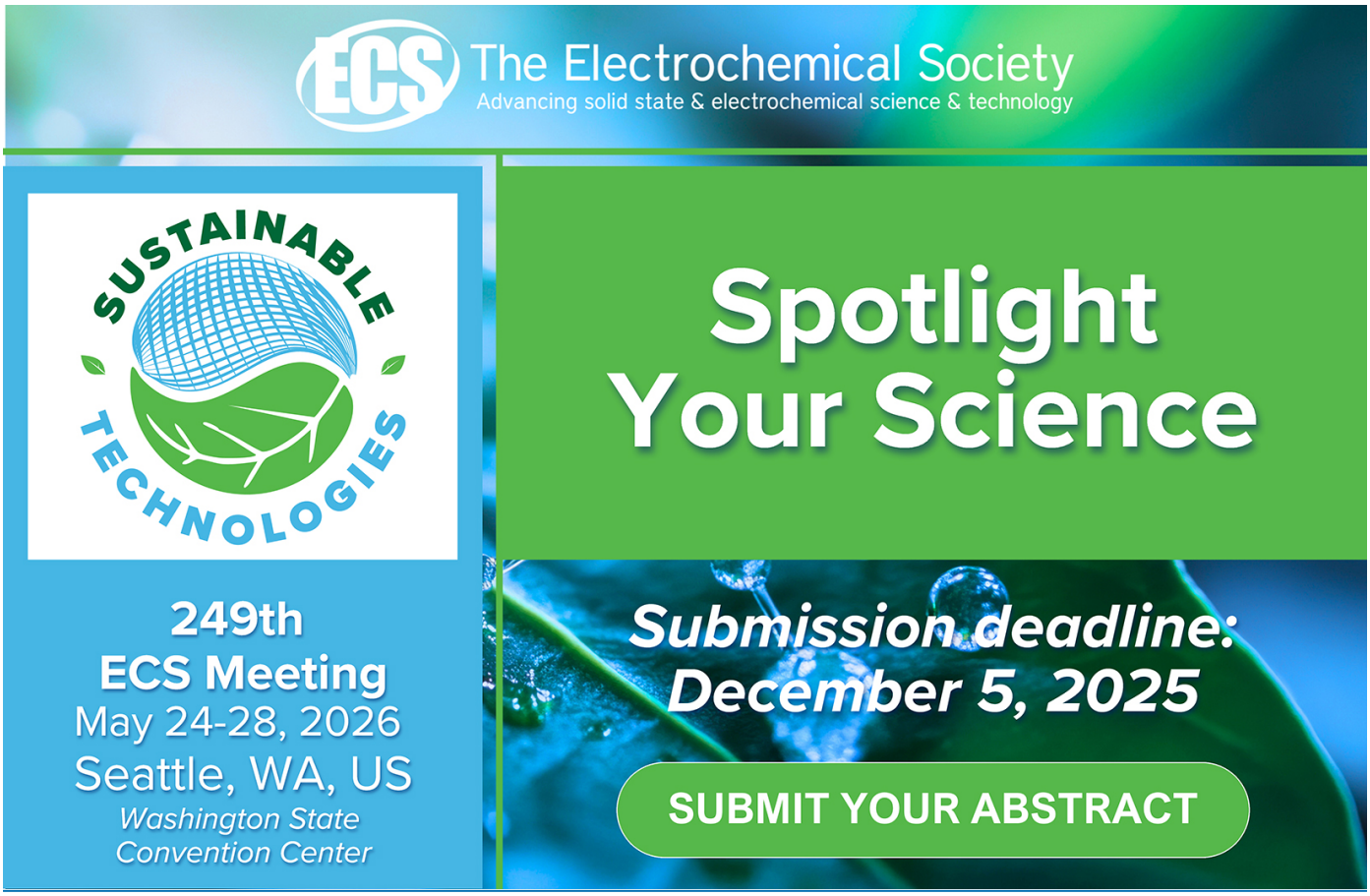
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Development of an automated system for the determination of thermal conductivity in granular materials

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Abstract. In many devices such as refrigerators, ovens, industrial kitchens, integrated circuits among others, where heat transfer is involved, it is important to know the thermal behavior of the material and the geometric model (cylindrical, spherical, etc.), with which such equipment will be built, to subsequently perform analysis of the parameters evaluated and thus enhance their efficiency. For this reason, it is important to know variables such as thermal conductivity, wall thickness, material, and geometry for new generation equipment. As a result, this work involved the construction of a test bench for the analysis of thermal conductivity in insulating materials, which began with the selection of the components that made up the device, such as resistors, types of thermocouples, specimen geometry, sensors, and finally, the construction of a data acquisition and analysis control system using Arduino and Labview. Subsequently, a device was obtained to measure the temperature in the cylindrical walls with different granular materials. This project was developed in an innovative way, where the thermal behavior of non-pure agglomerated granular materials will generate research in the study area, with the purpose of implementing it in different projects in which heat transfer is involved.

1. Introduction

The thermal conductivity (k) of materials is a physical property that can be determined by measuring the temperature gradient between two points on the same material. That is, it is the value that represents the physical magnitude related to the ability of a material for allowing the flow of heat (Q) [1]. When a thermal imbalance exists, energy flow is produced. This physical phenomenon is known as heat transfer, which cannot be directly observed. As a result, it is necessary to determine it from the observation of properties that can be measured, such as temperature (T) and k [2].

Among the main thermal properties of the materials are thermal conductivity, heat capacity, thermal diffusivity, and thermal effusivity. The heat transfer mechanism in a material is known as conduction, which is defined as the transfer of thermal energy from matter to adjacent matter by direct contact without mixing or transferring of matter [3]. Heat conduction is a physical phenomenon that depends on conductivity and is defined by the chemical composition and physical morphology of the material. For engineering applications, it is necessary to know the k of a material, to determine the viability regarding its use [4]. There are many materials that can be used for thermal insulation of houses [5]. Some applications specifically require avoiding heat transfer by conduction in the materials. In other words, the material must behave as a thermal insulator. For example, furnace walls,

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turbine casings, cooling systems, among others [6]. Likewise, some applications need to increase the efficiency of heat transfer through the material. For example, mechanical and electronic devices need to dissipate heat to avoid breakdowns or permanent damage [7]. During the design, the engineers need to know the properties of the materials that are available to be used. However, this information is in many cases, not supplied by the manufacturers [8].

The problem of not knowing the physical properties of materials before selecting them for engineering applications is a challenge that translates into manufacturing errors and repair costs [9]. A device that works based on physical principles to determine the k of materials, through the measurement of real magnitudes such as temperature, density and diameter or thickness of the material, becomes a tool to evaluate the feasibility of using a certain material according to its behavior as a heat sink or thermal insulator [10].

This work presents the design, construction, and setting up of an automated device for determining k in granular materials according to the physical and mathematical model for heat transmission in a cylinder. This model is frequently used because of its simplified implementation and effectiveness in the results obtained [11,12].

2. Methodology and materials

The methodology used makes it possible to verify the operation of the test bench. Figure 1 shows the methodology used according to the established requirements.

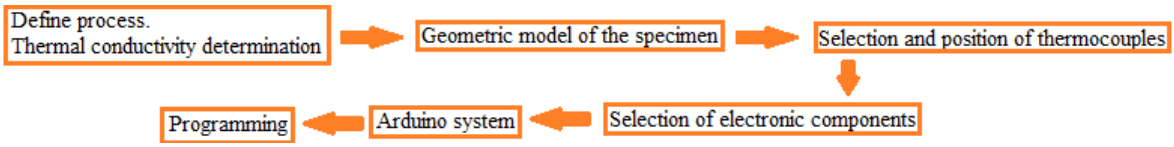


Figure 1. Proposed methodology, and operation of the test bench.

The thermal conductivity of the sample determines through the linear scheme is shown in Figure 2, where Fourier's law of heat conduction is applied in steady-state flow for plates. In the proposed model, the thermal conductivity was calculated by compacting the granular material in a test specimen. Then, a heat generator with an electrical resistance of 200 W was used to provide a controlled heat input. A relay system was used to allow controlling the turning on/off of the resistors. Also, thermocouples were used at a specific distance to determine temperatures T_1 and T_2, which are displayed on a liquid crystal display (LCD) screen. Using electronics, the voltage signals were converted into digital signals, and at the same time, the area $A = \pi r^2$ was determined for the cross-section of the tube in which the sample of the granular material is found. With these data, the thermal conductivity of the granular material of the sample is calculated with Equation (1) and then compared with the data in the books, correlating the conductivity [13].

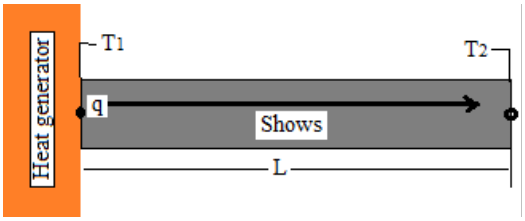


Figure 2. Basic schematic.

$$-k = \frac{q_x * L}{A(T_2 - T_1)} \quad (1)$$

Where k is the thermal conductivity coefficient, q is the heat flux, A is the normal area to heat flow, T2 y T1 are the temperatures measured at points 1 and 2, respectively.

The geometric model used for the study of heat transfer by conduction (Fourier's law), was the cylinder model, as a show in the Figure 3, for this point it was taken into account the description and the equation described for the model of Equation (2).

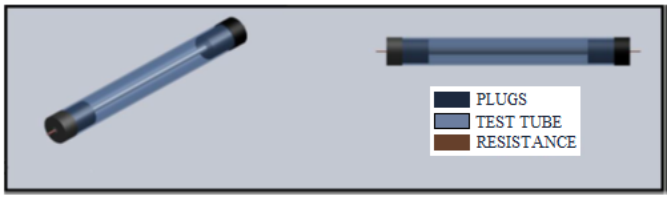


Figure 3. Geometric model.

This geometric model, as a show in the Figure 3 is used to determine the k, initially supplying a voltage to the resistor, which generates radial heat. Subsequently, the temperatures taken by the thermocouples can be observed in the sample of granular material, which is in contact with the resistor and casing of the tubular specimen. Then, applying the considerations and the infinite cylinder equation, as shown in Equation (3), the thermal conductivity k present in the sample is determined. Bearing in mind the relationship between voltage, current, and heat flow (Equation (2)) is obtained Equation (3).

$$Q = V * I \tag{2}$$

$$k = \frac{V * I * Ln\left(\frac{r_2}{r_1}\right)}{2 * \pi * l * (T_1 - T_2)} \tag{3}$$

The bayonet thermocouple (see Figure 4), is a type K thermocouple, which was adjusted to the requirements, with a bulb diameter of 4.8 mm and a length of 15 mm. It has an extensive cable covered in fiberglass and a correlation between temperature and voltage. To avoid the temperature variation that occurs axially, three sensors were used, and the results were averaged, guaranteeing a radial heat flow. The sensors were placed at points T2, T3, and T4, as a show in the Figure 5. The thermocouple measuring the temperature produced by the thermal resistor was placed in position T1.



Figure 4. Bayonet thermocouple.

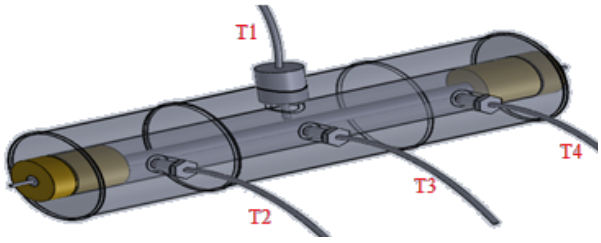


Figure 5. Location point of the thermocouples.

The following is a description of the components that make up the circuit for data acquisition in the Arduino system. LCD display system with I2C. The I2C LCD adapter module used is based on the I2C PCF8574 controller, which is a digital input/output expander controlled by I2C. This module is used specially to control an alphanumeric LCD.

An LCD was used as a display medium for recording the temperatures taken by the thermocouples in the specimen. In addition, it was used as a visualization of the voltage, current, thermal conductivity of the material used, and the setpoint, as shown in Figure 6. The temperature meter is the device that measures the output of the thermocouple type K and provides the result via an SPI interface. The

temperature measuring of the MAX6675 chip ranges from 0 ºC to 1024 ºC, with a supply voltage of 3.3 volts current continues (VDC) to 5.5 VDC, which facilitates the connection to the Arduino. The connection leads for this module are shown in the block diagram of Figure 7 [14].



Figure 6. Temperature meter.

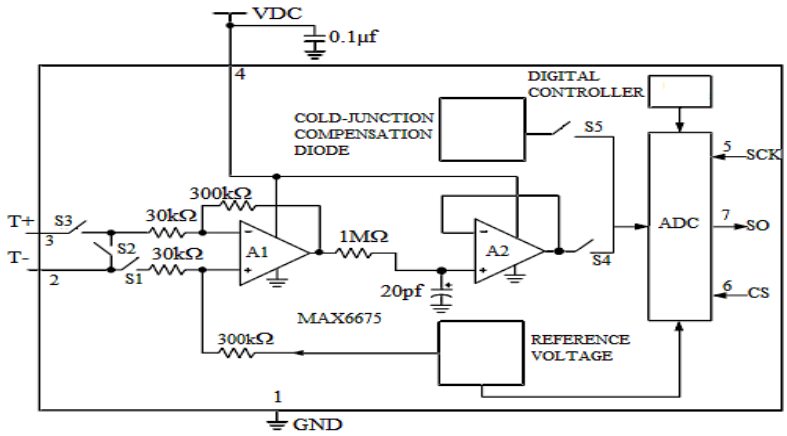


Figure 7. Temperature sensor block diagram. Adapted from [14].

The current sensor ACS712, which can be used with Arduino, monitoring the power consumed by the resistor. This module, based on Allegro MicroSystems' ACS712 integrated circuit, allows measuring the amount of current flowing through an alternating current (AC) or direct current (DC) circuit. The sensing method is through a Hall effect sensor that provides an output voltage proportional to the current flowing in the circuit. The path for the current measurement is inside the integrated circuit and is isolated from the processing circuit, as shown in Figure 8 [15].

Voltage sensor AC with analog output Zmpt101b of voltage transformer function and trimmer that adjust the offset is ideal to implement in any type of microcontroller, either, pic, Atmel, Motorola, Intel, Arduino, etc., as long as they incorporate ADC (analog input). A supply voltage of 3.3 VDC to 5 VDC is used, with the measuring range is between 50 VAC to 250 VAC. The 4000 W electric voltage regulator with bidirectional high-power thyristor support currents up to 40 A, 0 V – 220 V between arbitrary settings, which helps to control the voltage supplied to the resistor. The solid-state relay 25A SSR-25 is used in order to allow circulating current through the resistor, which in turn is controlled by the voltage regulator.

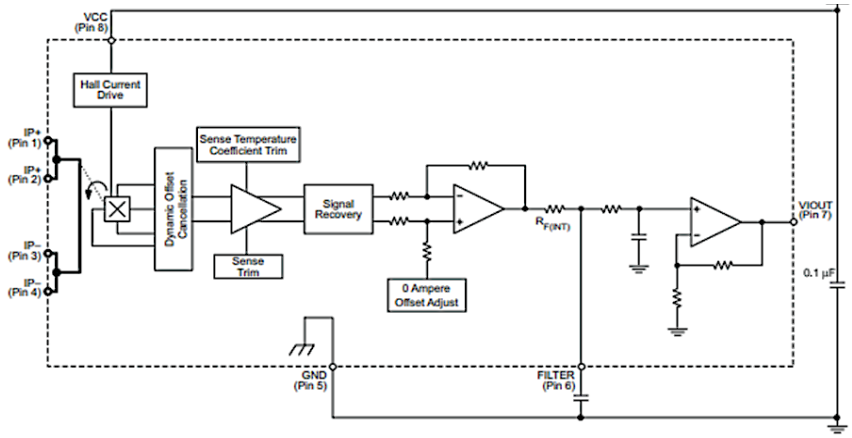


Figure 8. Block diagram current sensor. Adapted from [15].

Arduino system is an open-source electronics platform based on flexible, easy-to-use software and hardware for prototyping. It was created for artists, designers, hobbyists, and anyone interested in creating interactive environments or objects". This platform consists of hardware support formed by a

board that provides the power, the oscillator, and the program load in Atmel 8 bit series microcontrollers and software support formed by a development environment based on Wiring, which is an open framework for microcontroller programming; and a language called Processing, used for learning, making prototypes, and products, as a show in Figure 9. It also has its software that can be downloaded from its official website that already includes the drivers of all available cards making easier the loading of codes from the computer.

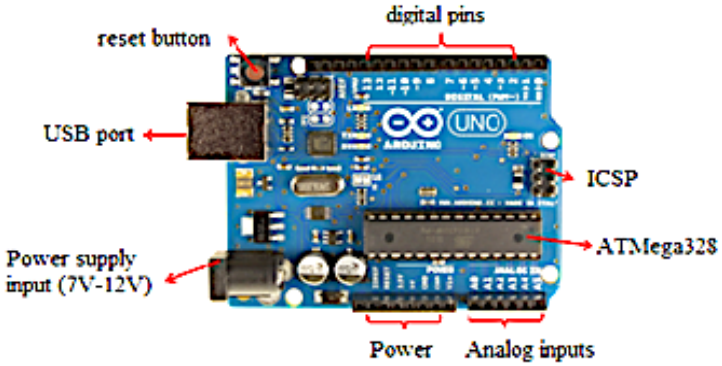


Figure 9. Arduino board.

Arduino programming is performed, with free libraries that are compiled and installed on the Arduino card, with the necessary adjustments listed as follows: LiquidCrystal_I2C.h, Wire.h, and Max6675. Figure 10 shows the hardware used in which the part of the electronic system corresponding to the support will be described. At the top, the USB-B serial connector is shown, which employs the RS-232 standard used to connect the board to the computer and load the programs. At the top, there is a power supply through a center-positive jack that operates from 7 VDC to 12 VDC. On both sides of the figure, there are digital input/output pin strips at the top, and analog on the bottom. Thein in-circuit serial programming (ICSP) can be used to record a boot manager through an external programmer. Finally, the reset button, that resets the Atmega.

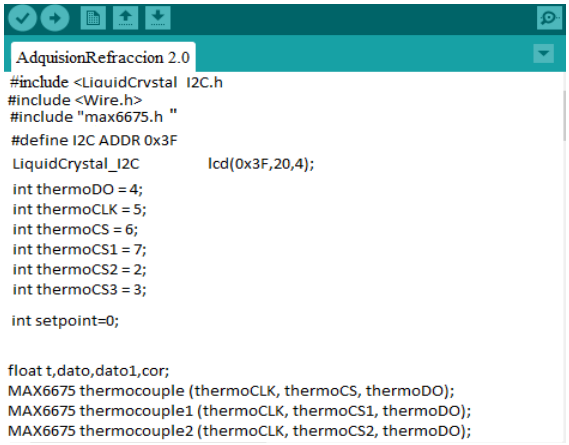


Figure10. Development environment.

The software used is Arduino, which provides a development environment based on Wiring, as a show the Figure 10, which is an open framework for programming microcontrollers and consists of a text editor to write code and below it a message area. At the top, there is a toolbar with the basic functions of verifying/compiling the program, etc. The most useful tool is the serial monitor, with which it is possible to be in continuous communication with the board. Before starting a program, it is necessary to configure the board to be used and the port where it will be connected. To do this, select

the board in the menu bar tools > board, and then in tools > serial port, the port where it will be connected. By selecting the board to be used, the central processing unit (CPU), speed, file and bootloader configuration are actually being configured. To start a default program, the Arduino bootloader is used, which is a pre-installed software in Arduino and allows uploading the code without using additional hardware. It starts right after the board reset and in light emitting diode (LED) flashes. After this, the program that has been loaded into the microcontroller starts.

3. Results

The functioning of the thermal conductivity equipment is developed in the following way: the loading process of the insulating material is started, where it is introduced to the specimen and compressed with the vibration system, compacting the material to be tested. Subsequently, the external thermocouples and the terminal resistors are installed. Then, the procedures to be carried out for the beginning of the test are presented, which are the connection port, the set point, data collection time, and test duration. Finally, after a certain time the average temperature curve Vs thermal conductivity as a show the Figure 11 is displayed, and a table of the test results of temperature, thermal conductivity, voltage, and amperage with their respective operating time is presented, as a show in the Table 1.

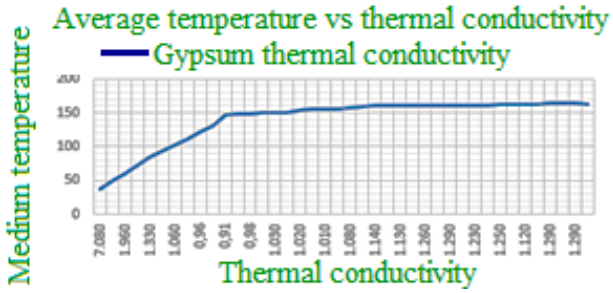


Figure 11. Plaster curve.

Table 1. Plaster data.

T (Minutes)	T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	K (W/m*°C)	Volts (V)	I (A)
1	43	30	32	31	7.080	67	0.900
2	65	31	33	33	2.910	70	0.900
3	85	34	37	35	1.960	69	0.900
4	104	39	43	39	1.580	68	0.900
38	202	124	131	122	1.290	64	0.900
39	202	124	131	123	1.290	65	0.900
40	200	124	132	123	1.160	61	0.900

4. Conclusions

The device determines the thermal conductivity in granular materials based on the physical principles of conduction heat transfer by applying Fourier's law in a steady state. The device allows measuring physical quantities such as temperature, length, area, as well as voltage and current, during the conduction heat transfer process. This is done in order to determine the thermal conductivity coefficient in granular materials through the finite cylinder model.

This work uses the physical principles and mathematical model of the conduction heat transfer phenomenon in a material. The aim is to solve a real problem in engineering applications, such as determining the thermal conductivity of a material, which is necessary to determine the possible use of such material as an insulator or heat sink. The automation of the system brings versatility to the measurement of thermal conductivity and allows the device to be used with different granular materials.

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