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Manufacture and Design an Apparatus for Measuring the Thermal Resistance of Building Materials

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Abstract

A good thermal design of buildings plays a key role in reducing the thermal loads of heating and air conditioning systems and thus reducing energy consumption. This study develops a steady-state apparatus for measuring the thermal resistance of building materials by using an absolute technique. The apparatus is designed to accommodate the full and actual size of the tested samples of building materials used in the Syrian market to ease testing. Therefore, suitable samples do not have to be built for the apparatus; the thermal resistance is measured for many samples, and the results are compared with the thermal insulation code for buildings in the Syrian Arab Republic. The results show that the difference between the resistance values obtained from the experiments and the Syrian thermal insulation code is due to the materials used in the local markets and their non-compliance with the code. These materials need testing and quality control during the manufacturing process.

Keywords: thermal resistance, thermal conductivity coefficient, steady-state, absolute technique

1. Introduction

In this era, wasted energy is the biggest problem in industrial, commercial, and residential fields. All these fields have a common factor, i.e., buildings. A significant amount of energy is used to make the buildings comfortable to live or work in. However, a considerable amount of energy is wasted on the building envelope. This problem is unavoidable, but the amount of energy wasted could be minimized. Additionally, building materials could be improved to make better designs for energy-sustainable buildings. Furthermore, updating standards and regulations can help keep up with the latest metrology technology. Generally, there are two topics that receive much attention in material engineering, i.e., structure and thermal. This study will focus on the thermal side. There are multiple thermal parameters used for energy calculations in heat transfer applications. These values are available in books and references. However, with the emergence of new materials, these sources need new-found methods with these parameters [1].

The heat transfer discipline depends on explaining thermal energy transfer and its rate under specific conditions. The key elements in determining heat transfer are thermal properties, temperature difference, and dimensions. These factors form the definition of thermal resistance [2]. Thermal resistance (R) in this study is limited to conduction only. It is defined as the resistance of energy flow in a structural element through its thickness [2]. Therefore, increasing this resistance means the ability of the structural elements to resist the energy flow and reduce the heat transfer. These materials are considered poor conduction materials, called thermal insulators. The thermal resistance is calculated by dividing the thickness of the material (δ) by its thermal conductivity (λ), and its unit is $m^2.°C/W$, as shown in Eq. (1).

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$$R = \frac{\delta}{\lambda} \tag{1}$$

The thermal resistance increases when the thermal conductivity decreases or the heat sink area becomes larger while the spreading thermal resistance value stays the same. Also, the effective thermal conductivity rises when the heat source area is smaller, and the heat sink area is larger [3-5]. Additionally, the thermal resistance increases when the thickness of the material increases. The cost of building materials increases exponentially with wall thicknesses. Therefore, finding the optimal thickness can minimize the energy waste and the overall cost of the building. Many methods have been developed and used to measure the thermal resistance of different materials [6]. However, most of these methods have accuracy limits based on the temperature and thermal conductivity of the samples. Proceeding from the importance of thermal resistance in heat transfer calculations, it is necessary to determine and measure the resistance value experimentally.

This study identifies the methods of measuring the thermal resistance, develops an apparatus to measure the thermal resistance, and tests some samples of building materials by using the developed apparatus. The thermal resistance of these samples is also calculated theoretically based on the thermal insulation code for buildings in the Syrian Arab Republic. Finally, a comparison is made between the thermal resistance values obtained based on the code and the apparatus.

2. Methodology and Techniques

2.1. Steady-state method

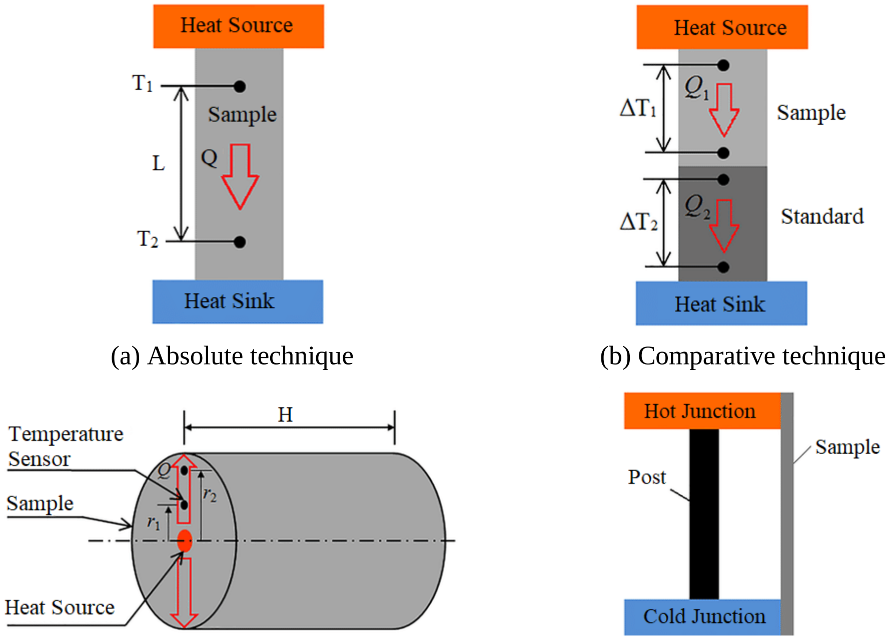
In the steady-state method, temperatures are measured at a heat source and a heat sink. The temperature difference is calculated at a known distance and a constant heat flow through a sample. Fig. 1 shows a schematic diagram of steady-state methods.

(1) Absolute technique: This method is used for the sample in the form of a cuboid or cylinder. The sample is placed between a heat source and a heat sink, and the temperature difference is measured over a known distance to the sample by thermocouples, which are the most widely used devices because of their cheapness and measurement accuracy of less than 1% [7].

(2) Comparative technique: In this method, the tested sample is placed with another sample made of a material with a known thermal conductivity coefficient. The thermal conductivity is derived from the measured temperature gradients in the tested sample and the thermal conductivity of the reference materials [8].

(3) Radial heat flow technique: This method allows experiments to be carried out at various temperatures, especially when the temperatures are more than 700℃, where the heat loss by radiation cannot be neglected. Normally, this method uses the sample with a circular or duct shape. Heat is provided to the sample by using the heaters at the axis, and the heat flows out diagonally. Thermocouples are used to measure the temperature with an accuracy of ±0.1℃ [9].

(4) Parallel thermal conductance technique: This method is suitable for the sample with small diameters, such as carbon fibers, with a diameter of 10-100 mm. With this method, it is difficult to measure the temperature by thermocouples and determine the heat flow. A parallel heat conduction method is proposed for the needlelike sample that cannot support heaters and thermocouples [10]. Before measuring the thermal resistance of the sample, the sample is measured concerning the sample support first to determine the heat loss rates related to the sample support. Then, the test sample is connected to the sample support, and the thermal resistance is measured again.



(a) Absolute technique (b) Comparative technique

(c) Radial heat flow technique (d) Parallel thermal conductance technique

Fig. 1 Steady-state methods

2.2. Transient-state method

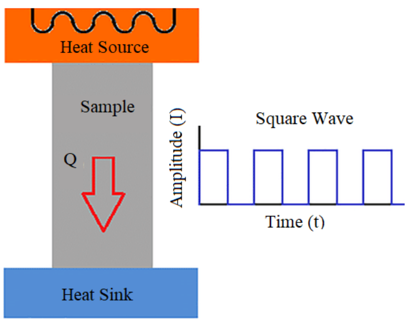
The transient-state method determines the energy dissipation as a function of time. Several transient methods have been developed to eliminate the negatives of the steady-state such as the heat loss and long waiting time to reach a constant temperature difference. Fig. 2 presents a schematic diagram of transient-state methods.

(1) Pulsed power technique: This method is similar to the steady-state method, but the heating current is a square pulse wave. One of the advantages of this method is that it allows quick measurements, especially when there are many samples [11].

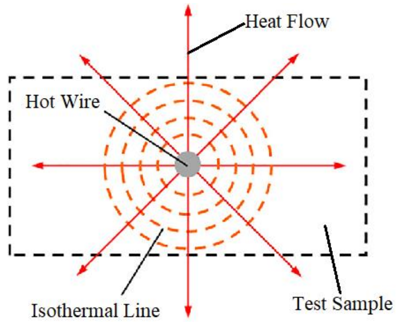
(2) Hot wire technique: This method measures the temperature rise at a known distance from the linear heat source. The method assumes a one-dimensional heat flow inside the sample, which means that the heat source is linear with an infinite length and infinitesimal diameter. When there is an electric current of constant intensity passing through the hot wire, the heat conduction coefficient of the sample can be derived. The available time is tested by using the resulting temperature change at a known distance from the hot wire during a period. The hot wire method is used to measure the materials with a low coefficient of thermal conductivity (such as plastics and fibers) [12].

(3) Transient plane source (TPS) technique: This method uses a thin metal strip or a metal disc as a flat heat source and a temperature sensor. The metal disc is electrically isolated and placed between two test samples; all other surfaces are thermally insulated. A small constant electric current is applied to the metal disc during the experiment to heat it. The thermal properties of the test samples can be determined by observing the temperature increase for a short period, and the measurement accuracy of the temperature sensor is ±0.01℃ [13].

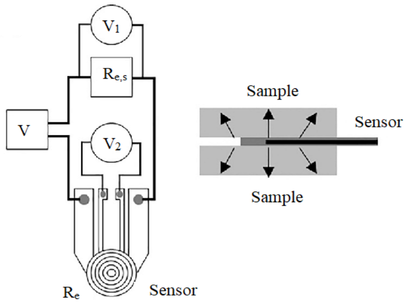
(4) Laser flash technique for thermal diffusivity: Thermal contact resistance is a significant source of error when measuring the temperature. The thermal diffusion method is used by laser flash to sense the temperature without contact to achieve high accuracy. This method uses rapid optical heating, and the temperature is measured using thermocouples, an infrared detector, or an optical pyrometer. The sample is prepared by coating or spraying a layer of graphite or any high emissivity material on both sides, to make an absorbent from the front side and an emitter on the backside to sense the temperature [14].



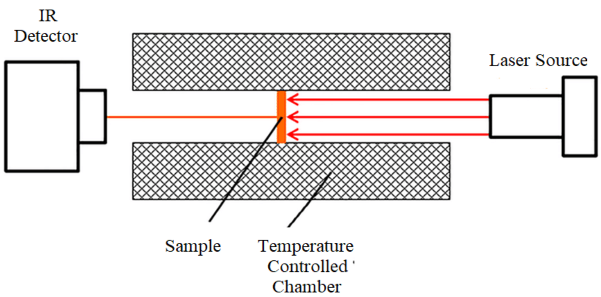
(a) Pulsed power technique



(b) Hot wire technique



(c) Transient plane source technique



(d) Laser flash technique for thermal diffusivity

Fig. 2 Transient-state methods

There are two general types of apparatus for determining the thermal resistance of materials. The first type (the hot plate apparatus), which is the most common, is used to determine the thermal resistance from one material surface to the other surface. The apparatus consists of a heating section lined with double-sided copper plates. The copper plates are divided into two parts. These two parts are completely separated by an air gap that prevents any metallic contact between the inner and outer parts of the heating plate, as the inner part is the test part. The outer part is a protective and insulating ring to prevent heat loss during the experiment [15-17]. The second type (Hotbox apparatus) is used to determine the total thermal resistance of the air on one side to the air on the other side of the material.

The hot plate apparatus is generally accepted to determine the heat resistance. The main goal of any device is to obtain accurate results. This result can be achieved by taking accurate temperature measurements and achieving a correct heat flow direction through the material. Special precautions must be taken to prevent heat loss from the test values and ensure that the heat flow lines are perpendicular to the test surfaces.

3. Equipment and Procedures Used in Apparatus Design

3.1. Purpose of apparatus

The design of the apparatus, which is based on the absolute technique in the steady-state method, aims to measure the thermal resistance by applying a constant heat flow during the experiment and measuring the temperature difference between the heat source and the heat sink.

3.2. Apparatus design and manufacture

The thermal resistance measurement apparatus is designed based on the absolute technique in the steady state, where a constant heat source heats the sample, and the temperature difference is measured over a distance known to the sample by temperature sensors. A thermal insulator surrounds the sample and the heating part to ensure the one-dimensional heat transfer and reduce the heat loss by convection and radiation. Fig. 3 shows the design of the apparatus in SolidWorks, where the dimensions are set based on the building materials.

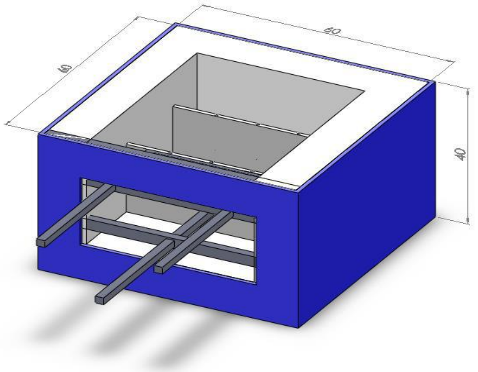


Fig. 3 Apparatus design in SolidWorks

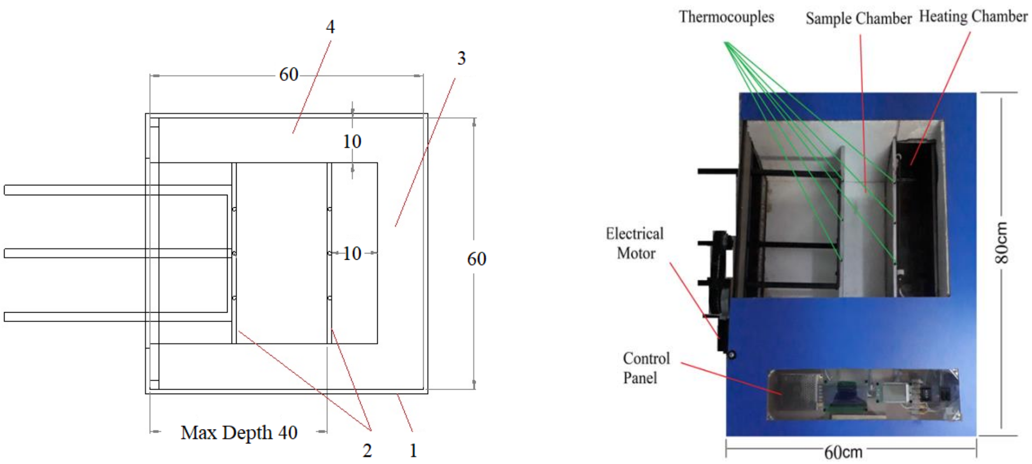
3.3. Basic parts

The thermal resistance measurement apparatus for building materials mainly consists of a metal structure made of iron bars and a number of thermal insulation types depending on the temperatures to prevent the heat loss. Table 1 shows the basic parts of the apparatus.

The insulation materials, such as polystyrene, mineral wool, and glass, can be replaced with foam geopolymer materials based on fly ash. They are a non-flammable material characterized by relatively good insulation parameters [18]. Fig. 4 illustrates the horizontal projection of the apparatus with its constituent parts.

Table 1 Basic parts of the proposed apparatus

No.	Part name	Dimensions		
		Length (cm)	Width (cm)	Height (cm)
1	Metal frame	60	60	40
2	Aluminum plate	40	1	20
3	Mineral wool	40	5	40
4	Polystyrene board	40	10	40



(a) Dimensions of the apparatus (b) The apparatus after assembly

Fig. 4 Horizontal projection of the apparatus after assembly

3.4. Other parts

The apparatus contains other systems to complete its work. These systems are the heat source, control system, and sensors. An electrical heater is used as the heat source to provide heat to the system. The control system is used to maintain the temperature at around 200℃, display the temperature from the sensors, and log the data. The instruments used in these systems are described below.

Fig. 5 Thermocouples (type K)

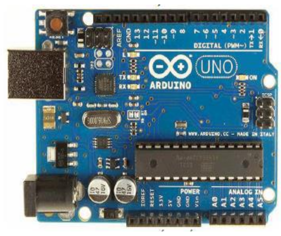


Fig. 6 Arduino Uno R3 board

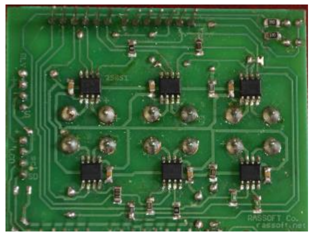


Fig. 7 MAX6675 assembled printed circuit board (PCB)

Fig. 8 LCD (type 2004A)

Fig. 9 Power display

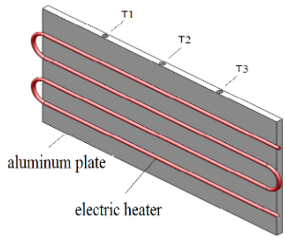


Fig. 10 Electric heater on the aluminum plate

Fig. 11 Power supply

(1) Thermocouples: Six K-type thermocouples, which have a length of 100 mm and a diameter of 5 mm, are shown in Fig. 5.

(2) Data logger: The code is designed and written to be compatible with the heat resistance apparatus based on the Arduino Uno R3 microcontroller. It is an open-source electronic board to easily develop many control projects using the open-source programming language Arduino C, as shown in Fig. 6 [19].

(3) Analog-digital converter (ADC) and cold junction compensation: As shown in Fig. 7, this study selects an MAX6675 integrated circuit compatible with K-type thermocouples and a 12-bit ADC with a heat-sensing diode [20].

(4) Temperature display and data recording: As shown in Fig. 8, a liquid-crystal display (LCD) screen (4 × 20) is installed to read the temperature values measured by thermocouples.

(5) Display power provided: A power screen, as shown in Fig. 9, is installed to read the power values provided by the electric heater.

(6) Electric heater: An electric heater works as a heat source, wraps the heater, and is fixed by brackets on the aluminum plate. The electric heater with a length of 1 m and a diameter of 5 mm is installed as shown in Fig. 10.

(7) Electrical power supply: As shown in Fig. 11, an electrical supply source (12 V/5 A) is installed to supply the equipment with constant voltage.

3.5. Apparatus calibration

Apparatus calibration is done to determine the amount of heat flowing through the sample and to determine the error that results from the heat loss by convection, radiation, contact resistance, and resistance of aluminum plates. The calibration is done using a material with a known thermal conductivity coefficient, such as gypsum with dimensions of 40 × 20 cm, a thickness of 1.6 cm, and a thermal conductivity coefficient of 0.16 W/m.℃. The heat is presented on the front side of the sample at a temperature of T_{ai} = 200℃ by an electric heater. After reaching the steady state, the mean temperature at the front face of the sample is T_{ai} = 200℃, and the mean temperature at the opposite side is T_{ao} = 85℃. Fig. 12 shows the mean temperatures T_{ai} and T_{ao}.

Through this calibration, the value of the heat provided is known without losses by convection, radiation, contact resistance, and resistance of aluminum plates. The error value from the losses is included in the calculation code for Arduino Uno.

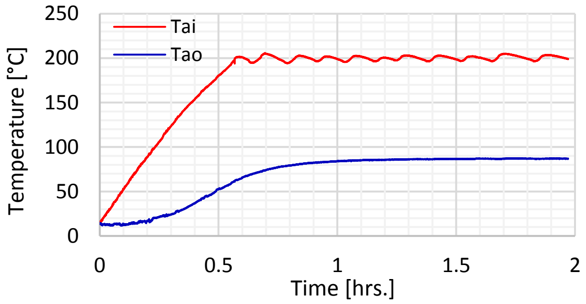


Fig. 12 Mean temperatures (T_{ai} and T_{ao}) of the gypsum board

4. Tests and Experiments

Experiments are conducted on the materials used in the Syrian local markets, where two types of the most famous samples are selected to verify their thermal resistance and compare the results with the Syrian thermal insulation code.

(1) The sample is a hollow cement block:

The sample has a thickness of 10 cm and is placed within the apparatus. The experiment is conducted by adding heat to the front side of the sample using the electric heater. After the system reaches the steady state, the mean temperature at the front side (the heat source) Tai is 200℃, and the mean temperature at the opposite side Tao is 85℃, the temperature difference ΔT is 115℃. The heat of 125 W is introduced to the system, resulting in the thermal conductivity coefficient λ of 1.28 W/m.℃. Fig. 13 illustrates the tested sample's dimensions, and Fig. 14 shows the mean temperature Tai measured on the front side of the sample (heat source) over time and the mean temperature Tao on the backside of the sample (heat sink).

(2) The sample is a wall section:

The wall section contains a hollow cement block with a thickness of 10 cm and two layers of cement (plaster) with a thickness of 2 cm. The experiment is conducted by adding heat to the front side of the sample using the electric heater. After the system reaches the steady state, the mean temperature at the front side (the heat source) T_{ai} is 200℃, the mean temperature at the opposite side T_{ao} is 65℃, and the temperature difference ΔT is 135℃. The heat of 125 W is introduced to the system, resulting in the thermal conductivity coefficient λ of 1.62 W/m.℃. Fig. 15 illustrates the tested sample's dimensions, and Fig. 16 shows the mean temperature T_{ai} measured on the front side of the sample (heat source) over time and the mean temperature T_{ao} on the backside of the sample (heat sink).

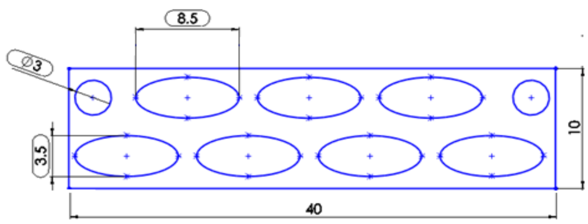


Fig. 13 Dimensions of the hollow cement block

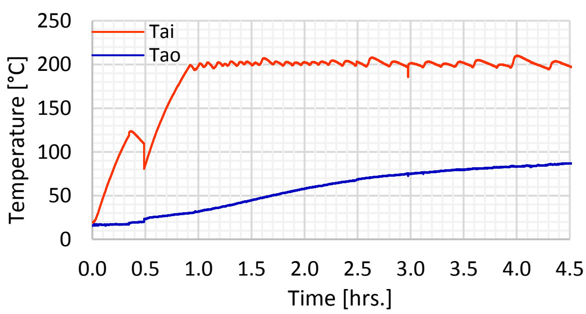


Fig. 14 Mean temperatures (T_{ai} and T_{ao}) of the hollow cement block

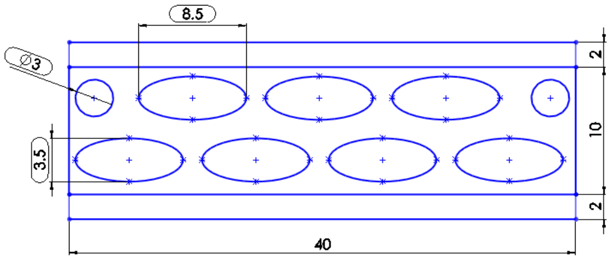


Fig. 15 Dimensions of the wall section

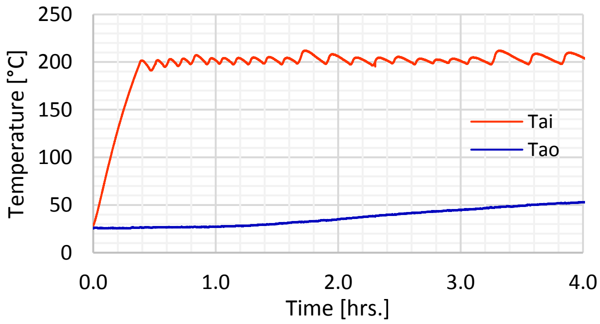


Fig. 16 Mean temperatures (T_{ai} and T_{ao}) of the wall section

As shown in Table 2, the physical and thermal characterization of the tested materials includes: length (a), width (b), weight (W), density (ρ), thermal conductivity coefficient (λ), thermal resistance (R), thermal resistance according to the code [21] (R*), absolute error, and relative error.

Table 2 Physical and thermal characterization of materials

Materials / Characteristics	Hollow cement block	Wall section
a (cm)	40	40
b (cm)	20	20
δ (cm)	10	14
W (kg)	12.1	16.4
ρ (kg/m^3)	1513	-
λ (W/m.°C)	1.282	1.624
R (m^2.°C/W)	0.078	0.086
R* (m^2.°C/W)	0.100	0.139
Absolute error	0.022	0.053
Relative error	22 %	38 %

5. Conclusions

This study designs an apparatus for measuring the thermal resistance of the building materials used in the Syrian Arab Republic. The results indicate that the thermal resistance values obtained by the experiment differ from the values obtained by the thermal insulation code for buildings in the Syrian Arab Republic. This difference is due to the materials used in the local markets and their non-compliance with the code. These materials need testing and quality control during the manufacturing process.

Knowing the heat resistance value is necessary to calculate the lost or gained thermal energy through the structural element and to judge the efficiency of thermal insulation with various structural elements. The lower the value of the thermal conductivity coefficient, the greater the thermal insulation capacity and the higher the percentage of savings in thermal energy used for heating and air conditioning purposes.

To measure the thermal resistance, it is essential to develop an apparatus which can work in different positions to achieve the horizontal and vertical heat transfer, determine the amount of heat, and reduce the measurement errors and heat loss.

Nomenclature

R	Thermal resistance (m^2.°C/W)
T_{ai}	Mean temperature (heat source) (°C)
T_{ao}	Mean temperature (heat sink) (°C)
W	Weight (kg)
δ	Thickness (cm)
λ	Thermal conductivity coefficient (W/m.°C)
ρ	Density (kg/m^3)

Conflicts of Interest

The authors declare no conflicts of interest.

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