Low-cost portable system for measuring thermal conductivity of building

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Abstract. The developed system allows to measure the thermal conductivity of solid materials used as thermal insulators in building bioclimatic houses on high Andean zones. A unidirectional heat flow model through a sample of dimensions 4.0 cm x 4.2 cm x 1.35 cm has been considered. K-type thermocouples were used to measure the temperature’s gradient. The obtained values were: 0.97 Wm$^{-1}$°C$^{-1}$ for glass, 0.38 Wm$^{-1}$°C$^{-1}$ in the ignimbrite, 0.58 Wm$^{-1}$°C$^{-1}$ for the roof brick and 0.34 Wm$^{-1}$°C$^{-1}$ in the adobe with *Stipa ichu*. These materials have been evaluated considering their abundance and use in house building on the Arequipa department high zones.

1. Introduction
Cold weather is a source of issues that people from peruvian highlands have to cope with. In particular Arequipa department, have a yearly death toll of vulnerable inhabitants, as elderly people and children, caused by pneumonia and other respiratory diseases. This is even more serious in a pandemic context. Former studies have shown that building materials for typical housing on the Arequipa’s highlands are the cause of the death toll. Technology to fight the cold weather generated issues is well known and of course, materials to build thermal confort housing have been well studied, but the thermal analysis of the materials commonly used are carried out in specialized laboratories. Therefore a low cost has been built in order to measure, in situ, the thermal conductivity properties from traditional materials.

Jananpa *et al.* [5] developed a system of thermal conductivity measurement using an array of type T thermocouples and carried out experiments with some materials, for which they obtained the thermal conductivity using a linear fit for R between 0.90 and 0.98, values that are similar to those reported in the literature. Cuenca *et al.* [3] made thermal conductivity measurements for several materials, including: drywall, adobe with *Stipa ichu*. The results that were obtained with the former materials were respectively: 0.265 Wm$^{-1}$K$^{-1}$, 0.357 Wm$^{-1}$K$^{-1}$.

2. Theoretical framework
If we consider heat conduction through a big planar wall as seen in figure 1, we can take as unidirectional the heat flow through the sample, since the heat flow through these geometries is prominent just in one direction and negligible otherwise, as pointed by Bergman *et al.*[1] and Cengel *et al.* [2].

Next we write the general equation of heat flow in rectangular coordinates.

\[
\frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \dot{q} = \rho c \frac{\partial T}{\partial t} \tag{1}
\]
In most practical applications we can suppose that thermal conductivity remains constant in a steady state (equilibrium). For our case, the above equation reduces to the equation 2.

\[
\frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) = 0
\]  

(2)

Figure 1. Unidirectional flow through a plane wall [2].

Considering a unidirectional flow of heat and with the boundary conditions \(T(x = 0) = T_1\) and \(T(x = L) = T_2\), furthermore \(q\) is negligible because, because the sample does not have a heat source. Eq. 2 implies that \(\frac{\partial T}{\partial x} = 0\)

if we integrate eq. 2, two times respect to \(x\), we get

\[
T(x) = C_1 x + C_2
\]  

(3)

evaluating eq. 3 on the boundary conditions we get the following expression

\[
T(x) = \frac{T_2 - T_1}{L} x + T_1
\]  

(4)

next, we replace \(T(x)\) in the Fourier law equation

\[
\dot{Q}_{\text{cond}} = -\lambda A \frac{dT}{dx}
\]  

(5)

in order to get an expression in terms of the temperature \(T\) and the length \(L\) we have the following

\[
\frac{\dot{Q}_{\text{cond}}}{A} = -\lambda \frac{d}{dx} \left( \frac{T_2 - T_1}{L} x + T_1 \right)
\]  

(6)

\[
\frac{\dot{Q}_{\text{cond}}}{A} = \lambda \frac{\Delta T}{L}
\]  

(7)

\[
\lambda = \frac{\dot{Q}_{\text{cond}} L}{A \Delta T}
\]  

(8)

3. Methodology

The device has two parts. In the first one figure 3 the aluminum exchanger goal is to extract heat from the system by mean of a water flow whose heat is extracted by a Peltier cell and is dissipated through the cooler in the middle. The second one figure 4 is the thermal conductivity measurement system that allows to measure the heat flow from the hot zone to the cold one. The goal in extracting heat from the system is to create a difference of temperature to generate a heat flow through the sample, for this, a water flow of 5 liters per minute through a channel between the aluminium exchangers is generated by a water pump, producing a minimal temperature of 8 °C on the cold copper plate 2. The system for the evaluation of the sample (figure 4), is composed of: a second exchanger, a copper plate (where is located...
a sensor which measures the cold plate temperature), the sample, a second copper plate, which measures the hot plate temperature, the heaters which have two sides each one. In one side a resistor of 5.2 ohm has been engraved. On the other side we have a copper plate connected to a temperature sensor. Then, there is a second plate with the same characteristics than the former that serves as a guard. There is a gap of 1 mm between the two plates, this is to eliminate the heat flow through the heater and assure a unidirectional flow, this is so because the guard and the hot plate have the same temperature. And finally a dissipator in contact with the guard by mean of a bakelite sheet.

![Figure 2](image_url)

**Figure 2. Block diagram for thermal conductivity measurement system.**

### 4. Experimental setup

Figure 2 shows the diagram for the proposed prototype. At the top is located the cooling module that is composed of a radiator, a Pelier module, and a heat exchanger (cPw). At the bottom can be seen a set of surfaces. The cold plate is composed of the heat exchanger and a copper sheet. The hot plate is composed of a copper sheet that is in touch with a serigraphy resistance 1, which is the main heat source. Finally, the guard, it has also a serigraphy resistance facing downwards. The cold and hot plates are squared in shape. A power supply of 220 V AC to 12 V DC feeds the 0-24 V DC-DC modules that control the voltage supplied to the hot plate, the guard, Pelier cell, and the radiator.

Type K thermocouples were inserted at the edges of the two copper plates and in the side without serigraphy of the baquelite. The load voltage from the main heater and the temperature were measured with a GL800 data logger connected through a USB cable to a computer.

Considering that all the electrical power delivered to the hot plate is transformed into heat, we have that \( \dot{Q} = IV \) so we can write

\[
\lambda = \frac{IVL}{A(\Delta T)}
\]  

(9)

where \( I[A] \) is the current, \( V[V] \) is the voltage, \( L[mm] \) is the thickness of the sample, \( A[mm^2] \) is the area, \( \Delta T[{^\circ}C] \) is the temperature gradient and \( \lambda \) is the thermal conductivity of the sample. To calculate the Uncertainty in indirect measurements we use propagation of uncertainties [8] shown in equation 10.
\[ \delta \lambda = \frac{\nu h}{\Delta T} \left[ \left( \frac{\delta I}{I} \right)^2 + \left( \frac{\delta V}{V} \right)^2 + \left( \frac{\delta h}{h} \right)^2 + \left( \frac{\delta A}{A} \right)^2 + \left( \frac{\delta \Delta T}{\Delta T} \right)^2 \right]^{1/2} \]  

(10)

5. Results and discussions

Tests were made with materials typically used in high andean zones from Arequipa department, such as si and glass with the goal of obtaining thermal conductivity. The results are shown in table 1. As can be observed, the time spent to get thermal conductivity is from 2.5 hours to 5.5 hours after reaching

Figure 3. Cooling system with Peltier cell and heat exchanger cube.

Figure 4. Thermal conductivity meter structure. 1: aluminium exchanger. 2 and 4: copper plates. 3: sample. 5 and 6: baquelite serigraphy resistors

Figure 5. Test materials. a) glass, b) adobe, c) ignimbrite block, d) roof brick.
equilibrium, it depends on the target material. It can also be observed that the used temperature’s gradient is between 19.4 °C and 39.1 °C. In order to know the thermal power provided by the electrical resistance, the current and voltage that feed the hot plate were measured.

In order to make tests, first, hoses were filled with 300 ml of water and then by mean of the Peltier module, heat was extracted from the system until a temperature between 8 °C and 10 °C was reached, at the same time the hot plate were heated between 30 °C and 35 °C. After, the stability of the difference of temperature between the cold plate and the hot one was taken into account. It took approximately 3 to 4 hours to reach the desired stability. Then the data acquisition was done by a time lapse between 2.5 and 5.5 hours, depending on the material. The temperature difference is 0.2 degrees on average, as the system is expected to reach equilibrium and the data and the results are detailed in table 1.

The heat source for this device is a screen-printed resistor on Bakelite with a thickness of 0.62 mm and a lateral surface of $0.08 \times 10^{-3} \text{m}^2$, which corresponds to the 4.1 % of the total surface of the heat source. Under these conditions, in the simulation it was observed that the convective heat flow, through the lateral surface, has a value of approximately 1.2 %, from the total heat, so it is considered that the heat flow, is unidirectional through the sample and that the temperature gradient, is from the hot surface towards the cold surface.

![Figure 6. Prototype experimental setup. At the left side, the cooling system. At right side, the thermal conductivity system of measurement](image)

| Sample            | Thickness (mm) | Time (h) | Change of temperature $\Delta T$ (°C) | Power (W) | Dimensions (mm) | Density (kgm$^{-3}$) | Thermal conductivity (Wm$^{-1}$C$^{-1}$) |
|-------------------|----------------|----------|---------------------------------------|-----------|------------------|----------------------|----------------------------------------|
| glass             | 3.85           | 5.5      | 19.4                                  | 7.821     | 39.70x40.10      | 2490.01              | 0.97 ± 0.04                           |
| ignimbrite        | 5.85           | 4.7      | 36.6                                  | 3.864     | 39.95x41.35      | 1010.99              | 0.37 ± 0.01                           |
| ladrillo          | 7.00           | 5.5      | 28.5                                  | 4.562     | 42.75x44.90      | 1748.99              | 0.58 ± 0.02                           |
| adobe whit stipa ichu | 12.30       | 2.5      | 39.1                                  | 1.941     | 41.00x42.30      | 1485.10              | 0.340 ± 0.07                          |
Figures 7 and 8 show the histograms of thermal conductivity for adobe and ignimbrite; the results are shown in table 1. The histograms shown indicate the stability of the measurement and when equilibrium is reached, and in the histogram the "number of measurements" axis refers to the number of data taken with the datalogger; the width of the distribution contributes to the error of the measurement; which has to be added to the uncertainty propagation error described in the equation 10.
The number 2, 4, 5 and 6 refer to the temperature measurement point in Figure 4.

**Figure 11.** Comparison of the experimental result measured in this work for ignimbrite: A1 reported in [4]; A2 is the experimental thermal conductivity and A3 referenced [5].

**Figure 12.** Comparison of the experimental result measured in this work for adobe: B1 is the experimental thermal conductivity; B2 reported in [7] and B3 referenced in [6].

**Figure 13.** Results of the thermal conductivity of the materials studied.
An Rigaku miniflex 600 X ray equipment was used to get the diffractogram which is shown in 15. The powder samples have been deposited on the sample tray which has dimensions 20.0 mm x 20.0 mm x 0.70 mm. The scanning angle 2θ is within 5°-80°. The figure also shows the presence of albite 47.2 %, cristobalite 24.6 %, heulandite 15.7 %, sanidine 10.7 %, tooleite 1.4 % y de iricnite 0.5 % and for the adobe, the presence of labradorite 27.4 %, Anorthite 22.3 %, bytownite 18.8 %, albite 17.8 % tamarugite 9.3 % y sulphur 4.5 %.

6. Conclusions
A low cost thermal conductivity measurement equipment has been built with components commonly used in CPUs cooling. It has been achieved thermal conductivity measurements in the order of 0.04 Wm⁻¹°C⁻¹.

The results obtained show that, adobe and ignimbrite, used traditionally for house building on high zones of the Arequipa department, are more appropriate than the materials currently used such as brick and concrete.

The values for thermal conductivity obtained in this research work for glass, ignimbrite, brick and, adobe with stipa ichu are respectively: 0.97 Wm⁻¹°C⁻¹, 0.37 Wm⁻¹°C⁻¹, 0.58 Wm⁻¹°C⁻¹ y 0.34 Wm⁻¹°C⁻¹ respectively.

The thermal conductivity measurement system developed in this research work use only a sample. A possible improvement is to replace the guard by another sample and add a second aluminium exchanger. In addition, a lateral insulation system can be included which, we think, would improve considerably its performance.

The thermal conductivity measurements were recorded when the system achieved thermal equilibrium, this can be clearly seen from the histograms shown in figures 7 and 8, which have overcome a normality test, which point, that errors can be associated only to random factors.

7. References
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