Design and construction of a portable apparatus to measure thermal conductivity

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Abstract. The characterization of the thermal insulation properties of construction materials represents a fundamental step on building insulation assessment. The present work aims to design and build a portable apparatus, namely, Portable LAMBDA UNI, capable of measuring the thermal conductivity of insulation materials. This portable apparatus is based on the standard ASTM C 518, which is a secondary method for measuring thermal conductivity. The apparatus also measures the effective thermal conductivity of square prism thermal insulation materials of 60 mm per side and a maximum thickness of 14 mm. The thermal conductivity of the drywall and adobe with Stipa ichu was measured with the Portable LAMBDA UNI, with the values being 0.265 W m⁻¹ K⁻¹ and 0.357 W m⁻¹ K⁻¹, respectively.

1. Introduction
The thermal conductivity measurement of materials used in housings, industries, and commercial buildings is fundamental for solving problems related to energy efficiency and thermal comfort. In the Peruvian Andean regions, a traditional construction material is adobe, and the thermal conductivity of adobe with and without Stipa ichu was measured, thereby obtaining 0.371 and 0.349 W m⁻¹ K⁻¹, respectively [1]. These thermal conductivity values of native materials are fundamental for their use as input values in the simulations of heat transfer balance to evaluate the performance of houses using bioclimatic techniques [2–3]. Bioclimatic techniques must be considered in the Andean construction to provide a healthy and comfortable thermal environment in the interior of housings. Two well-known methods establish heat flux in a steady state: (1) the guard hot plate (GHP) method regulated by the norm ASTM C177 [4], which is a primary method, and (2) the heat flow meter (HFM) method regulated by the norm ASTM C518 [5], which is a secondary method. In most cases described in the literature for measuring low thermal conductivity samples (in the order of the thermal conductivity of air), the sample size must be large enough, varying from a few hundred centimeters to over a meter [6]. However, researchers involved in the development of insulating materials have developed small specimens of new materials; therefore, a portable apparatus should be useful to manufacturers of insulation materials and polymers.

The constructed portable apparatus is based on the standard ASTM C 518 that establishes a steady state for one-dimensional heat fluxes through a test specimen between two parallel plates at different constant temperatures. Measuring the temperatures of the cold ($T_C$) and hot plates ($T_H$), the thickness of the sample ($L$), and the heat flux ($Q/A$), the thermal conductivity ($\lambda$) can be obtained [5]:

$$\lambda = \frac{QL}{A(T_H - T_C)}$$

(1)
2. Portable LAMBDA UNI apparatus
The portable apparatus for measuring the thermal conductivity of solid materials comprises an insulating base, electrical resistance, hot plate, heat flow transducer, specimen, heat flow transducer, cold plate, Peltier module, and heat sink unit, which are disposed vertically at the top of the apparatus presented in figure 1.

![Diagram of the apparatus](image)

**Figure 1.** Schematic of the thermal conductivity portable LAMBDA UNI apparatus.

Two heat flow transducers FHF02 of Hukseflux are used in the system, and they have a thermopile inside of them to measure the surface temperature of the hot and cold plates. \(T_H\) represents the hot temperature, and \(T_C\) stands for the cold temperature. Hence, the gradient temperature (\(\Delta T\)) through the specimen can be determined. They also measure the heat flux through the specimen. \(Q_H\) is the heat flux in the hot plate, and \(Q_C\) is the heat flux in the cold plate. Thus, the average heat flux \(Q\) can be determined.

2.1 Cold plate
The cold plate is made of copper square prism with a side of 60 mm and a thickness of 5 mm and is thermally coupled with a Peltier module. This Peltier module needs a heat sink unit that comprises an aluminum sink and a fan. Moreover, the Peltier module and heat sink unit are coupled with thermal paste to reduce air gaps or spaces from the interface area to maximize thermal dissipation. The Peltier module and fan both work with 12 V (nominal).

2.2 Hot plate
The hot plate is made of copper with a side of 60 mm and a thickness of 5 mm and is thermally coupled with a heater HTR01 of Hukseflux. This heater is connected to a power supply and controlled by a pulse-width modulation (PWM) signal. The heater has a resistance of 100 \(\Omega\), a heating area of \(2062 \times 10^{-4} \text{ m}^2\), and a thickness of 0.1 mm.

2.3 Heat flux transducer, thermocouples, and control system
The portable LAMBDA UNI needs a control system to obtain one-dimensional heat flows in the specimen at the steady state conditions to achieve precise temperature differences across the specimen.
The heating unit and Peltier module of the portable apparatus are controlled by a proportional–integral–derivative (PID) controller. The thermopile inside of the heat flow transducers measures the surface temperature of the cold and hot plates by an ADC converter. The temperatures of the cold and hot plates provide feedback to the controller and are compared with the user-configured temperatures. Thereafter, the PID control sends a PWM signal to the power stage and supplies the Peltier module and heater to regulate the cold and hot temperatures. The schematic diagram in figure 2 shows the working principle of the control system for the hot and cold temperatures.

![Figure 2. Schematic control system of the Portable LAMBDA UNI.](image)

The portable apparatus has the configuration proposed by the norm ASTM C518, with the novelty that it does not use a coolant for the cold plate. While this device uses a Peltier, cell attached to a heat sink. It also uses an extra-flat heating resistance; these elements make the device compact and easy to move. It uses two identical heat flux transducers that are in thermal contact between the specimen and the hot or the cold plate, and each one has a sensing area of $9 \times 10^{-4} \text{m}^2$. The heat flux and the cold and hot temperatures are monitored within 3 h to have the steady state, and the controller receives the temperature set point via the computer interface. A minimum stabilization time of 1 h must be considered after starting and setting up the working temperatures for the hot and cold plates. After this period, a steady state region must be selected to calculate the thermal conductivity.

2.4 Maximum thickness of the specimen
The thickness should be limited as the edge heat loss error increases while the specimen thickness increases, when the width of the guard area decreases, or when the edge insulation is inadequate [7]. Choosing the maximum thickness is possible to use the results of an analysis for a similarly-sized guarded hot plate as a guide [5]. For an guard width that is approximately one-half the linear dimension of the metered section, the recommended maximum thickness of the specimen is one-third the maximum linear dimension of the metered section [5]. As a result of this detail, the maximum thickness of the specimen evaluated using the Portable LAMBDA UNI is 14 mm.

3. Results and discussion
The data were collected for 3 h in the stationary state for the drywall and adobe with *Stipa ichu*. The system reached the stationary state after 1 h from the start of the experiment. Figures 3 and 4 exhibit the last 2 h in the stationary state of the heat fluxes and temperatures of the hot and cold plates for the drywall and adobe with *Stipa ichu*.

Table 1 depicts the thermal conductivity values of the drywall and adobe with *Stipa ichu* with a thickness of 12.5 mm and 13.9 mm, respectively.
Figure 3. (a) Heat flux of the cold (red line) and hot (black line) plates vs time for the drywall and (b) the temperatures of the hot (black line) and cold (red line) plates vs time for the drywall.

Figure 4. (a) Heat flux of the cold (red line) and hot (black line) plates vs time for adobe with *Stipa ichu* and (b) the temperature of the hot (black line) and cold (red line) plates vs time for adobe with *Stipa ichu*.

Table 1. Experimental parameters and results for the thermal conductivity of the drywall and adobe with *Stipa ichu*.

| Material               | Room temperature (°C) | Mean temperature (°C) | Thickness (mm) | Temperature difference between plates (°C) | Heat flux (W m⁻²) | Thermal conductivity (W m⁻¹ K⁻¹) |
|------------------------|-----------------------|-----------------------|----------------|-------------------------------------------|-------------------|----------------------------------|
| Drywall                | 18.4                  | 19.1                  | 12.5           | 10.8                                      | 229.3             | 0.264 ± 0.013                    |
| Adobe with *Stipa ichu* | 20.5                  | 20.8                  | 13.9           | 10.0                                      | 257.9             | 0.357 ± 0.014                    |
The thermal conductivity reference value of adobe with *Stipa ichu* was obtained with a system based on the norm ASTM C177 located in the thermal conductivity laboratory of the thermometry division of the National Metrology Center (CENAM, Mexico). The sample dimensions of the tested adobe were 170 mm x 170 mm x 25 mm [6]. Furthermore, the thermal conductivity of reference value of Drywall was obtained from the manufacturer specification, Volcan type Volcanita ST.

Table 2 shows the comparison of the thermal conductivity measured with the Portable LAMBDA UNI and certified measurement. The adobe with the *Stipa ichu* sample used in this investigation was from the same lot and then had the same preparation and composition of the adobes evaluated at the CENAM [6]. The relative error differences between the reference and the reported value for the adobe with *Stipa ichu* and the drywall are 4.0% and 1.53%, respectively.

### Table 2. Experimental parameters and results for the thermal conductivity of the adobe with *Stipa ichu*.

| Specimen               | ΔT (K) | λ (W/m. K) | λ<sub>reference</sub> (W/m. K) |
|------------------------|--------|------------|-----------------------------|
| Adobe with *Stipa ichu*| 10     | 0.357      | 0.349                       |
| Expanded polystyrene   | 10.8   | 0.264      | 0.260                       |

Additionally, other construction materials were evaluated, such as expanded polystyrene, glass wool, clay brick and Capirona wood. The experimental results are shown in table 3 and the values agree with the literature and the thermal conductivity of Capirona wood and clay brick called Pastelero in Peru has measured for the first time.

### Table 3. Thermal conductivity of some material construction.

| Material            | Room temperature (ºC) | Mean temperature (ºC) | Thickness (mm) | Temperature difference between plates (ºC) | Heat flux (W m⁻²) | Thermal conductivity (W m⁻¹ K⁻¹) |
|---------------------|------------------------|------------------------|----------------|-------------------------------------------|-------------------|----------------------------------|
| Expanded polystyrene| 18.5                   | 21.1                   | 12.5           | 13.7                                      | 56.1              | 0.0511 ± 0.016                   |
| Glass wool batt      | 20.5                   | 20.6                   | 10             | 14.9                                      | 62.8              | 0.0434 ± 0.013                   |
| Clay brick           | 18.4                   | 17.0                   | 7.9            | 8.2                                       | 591.2             | 0.569 ± 0.015                    |
| Capirona wood        | 20.1                   | 20.2                   | 10.5           | 10.7                                      | 174.9             | 0.171±0.012                      |

### 4. Conclusions
The thermal conductivity of some materials obtained with the Portable LAMBDA UNI manifests its capacity to measure it with a relative error with respect to the references of less than 4% for the evaluated materials.

### Acknowledgment
This work was conducted under the auspices of the Peruvian National Council for Science and Technology (CONCYTEC) under the contact N° 024-2016-FONDECYT and the Vice Presidency for Research of the National University of Engineering (VRI-UNI) under the project MF-FC-4-2019.
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