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Measurement of the Thermal Conductivity of Building Materials Using the Asymmetric Hot Wire Method

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Abstract

This article presents a method for measuring the thermal conductivity of building materials using the asymmetric hot wire technique in transient conditions. Two approaches for estimating thermal conductivity are developed: one based on a simplified model and the other on a quadripolar model. These methods were applied to various cases of materials simulated in COMSOL. The results of the theoretical study show that thermal conductivity can be estimated with an accuracy of less than 1% using the quadripolar model. On the other hand, the simplified model shows much greater deviations from the quadripolar model, particularly for highly insulating and lightweight materials with a conductivity between 0.025 and 0.048 $W \cdot m^{-1} \cdot K^{-1}$. Experimental studies conducted on various building materials and bulk products (powders and aggregates) confirmed the accuracy of the results obtained in the COMSOL simulations. A comparison between the thermal conductivity values measured using the asymmetric hot wire method on three validation samples and those derived from the effusivity measurement using the asymmetric hot plate method, coupled with the thermal diffusivity obtained using the 3L method, revealed a deviation of less than 1.5%.

Keywords

Building Materials, Hot Wire, Thermal Conductivity, Quadripolar Model, Heat Equation

1. Introduction

Knowledge of the thermal properties of building materials is of paramount importance in predicting the thermal comfort of the spaces they enclose.

With this in mind, several methods have been developed to measure these properties. They are generally classified into two main categories: steady-state methods and transient methods [1].

Steady-state methods, such as the box method, are well suited to measuring the thermal conductivity of building materials [2] [3]. Other methods include the hot plate method, used for the thermal characterisation of materials [4] [5], and the stationary hot strip method, used to measure the conductivity of thin anisotropic materials [6]. However, these approaches have major limitations, including excessive test duration and certain uncertainties related to measurement accuracy [7].

In order to obtain more absolute and accurate measurements, reduce testing time and access thermal parameters other than conductivity alone, while broadening the range of materials studied, researchers are turning to transient contact methods, such as the hot wire [8]-[10] or hot disc [11] [12] methods. These methods make it possible to evaluate the thermal conductivity and diffusivity of various solid materials, nanofluids and fibre-reinforced composites. However, these methods lack precision for characterising low-density insulating materials [13]. For its part, the flash method, developed by Laurent and Degiovanni [14], allows the measurement of thermal diffusivity. It does not apply correctly to lightweight insulators, as two problems arise: on the one hand, the assumption of surface absorption of the flux becomes inaccurate in the case of highly porous materials; on the other hand, the measurement of surface temperature by thermocouple proves to be imprecise.

In the same vein, the symmetrical hot plate method has been proposed for measuring the thermal effusivity of materials [15].

The setups used to date are generally based on a symmetrical configuration, which allows for simplified modelling and calculations. However, this type of setup has two major drawbacks in certain cases:

For hard materials, the presence of thermocouple wires between the heating probe and the surface of the material imposes a minimum distance (equal to the diameter of the wires) between the two, thus creating significant and asymmetrical contact resistance.

In some situations, it can be difficult to obtain two samples with identical properties and surface conditions. This is particularly the case for certain construction materials whose properties are to be measured at a given water content.

To overcome these two limitations, an asymmetric semi-infinite hot plate setup has been developed to measure the effusivity of heavy building materials [16] [17]. In this device, one of the two samples is replaced by a deformable insulator with known thermal effusivity, typically polyurethane foam. The thermocouple is placed on the side of the probe in contact with the foam. Thanks to its deformability, the foam allows the thermocouple to be inserted without creating any significant contact resistance. In addition, the presence of this resistance on the side of an insulating material further reduces its impact on the measurement.

To date, no measurements of thermal conductivity in transient conditions have been carried out using an asymmetrical setup.

This is the focus of this article, which aims to develop a new method for measuring the thermal conductivity of building materials in transient conditions, based on the asymmetric hot wire technique.

The asymmetric transient hot-wire method is distinguished by its ease of implementation, low cost, and wide measurement range covering materials with thermal conductivities between 0.025 and 2.5 $W \cdot m^{-1} \cdot K^{-1}$.

The method is also characterised by its ability to measure the thermal conductivity of bulk materials, as well as a maximum measurement time of approximately 1000 s.

In the rest of this article, we first describe the methods for estimating thermal conductivity, based respectively on a simplified model and a quadripolar model. Next, we present the various simulations performed in COMSOL on different types of materials in order to evaluate the accuracy of the two approaches. Finally, we conclude this study with experimental validation and measurements applied to representative construction materials.

2. Theoretical Study

We model the device shown schematically in **Figure 1**:

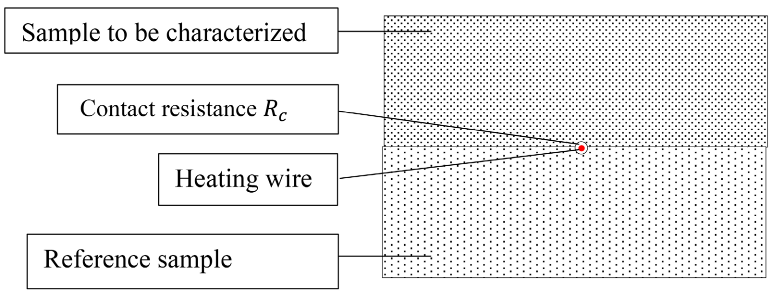


Figure 1. Diagram of the experimental setup for the asymmetrical hot wire.

Hypothesis:

- The interface between the two samples is adiabatic
- The heating wire is at a uniform temperature
- The two samples are semi-infinite

We also initially assume that the heat flux transmitted to each sample is proportional to the thermal conductivity of the sample, *i.e.*, if R is the electrical resistance of the wire, L its length and I the current flowing through the wire:

$$\varphi_{w \to s} = \frac{\lambda_s}{\lambda_s + \lambda_{ref}} RI^2 \tag{1}$$

This can be reduced to the classic hot wire device (two identical samples) shown in **Figure 2**, considering that the wire produces a heat flow:

$$\varphi_w = 2\frac{\lambda_s}{\lambda_s + \lambda_{ref}} RI^2 \tag{2}$$

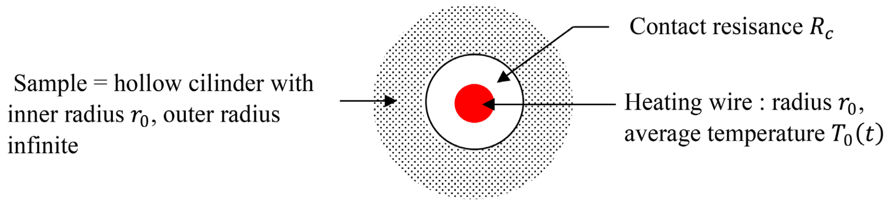


Figure 2. Diagram of the conventional hot-wire experimental setup.

Quadripolar model:

The heat equation is written in the sample as follows:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{a_s}\frac{\partial T}{\partial t} \tag{3}$$

The heat equation is written in the wire:

$$\frac{\partial^2 T_w}{\partial r^2} + \frac{1}{r}\frac{\partial T_w}{\partial r} + \frac{p_w}{\lambda_w} = \frac{1}{a_w}\frac{\partial T_w}{\partial t} \tag{4}$$

where p_w is the power density generated in the wire by the Joule effect.

With the following initial and boundary conditions:

$$\text{At} \quad t = 0: \ T_w(r,0) = T(r,0) = T_i \tag{5}$$

$$\text{At} \quad r = 0: \ \frac{\partial T_w(0,t)}{\partial r} = 0 \tag{6}$$

$$r = r_w: \ \lambda_w \frac{\partial T_w(r_w,t)}{\partial r} = \lambda_s \frac{\partial T(r_w,t)}{\partial r} \tag{7}$$

$$\frac{T_s(r_w,t) - T(r_w,t)}{R_c} = \lambda \frac{\partial T(r_w,t)}{\partial r} \tag{8}$$

$$r \to \infty: \ T(\infty,t) = T_i \tag{9}$$

This problem can be solved using Laplace transformation and quadrupole formalism, which allows us to write [1]:

$$\begin{bmatrix} \theta_w \\ \dfrac{\varphi_w}{p} \end{bmatrix} = \begin{bmatrix} A_w & B_w \\ C_w & D_w \end{bmatrix} \begin{bmatrix} 1 & R_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \theta \\ \dfrac{\theta}{Z} \end{bmatrix} \tag{10}$$

In the case of the small body hypothesis for the wire (r_w small and λ_w large), the quadrupole becomes:

$$\begin{bmatrix} A_w & B_w \\ C_w & D_w \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \rho_w c_w \pi r_w^2 Lp & 1 \end{bmatrix} \tag{11}$$

With:

$$\frac{1}{Z} = 2\pi\lambda_s L q_s r_w \frac{K_1(qr_w)}{K_0(qr_w)} \tag{12}$$

$$q_s = \sqrt{\frac{p}{a_s}} \tag{13}$$

where:

$T_w(t)$: Average hot wire temperature

$T(t)$: Sample temperature in the $r = r_w$

θ_w: Laplace transform of the difference $T_w(t) - T_i$

θ: Laplace transform of the difference $T(t) - T_i$

R_c: Contact resistance at the heating element/sample interface

c_w: Specific heat of the wire

ρ_w: Density of the wire

λ_s: Thermal conductivity of the sample

a_s: Thermal diffusivity of the sample

p: Laplace variable

r_w: Heating wire radius

L: Length of heating wire

φ_w: Power dissipated in the heating wire

I_0, I_1, K_0, K_1: Bessel functions

Hence:

$$\theta_w = \frac{\varphi_w}{p} \frac{A_w + (A_w R_c + B_w)/Z}{C_w + (C_w R_c + D_w)/Z} \tag{14}$$

Simplified model

If we consider a thin wire (r_w small) and take a long-term view ($p \to 0$), we can use the limited developments of Bessel functions in the vicinity of 0:

$$K_0(x) \approx -\ln(x) + \ln(2) - \gamma \tag{15}$$

$$K_1(x) \approx \frac{1}{x} \tag{16}$$

$$I_0(x) \approx 1 \tag{17}$$

$$I_1(x) \approx \frac{x}{2} \tag{18}$$

which lead to:

$$\overline{T_w}(t) = T_w(t) - T_i = \frac{\varphi_w}{4\pi\lambda_s L}\ln(t) + \varphi_w \left[R_c - \frac{\gamma}{4\pi\lambda_s L} - \frac{\ln\left(\frac{r_w}{2\sqrt{a_s}}\right)}{2\pi\lambda L} \right] \tag{19}$$

The curve $\overline{T_w}(t) = f[\ln(t)]$ is therefore, in the long term, a straight line with a slope of:

$$\alpha = \frac{\varphi_w}{4\pi\lambda_s L} \tag{20}$$

where:

$$\varphi_{w\to} = 2\frac{\lambda_s}{\lambda_s + \lambda_{ref}} RI^2 \tag{21}$$

Hence:

$$\lambda_s = \frac{RI^2}{2\pi\alpha L} - \lambda_{ref} \tag{22}$$

3. Estimation Method

Simplified method

We plot the curve $T_{exp}(t) = f(\ln(t))$ and perform a linear regression on the right-hand side of the curve corresponding to a time interval $[t_1, t_2]$. We obtain an equation of the type $T(t) = \beta + \alpha \ln(t)$. We then plot the residuals, *i.e.*, $T_{exp}(t) - [\beta + \alpha \ln(t)]$, and check that they are flat and centred on zero over the chosen time interval. If this is not the case, we modify the time interval and repeat the estimation.

We then deduce the thermal conductivity value λ of the sample by:

$$\lambda_s = \frac{RI^2}{2\pi\alpha L} - \lambda_{ref}$$

where:

R : Electrical resistance of the hot wire.

I : Current intensity.

L : Length of the wire.

λ_{ref} : Thermal conductivity of the insulator.

$\frac{R}{L}$'s value must be estimated beforehand by conducting an experiment with a sample of known thermal conductivity λ_{ref}. It is estimated using:

$$\frac{R}{L} = \frac{2\pi\alpha(\lambda_s + \lambda_{ref})}{I^2}$$

Quadripolar method

The following assumptions are made:

- heat transfer is 1D radial at the centre of the device,
- the medium is infinite,
- heat transfer is purely conductive,
- the temperature is uniform and constant throughout the system at the initial moment.

The temperature $T(t)$ at the centre of the probe can be deduced from the expression $\theta_w(p)$ by an inverse Laplace transform.

The inverse Laplace transform is performed using the MATLAB programme "invlap" based on De Hoog's algorithm [18]. The MATLAB programme "leasqr" based on the Levenberg-Marquardt algorithm is used to estimate the values of the parameters λ, R_C et C that minimise the sum:

$$S = \sum_{i=1}^{N} \left[T_{exp}(t_i) - T_{mod}(t_i) \right]^2$$

where N is the number of measurement points.

We performed a 2D modelling of the asymmetric hot wire method in COMSOL, allowing us to obtain the simulated curve of the wire temperature evolution during the experiment.

First, a reference sample of polystyrene, measuring 10 × 10 × 5 cm^3, was modelled. Then, a second sample, measuring 10 × 10 × 3 cm^3, representing the material to be characterised, was placed on top of the reference sample. A heating wire with a radius of 0.25 mm, surrounded by a 0.1 mm layer of air, was inserted between the two samples.

The heating wire has a thermal conductivity of 15 W·m^{-1}·K^{-1} and a volumetric heat capacity of 3.7 × 10^6 J·m^{-3}·K^{-1}.

The simulations were performed on different materials with thermal properties representing all construction materials.

Figure 3 shows an example of a temperature field obtained through numerical simulation using COMSOL.

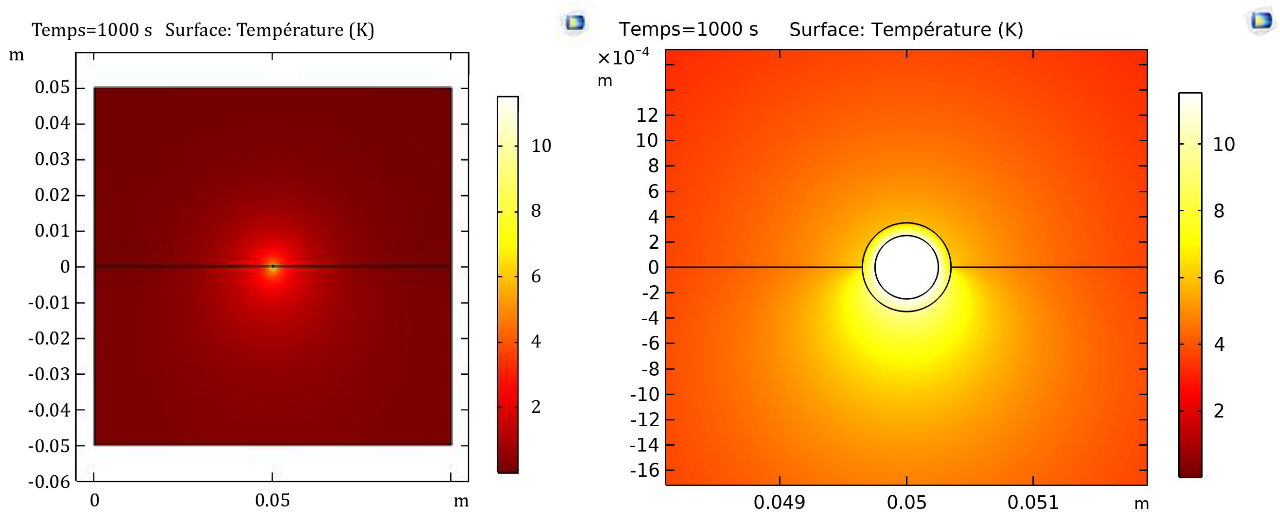


Figure 3. Example of a temperature field obtained by COMSOL.

For each material considered, we estimated the thermal conductivity using the two approaches described above: the slope method and the quadripolar model.

The results obtained for all the simulated materials, as well as the differences between the conductivity values defined in COMSOL and those estimated by the two methods, are presented in Table 1.

The results presented in Table 1 show that the difference between the thermal conductivity values defined in COMSOL and those estimated from the quadripolar model is less than 1%.

This accuracy remains constant for all materials with thermal conductivity between 0.025 W·m^{-1}·K^{-1} and 2.5 W·m^{-1}·K^{-1}.

Table 1. Comparison of the results of estimating the thermal conductivity of different materials between the slope method and the quadrupole model.

Case	Flow	λ	ρC	Slope method				Quadrupole model			
				t_{d1}	t_{f1}	λ_1	Percentage deviations 1	t_{d2}	t_{f2}	λ_2	Percentage deviations 2
1	1.0E+6	0.025	1.0E+4	300	400	0.0178	−28.9%	2	350	0.0249	−0.6%
2		0.025	5.0E+4	500	700	0.0214	−14.5%	2	600	0.0249	−0.3%
3		0.025	1.0E+5	600	800	0.0219	−12.4%	2	600	0.0249	−0.3%
4	2.0E+06	0.05	1.0E+05	500	700	0.0465	−7.0%	2	700	0.0500	0.1%
5		0.05	2.0E+05	600	800	0.0471	−5.9%	2	800	0.0501	0.2%
6		0.05	4.0E+05	600	800	0.0476	−4.8%	2	600	0.0502	0.4%
7	4.0E+06	0.1	1.0E+05	350	500	0.0938	−6.2%	2	500	0.1000	0.0%
8		0.1	5.0E+05	500	700	0.0972	−2.8%	50	500	0.1005	0.4%
9		0.1	1.0E+06	500	800	0.0974	−2.7%	50	500	0.1008	0.8%
10	4.0E+06	0.2	5.0E+05	400	600	0.1957	−2.2%	50	500	0.2005	0.3%
11		0.2	1.2E+06	400	700	0.1977	−1.2%	50	500	0.2005	0.3%
12		0.2	2.0E+06	400	700	0.1992	−0.4%	50	800	0.2013	0.6%
13	8.0E+06	0.5	1.0E+06	300	600	0.4930	−1.4%	50	600	0.5017	0.3%
14		0.5	1.5E+06	300	700	0.4950	−1.0%	50	600	0.5021	0.4%
15		0.5	2.0E+06	300	700	0.4960	−0.8%	50	600	0.5029	0.6%
16	1.6E+07	1	1.5E+06	300	700	0.9920	−0.8%	50	500	1.0013	0.1%
17		1	2.0E+06	300	700	0.9900	−1.0%	50	500	1.0045	0.4%
18		1	2.5E+06	300	700	0.9920	−0.8%	50	500	1.0060	0.6%
19	2.0E+07	1.5	1.5E+06	200	400	1.4650	−2.3%	50	500	1.4992	−0.1%
20		1.5	2.0E+06	200	500	1.4760	−1.6%	50	500	1.5014	0.1%
21		1.5	2.5E+06	300	600	1.4840	−1.1%	50	500	1.5031	0.2%
22	2.0E+07	2	1.5E+06	100	300	1.9320	−3.4%	50	400	1.9965	−0.2%
23		2	2.0E+06	200	400	1.9560	−2.2%	50	400	1.9988	−0.1%
24		2	2.5E+06	200	500	1.9670	−1.7%	50	400	2,006	0.3%
25	2.0E+07	2.5	1.5E+06	50	200	2.3500	−6.0%	50	400	2,491	−0.4%
26		2.5	2.0E+06	100	300	2.4200	−3.2%	50	400	2.4957	−0.2%
27		2.5	2.5E+06	200	400	2.4500	−2.0%	50	400	2.502	0.1%

However, the difference between the values defined in COMSOL and those obtained using the slope method exceeds 10% for low-conductivity materials with a conductivity between 0.025 $W{\cdot}m^{-1}{\cdot}K^{-1}$ and 0.048 $W{\cdot}m^{-1}{\cdot}K^{-1}$.

Beyond this range, *i.e.*, for conductivities between 0.05 $W{\cdot}m^{-1}{\cdot}K^{-1}$ and 2.5 $W{\cdot}m^{-1}{\cdot}K^{-1}$, the difference becomes less than 8%.

We can conclude that the lighter the materials (and therefore the more insulating they are), the less suitable the slope method is for accurately estimating their thermal conductivity. On the other hand, using the quadripolar model allows us to obtain an estimate with an error of less than 1% for all the cases considered.

Figure 4 shows an example of the curves obtained from a COMSOL simulation for cases 5 and 16 when estimating thermal conductivity using a quadripolar model of an asymmetrical hot wire.

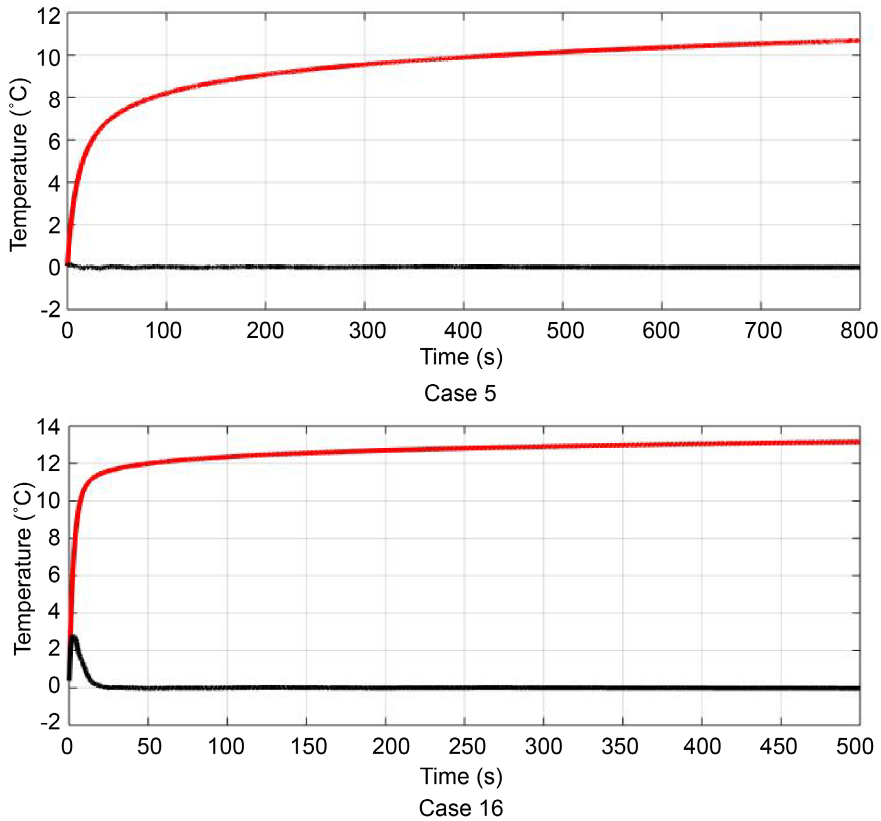


Figure 4. Experimental thermograms, models and residuals obtained when estimating thermal conductivity for case 5 and case 16, respectively.

On both curves, we observe that the residuals remain flat and centred on the estimation interval between 2 s and 800 s for case 5, and between 50 s and 500 s for case 16, in accordance with the estimation intervals presented in Table 1.

The curve corresponding to case 16 clearly illustrates that the flux sharing hypothesis is only an approximation**:** it is not strictly verified at short times (typically less than 50 **s** for the most conductive materials), during which the heat flux distribution remains unbalanced.

In fact, for case 16, the initial transient regime (a few seconds) is very rapid: the heat flow is not yet distributed evenly between the probe and the material.

During this short period (<50 s), the heat flow distribution assumption is not yet valid, because:

the temperature around the hot wire varies greatly;

the thermal gradient is very localised;

the distribution of the flow still depends on the geometry and conductivity of the sensor.

It is only after this characteristic time that the flow becomes quasi-symmetrical, allowing the analytical model based on flow sharing to be applied.

4. Equipment and Materials

4.1. Equipment

The equipment used for experimental thermal conductivity measurements using the asymmetric hot wire method is:

- 1 type K fine-wire thermocouple bonded to a 0.5 mm diameter Ni80Cr20 wire.
- 2 extruded polystyrene samples measuring 100 × 100 × 50 mm^3.
- A Basetech BT-305 0-30V/DC 0-5A 150W adjustable stabilised power supply.
- A Langlois TRG803 True RMS digital multimeter based on a UNI-T type device.
- Picolog data acquisition module with an acquisition time step of 0.1 s.

The basic measurement diagram is shown in **Figure 5**.

It consists of creating a groove in the polystyrene block in order to insert a resistive wire, to which a thermocouple is glued in the centre. The sample to be characterised is placed above the resistive wire, and the assembly is completed by a second polystyrene block positioned above the sample.

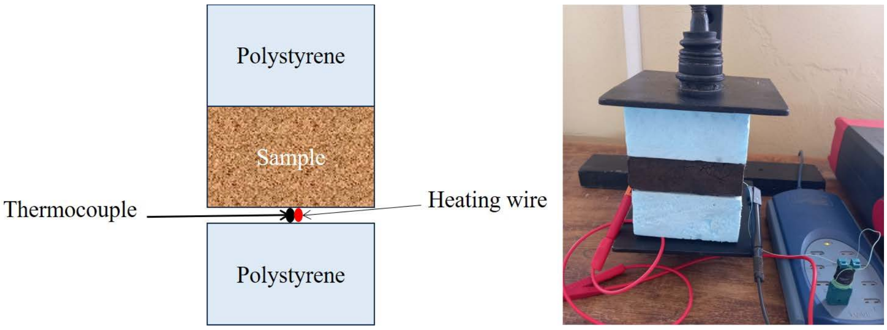


Figure 5. Asymmetric hot wire method device.

The transient asymmetric hot wire method can also be used for bulk products (powders or granular fibres) by confining the product placed above the heating resistor using an insulating frame, as shown in the device in **Figure 6**.

A constant current of I is passed through the heating element and the temperature change t is recorded at 0.1-second intervals. The thermal conductivity of the samples is estimated using the two estimation methods mentioned above.

4.2. Materials

The materials tested for thermal conductivity measurement using the asymmetric hot wire method are samples measuring 10 × 10 × 3 cm^3, with smooth, flat surfaces. They are divided into two groups: validation materials and study materials.

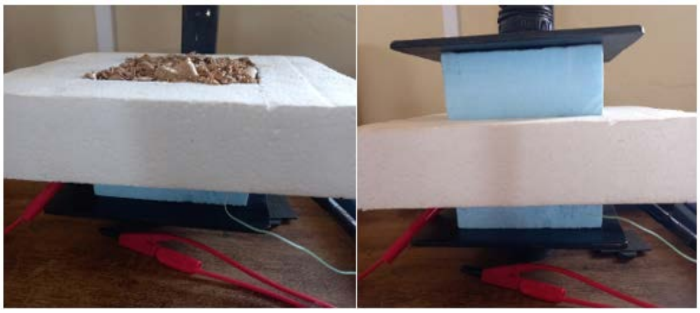


Figure 6. View of an asymmetric hot wire device for powdered or crushed fibre materials.

Validation materials:

Bauxite-based brick: thermal effusivity of 812 $W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}$ and thermal diffusivity of 2.52×10^{-7} $m^2 \cdot s^{-1}$.

PVC: thermal effusivity of 510 W $s^{1/2} \cdot m^{-2} \cdot K^{-1}$ and thermal diffusivity of 1.26×10^{-7} $m^2 \cdot s^{-1}$.

Conventional concrete: thermal effusivity of 1737 $W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}$ and thermal diffusivity of 6.02×10^{-7} $m^2 \cdot s^{-1}$.

Materials studied:

Pure clay: density of 2090 $kg \cdot m^{-3}$.

Clay + 8% typha composite: density of 1306 $kg \cdot m^{-3}$.

Clay composite + 8% typha + 6% gum arabic: density of 1469.58 $kg \cdot m^{-3}$.

Clay composite + 4% typha + 3% gum arabic: density of 1407.40 $kg \cdot m^{-3}$.

LDPE + flint composite: density of 1.77 $g \cdot cm^{-3}$.

Gum arabic powder: density of 5.42 $g \cdot cm^{-3}$.

Crushed typha fibre: density of 0.071 $g \cdot cm^{-3}$.

5. Experimental Results

5.1. Validation on Materials with Known Properties

The method was initially used to measure the thermal conductivity of materials with known thermal properties: PVC, brick made from bauxite residues and conventional concrete.

Table 2 shows the conductivity values deduced using the M3L method and asymmetric hot plate, those measured using the asymmetric hot wire, and the percentage differences.

Table 2. Comparison between the thermal conductivity values estimated using the developed method, those obtained using other reference methods, and the relative deviations observed.

Materials	Known conductivity	Conductivity measured by the asymmetric hot wire	Percentage deviations
PVC	0.181	0.183	−1.1%
Bricks made from bauxite residue	0.408	0.414	−1.5%
Conventional concrete	1.347	1.331	1.2%

Figures 7-9 show the curves obtained when estimating the thermal conductivities of the three validation materials listed in Table 2 using an asymmetrical hot-wire quadripole model.

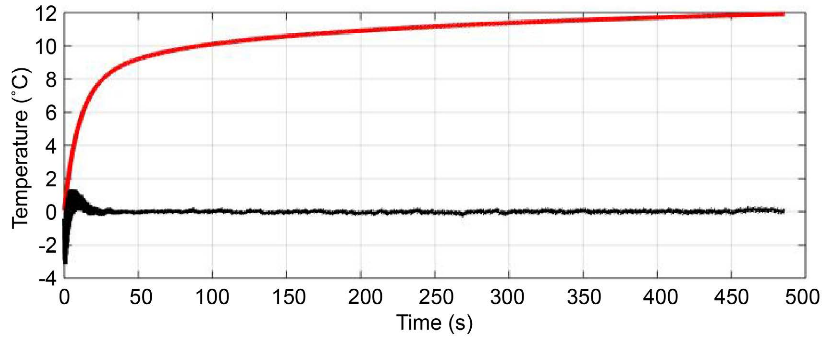


Figure 7. Experimental thermograms, models and residuals obtained when estimating the thermal conductivity of a PVC sample using the quadripolar model of an asymmetric hot wire.

In Figure 7, we can see that the residuals remain flat and centred at zero over the estimation interval between 50 s and 450 s, which confirms the validity of the quadripolar model of the transient asymmetric hot-wire programme.

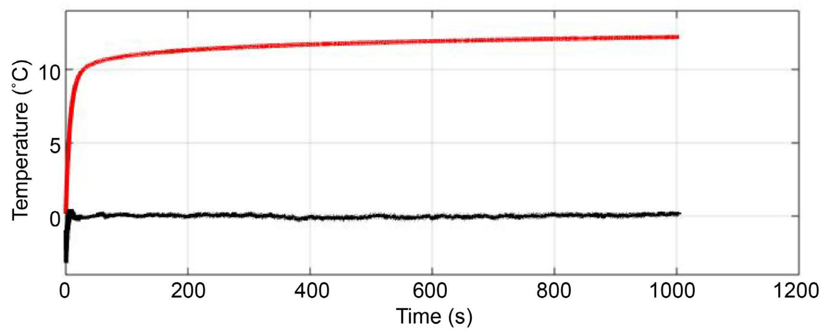


Figure 8. Experimental thermograms, models and residuals obtained when estimating the thermal conductivity of a brick sample based on bauxite residues using the quadripolar model of an asymmetric hot wire.

In Figure 8, the residuals remain flat and centred at zero over the estimation interval between 100 s and 800 s, confirming the validity of the quadripolar model of the transient asymmetric hot wire programme.

Figure 9 shows that the residuals remain flat and centred at zero over the estimation interval between 50 s and 450 s, confirming the validity of the quadripolar model of the transient asymmetric hot-wire programme.

The difference between the thermal conductivities estimated by the quadripolar asymmetric hot-wire method and those obtained using other methods remains less than 1.5%.

Furthermore, the simulated and experimental curves show flat and centred residuals during the same conductivity estimation intervals.

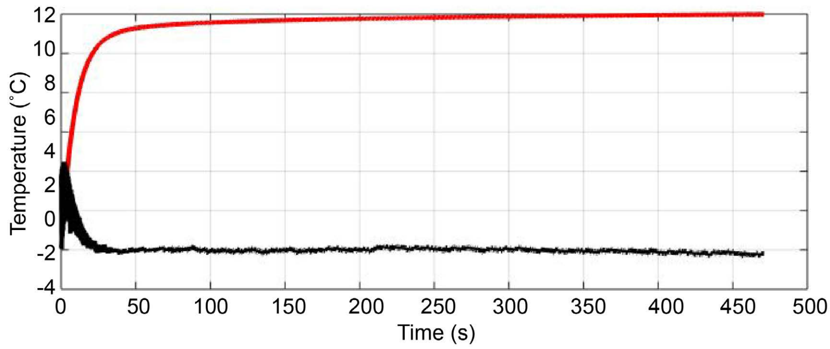


Figure 9. Experimental thermograms, models and residuals obtained when estimating the thermal conductivity of a conventional concrete brick sample using the quadripolar model of an asymmetrical hot wire.

Based on these observations, we can conclude that the asymmetric hot wire method allows the thermal conductivity of materials to be estimated with very good accuracy.

5.2. Measurements

After validating the asymmetric hot wire method on materials with well-known thermal properties, it was applied to other materials to measure their thermal conductivities.

The thermal conductivity values estimated using the quadripolar model and the simplified model are presented in Table 3.

Table 3. Estimated thermal conductivity values for different samples.

Samples	Estimation using the quadripolar model ($W \cdot K^{-1} \cdot m^{-1}$)	Estimation using the simplified model ($W \cdot K^{-1} \cdot m^{-1}$)
Pure clay	0.773	0.777
Clay + 8% cattail	0.207	0.212
Clay + 8% cattail + 6% gum	0.252	0.241
Clay + 4% cattail + 3% gum	0.345	0.353
Gum arabic powder	0.129	0.123
LDPE + Silex	1.012	0.991
Crushed cattail fibre	0.043	0.031

The measurement results obtained for clay-based materials are justified by the thermal conductivity values measured for gum arabic powder and bulk typha fibres. The estimated thermal conductivity for typha fibre confirms that it is a highly insulating material. Its incorporation into the pure clay matrix thus leads to a decrease in the thermal conductivity of the final composite.

On the other hand, the thermal conductivity measured for gum arabic powder is higher than that of cattail fibres. Its addition to the clay-cattail composite should therefore lead to an increase in overall thermal conductivity, which is confirmed by the experimental results obtained for the different mixtures of clay, cattail and gum arabic.

The experimental results presented in Table 3 also show that the two methods of estimating thermal conductivity applied to the various materials give very similar values. However, the difference between the two methods becomes noticeable when they are applied to lightweight, highly insulating materials, as predicted by the theoretical study.

Figure 10 shows an example of the experimental and theoretical curves obtained for pure clay and for the composite consisting of clay containing 8% typha and 6% gum arabic, when estimating thermal conductivity using the quadripolar model.

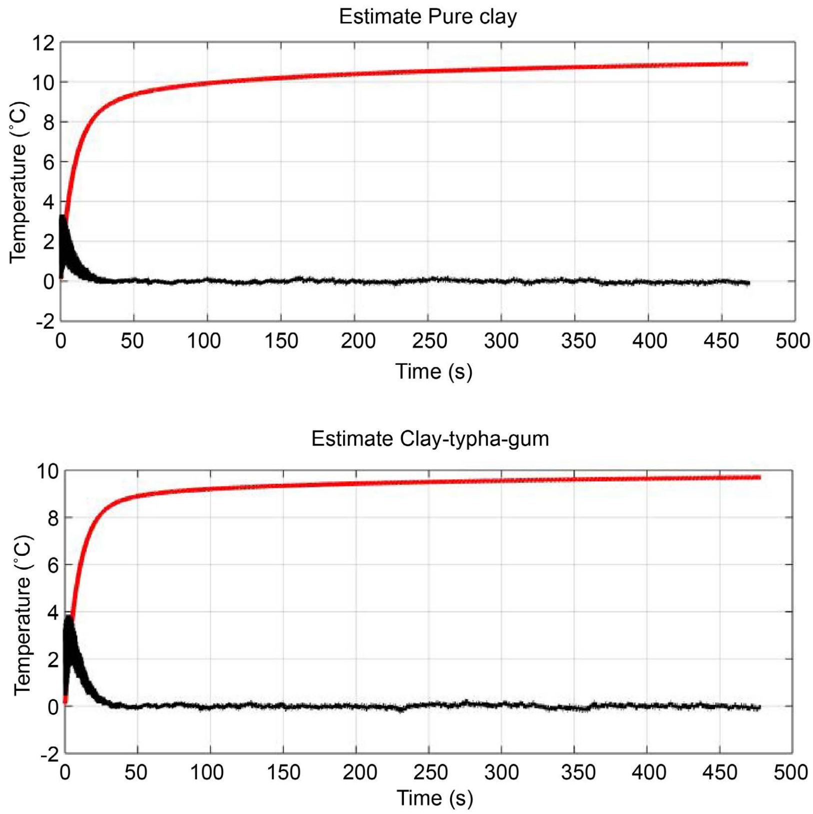
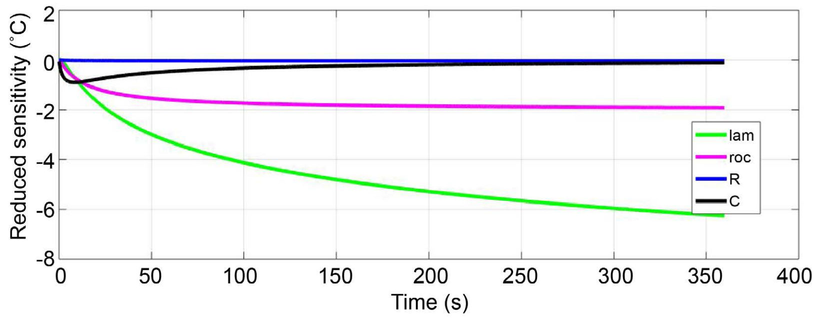


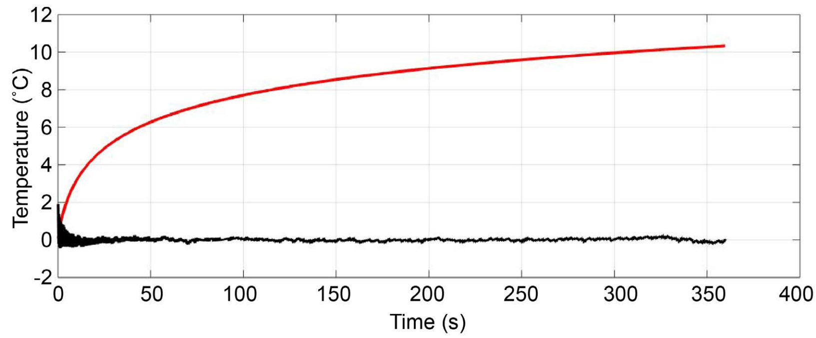
Figure 10. Experimental and theoretical curves obtained by applying the quadrupole model for pure clay and clay with 8% typha and 6% gum.

In both cases, the experimental and theoretical curves overlap perfectly, and the residuals are flat and centred around zero between 35 and 400 s, corresponding to the estimation interval. These observations confirm the validity of the complete model used in the asymmetric hot wire programme in transient conditions.

Figure 11 illustrates the reduced sensitivity curves, the experimental and theoretical thermograms, and the residuals obtained when estimating the thermal conductivity of gum arabic powder.



(a)



(b)

Figure 11. Estimation of the thermal conductivity of gum arabic powder: (a) reduced sensitivities; (b) experimental thermograms.

In **Figure 11(a)**, we see that between 35 s and 300 s, the reduced sensitivities at ρc and C are correlated and that the reduced sensitivity at R is negligible, so the only estimable parameter is thermal conductivity. **Figure 11(b)** shows that the residuals remain flat and centred at zero over the estimation interval, confirming the validity of the quadripolar model of the transient asymmetric hot wire programme.

6. Conclusions

The asymmetric hot-wire method, based on the use of a thermocouple attached to a resistive wire inserted into a groove on the face of polyurethane foam, has been described in this manuscript. The evolution of the hot-wire temperature was modelled using the quadripolar method.

Two models for estimating the thermal conductivity of building materials were tested: one based on the classic slope method and one based on the quadripolar model.

Numerical simulations carried out in COMSOL on several materials were used to evaluate the accuracy of the two proposed estimation methods.

An experimental study was also conducted on several building materials. This made it possible, on the one hand, to validate the estimation methods derived from the two models by measurements on materials with known thermal properties and, on the other hand, to highlight the limitations of the simplified model.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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