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An extended hot plate method for measurement of thermal conductivity variation with temperature of building materials

Saad Raefat[1,b], Mohammed Garoum[1,a,*], Najma Laaroussi[1], El Mehdi El Khattabi[2], Mohammed Rhachi[1]

[1] Materials, Energy and Acoustics TEAM, Higher School of Technology Salé, Mohammed V University in Rabat, 11060, 227 Avenue Prince Héritier, Morocco.
[2]Laboratory for Integration of Advanced Systems and Technologies-University Sidi Mohamed ben Abdellah-Faculty of Sciences Dhar El Mehraz, Fez, Morocco.

agaroum1@yahoo.fr,bsaad.raefat@gmail.com

Abstract: A new exploitation of the Hot Plate in Steady state HPS on the determination of thermal conductivity variation with temperature is presented. The mean temperature changement with temperature of the tested sample is ensured with varying the value of the voltage applied to the hot plate resistance, which enables to measure the thermal conductivity in different temperatures. Calculated thermal conductivity values obtained using a gypsum plaster sample, which specific heat capacity variation with temperature is accurately measured, validate the technic. Results show that the mean calculated thermal conductivity of the studied gypsum plaster is 0,143 W/m.k while the measured one is 0,148 W/m.k with a mean deviation of 3,81%. Moreover, the two trend lines of measured values and calculated ones have the same slope with a small intercept difference of 0,004.

1. Introduction

At lower temperatures, two classifications of experimental methods of the thermal conductivity determination exist: steady state and transient state methods. In the first category the sample thermal conductivity is directly calculated measuring the flow density and the temperature gradient once the system falls into equilibrium [1, 2]. In the second category the thermal diffusivity is measured instead, which takes into account the temperature fluctuations inside the sample, the thermal conductivity is then estimated from the thermal diffusivity knowing the specific heat and the density of the sample [3]. The hot plate method [4] is considered to be a first category technic for thermal conductivity measurements of small samples (0,01m^2). In steady state, its straightforward elements incorporation made its use simple and easy, while keeping an acceptable accuracy of measurements. In the present study this technic use is extended to the determination of the thermal conductivity variation with temperature of construction materials. A gypsum plaster sample was used to present and explain the experimental and numerical procedures. The specific heat variation with temperature of gypsum plaster was measured using an accurate differential scanning calorimeter in order to compare calculated and measured values of the thermal conductivity assuming a constant thermal diffusivity and density.

2. Description of used material

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The sample was made in a circular mold of 10cm in diameter and 2cm in thickness mixing 190g of gypsum plaster with 118,75g of water respecting a water ratio of 0,625 as indicated in NF P 15-201-1, it was left on an ambient temperature of 25 ° C and a RH of 80% for a sufficient time to consistency, subsequently introduced into an oven and dried at a temperature of 70 ° C + -3 ° C according to NF P 75-101. Once the sample mass becomes constant it is immediately coated on cellophane in order to keep its dry mass constant until measures.

3. Experimental approach:

3.1.Description of the stationary hot plate method

Figure 1 describes the experiment of the Hot Plate in Steady state HPS, the heating element is composed of a plane heating resistance of dimensions given in Table 1 inserted between the sample and the polyethylene having thermal conductivity of λ_p = 0,043 $W.m^{-1}K^{-1}$. Most of the heat dissipated by the heating element of a resistance R_h= 101Ω passes through its upper part, the different temperatures are measured by a thermocouple type K with a resolution of 0.001K. The set is then placed between two aluminium blocks in order to ensure a constant temperature on the unheated faces of the sample and the polyethylene foam in one hand, in the other hand to underwrite a faster establishment of the steady state, the three presented thermocouples measure the temperatures T_0, T_1, T_2 which correspond to temperatures measured; in the centre of the lower face of the heating element, on the unheated face of the sample and on the unheated side of the polyethylene, respectively.
Admitting the explained configuration one can write in steady state and supposing that the transfer by conduction is on one-dimensional:

$$\phi_0 = \phi_1 + \phi_2 \tag{1}$$

ϕ_0, ϕ_1 and ϕ_2 are expressed as:

$$\phi_0 = \frac{U.I}{S} \tag{2}$$

$$\phi_1 = \frac{\lambda_{plaster}}{e_{plaster}} \times (T_0 - T_1) \tag{3}$$

$$\phi_2 = \frac{\lambda_p}{e_p} \times (T_0 - T_2) \tag{4}$$

The voltage U applied through the heating element is estimated at an accuracy of 0.01 V.

By combining the previous equations we can write that:

$$\lambda_{plaster} = \frac{e_{plaster}}{T_0 - T_1} \times \left[\frac{U.I}{S} - \frac{\lambda_p}{e_p} \times (T_0 - T_2) \right] \tag{5}$$

Table 1. Dimensions of the elements of the circular HPS

Element	Heating element	polyethylene	Aluminium block
Dimensions (Diameter, thickness)	100x002 mm	100x10 mm	100x55 mm

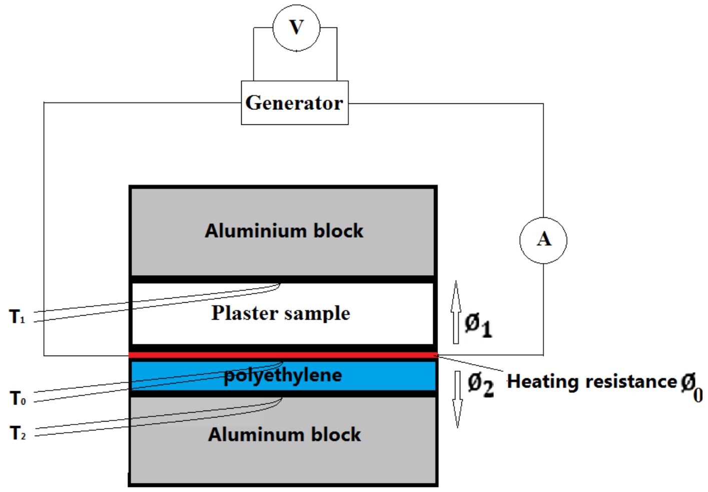

Figure 1: Schematic diagram of the circular HPS.

3.2. Using the HPS to determine the thermal conductivity variation

In this study the HPS elements are having a circular form; it is inserted in an insulated box in order to ensure a temperature stabilisation during the experimentation. In order to guarantee an acceptable accuracy the circular HPS (CHPS) is relied to a voltmeter and an ammeter to measure respectively the tension and the current as indicated in Figure 1. From equation (5) we noticed that the thermal conductivity, which corresponds to a mean temperature $T_m = (T_0 + T_1)/2$ of the sample, is proportional to the electric tension applied to the heating resistance. In order to evaluate the evolution of the thermal conductivity versus temperature the tension U is changed in the generator respecting a voltage step equal to 1V. For high mean temperatures T_m and for each value of U the thermal conductivity is measured once the steady state is established. However for low T_m four ice accumulators are disposed around the circular HPS as illustrated in Figure 2, which enables to measure thermal conductivity in low temperatures.

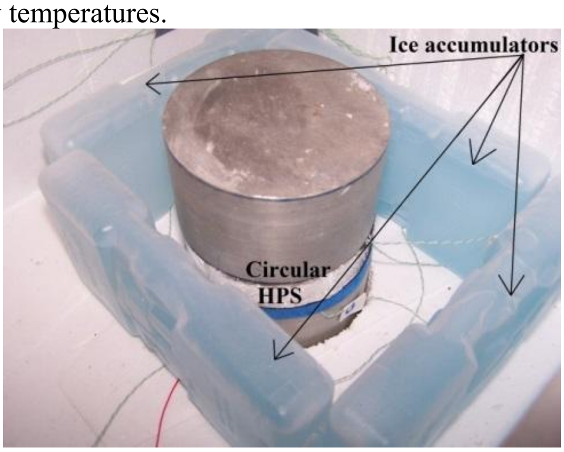

Figure 2: The circular HPS disposition in low temperatures measurements.

4. Results and discussion

4.1. Determination of thermal conductivity variation with temperature

Table 2 presents the measured thermal conductivity of plaster in the temperature range [19°C; 48°C], it is clear that the thermal conductivity slightly increases from 0,146 W/m.K for 19,1 °C to 0,154°C for 47,7 °C.

Table 2. Measured data using the circular HPS.

Circular HPS Disposition	U (V)	I (A)	T_0 (℃)	T_1 (℃)	T_2 (℃)	T_m (℃)	$\lambda_{plaster}$ (W/m.K)
With ice accumlators	12,08	0,119	26,148	11,584	12,058	19,103	0,146
	13,08	0,129	29,225	12,049	12,569	20,897	0,145
	14,09	0,139	32,678	12,780	13,224	22,951	0,144
	15,08	0,149	36,292	13,513	13,853	25,072	0,144
	16,08	0,159	39,749	14,111	14,267	27,008	0,146
	17,08	0,169	44,004	15,242	15,174	29,589	0,147
Without ice accumlators	10,08	0,100	36,316	26,213	26,082	31,199	0,145
	11,08	0,109	38,847	26,782	26,616	32,732	0,145
	12,08	0,119	41,895	27,628	27,462	34,679	0,147
	13,08	0,129	44,687	28,185	27,978	36,333	0,150
	14,09	0,139	47,986	28,907	28,692	38,339	0,151
	15,08	0,149	51,700	29,732	29,642	40,671	0,151
	16,08	0,159	55,324	30,366	30,332	42,828	0,152
	17,08	0,169	59,63	31,578	31,062	45,346	0,151
	19,08	0,189	65,133	30,364	30,205	47,669	0,154

4.2. Validation of the thermal conductivity variation

In order to validate the measured thermal conductivities values in the previous sub-section, other values were calculated knowing:

- The density: Calculated knowing the sample mass and apparent dimensions at dry state. The density is equal to 1002,909 kg/m^3.
- The thermal diffusivity: measured using the flash technic [5] in a mean temperature of the sample 28 ℃ and calculated adopting the global minimization procedures detailed in [6]. The calculated thermal diffusivity is 1,767 10^{-7} m^2/s.
- The specific thermal capacity: measured using the differential scanning calorimeter µDSC evo7 designed for the study of samples in isothermal modes over a wide temperature range [-45 ℃; 120 ℃], in this study the specific heat is measured in the temperature range [5 ℃; 50 ℃], the values of C_p corresponding to the studied temperatures in CHPS were extracted from the measures in this temperature range and collected in Table 3.

Table 3. Measured specific thermal capacity of gypsum plaster using the µDSC evo7

Tm (℃)	Cp (J.kg-1.K-1)	Tm (℃)	Cp (J.kg-1.K-1)	Tm (℃)	Cp (J.kg-1.K-1)
19,103	782,287	29,589	798,178	38,339	812,942
20,897	785,679	31,199	801,329	40,671	816,865
22,951	788,561	32,7315	803,463	42,828	820,828
25,0725	791,691	34,6785	806,943	45,346	824,533
27,008	794,014	36,3325	809,904	47,669	827,57

The thermal conductivity variation is then calculated using equation (6) and assuming that the thermal diffusivity and density remain constant versus temperature.

$$\lambda(T) = \rho \times a \times c(T) \tag{6}$$

Figure 2 presumes the thermal conductivity distribution of both measured and calculated values of thermal conductivity and the deviation percentage between them. It is shown that both values are having a positive trend with the same line slope 3.10^{-4} and a small difference of the intercept of 0,004. The deviation, measured using equation (7), goes from 1,83% to 5,29% with a mean value of 3,81%. These results validate the current exploitation of the HPS.

$$\text{Deviation}(\%) = \frac{\left|\lambda_{\text{calculated}} - \lambda_{\text{measured}}\right|}{\lambda_{\text{calculated}}} \times 100 \tag{7}$$

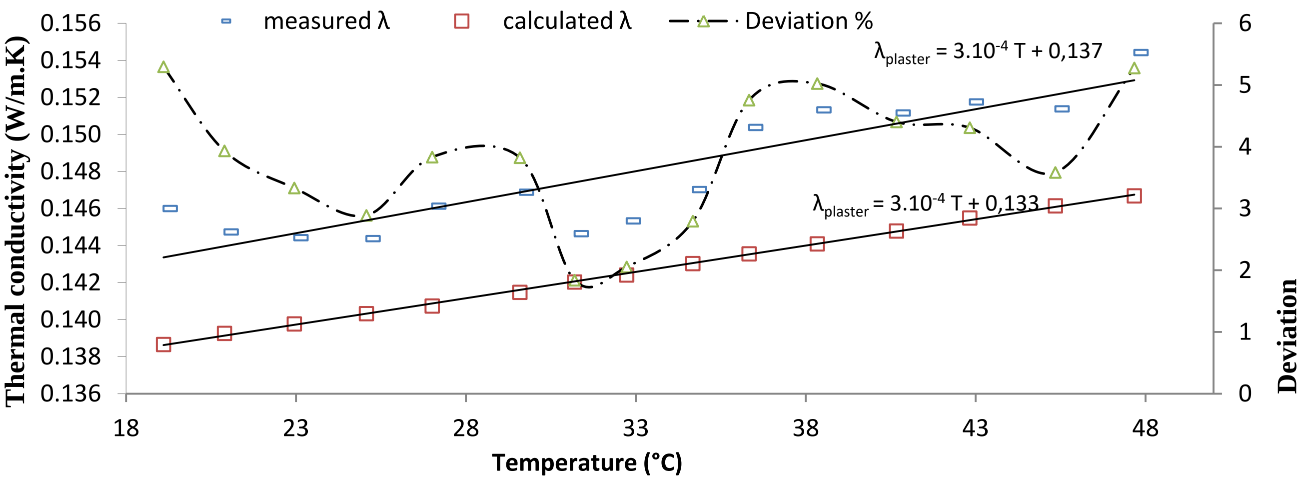

Figure 3: calculated and measured values of Gypsum plaster thermal conductivity versus temperature.

5. Conclusion

A straightforward exploitation of the hot plate method allowing the measurement of thermal conductivity variation with temperature of construction materials has been presented. The main interest of this study stays in its capability to perform a series of measurements in steady state ensuring a fast establishment of the thermal conductivity distribution versus temperature while conserving the same state of the sample. An experiment has been conducted on a sample of gypsum plaster enabling to compare its values with calculated ones; adopting experimental values of the specific heat variation with temperature and assuming a constant thermal diffusivity and density. We have given in this study the resulting deviations between calculated and measured values of thermal conductivity variation in the temperature range of [19°C; 48°C], this range is mostly located in interior temperatures of Moroccan buildings. A larger range could be studied using a heat source inside the box which contains the CHPS.

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