



# Thermophysical Characterization of Moulding Sands Using THB Method

Dorsaf Khalifa<sup>1</sup>(✉) and Foued Mzali<sup>1,2</sup>

<sup>1</sup> Université de Monastir, Ecole Nationale d'Ingénieurs de Monastir, LESTE, LR99ES31,  
5019 Monastir, Tunisia

dorsaf.khalifa@enim.u-monastir.tn

<sup>2</sup> Département de Génie Mécanique, Ecole Nationale d'Ingénieurs de Monastir,  
5019 Monastir, Tunisia

**Abstract.** In foundry practice and more specifically in sand casting, the filling and solidification processes depend on the thermophysical properties of the mould, such as thermal conductivity, thermal diffusivity and heat capacity. These properties depend strongly on the characteristics of the sand and are difficult to measure. In addition, numerical simulation in foundry, requiring the knowledge of these properties, in particular their variability in production, allows to predict casting defects and thus to avoid them, which makes it possible to reduce the percentage of reject. In order to understand the behaviour of foundry mould mixtures, a good knowledge of these properties is necessary. So in this study, a thermophysical characterization of two types of moulding sand was carried out using the transient hot bridge (THB) method: The green sand is used for the mould and the resin bonded sand is used for the core. The analysis of the variation of the thermal properties of the green sand has shown that these properties are very sensible of the variation of the density and the compression pressure. Comparing the two mixtures of sand, the green sand has higher thermal properties than the resin bonded sand because of the high quantity of the clay.

**Keywords:** Green sand · Resin bonded sand - THB · Thermophysical properties

## 1 Introduction

The thermal conductivity of moulding sand is particularly important for the cooling rate of casting. In addition to other factors (e.g. melt cleaning, degassing, grain refining, feeding technology), the cooling rate has a great influence on the microstructure obtained. In general, higher cooling rates generate fine grains, small secondary dendrite arms in the microstructure and thus improve, which in turn cause superior mechanical properties. On the other hand, today the design of casting technology uses numerical simulation of the solidification process which requires knowledge of several thermophysical parameters of the mould (Shohan and Sufian 2017) such as thermal diffusivity, heat capacity, thermal conductivity and density. All these parameters depend on several factors such as the compaction pressure and the density of the sand mould that affect the green sand process

(Guharaja et al. 2006). Unfortunately, these relationships are unknown in most cases, so there is a need to establish the dependencies between these parameters (Cast Metal Coalition 1998) as well as a need to perform a comparison between experimental results and numerical calculations of solidification and filling processes. Several methods have been used for thermal characterization of insulating material: needle probe (Jannot et al. 2021), Transient hot bridge THB (Hammerschmidt and Meier 2006; Mzali and Meier 2010; Faouel et al. 2012), etc. Since the THB method has given good results (Mzali and Meier 2010), therefore in this study, thermophysical characterization of green sand and resin bonded sand was carried out using the last method. For the green sand, the variation of the thermal properties as a function of density and compression pressure were analyzed.

## 2 Material and Methods

### 2.1 Sample Preparation

In this study, two types of moulding sand were characterized: Green sand (used for the mould) and resin bonded sand (used for the core). The compositions of the two types of sand are detailed in Table 1.

**Table 1.** Composition of materials

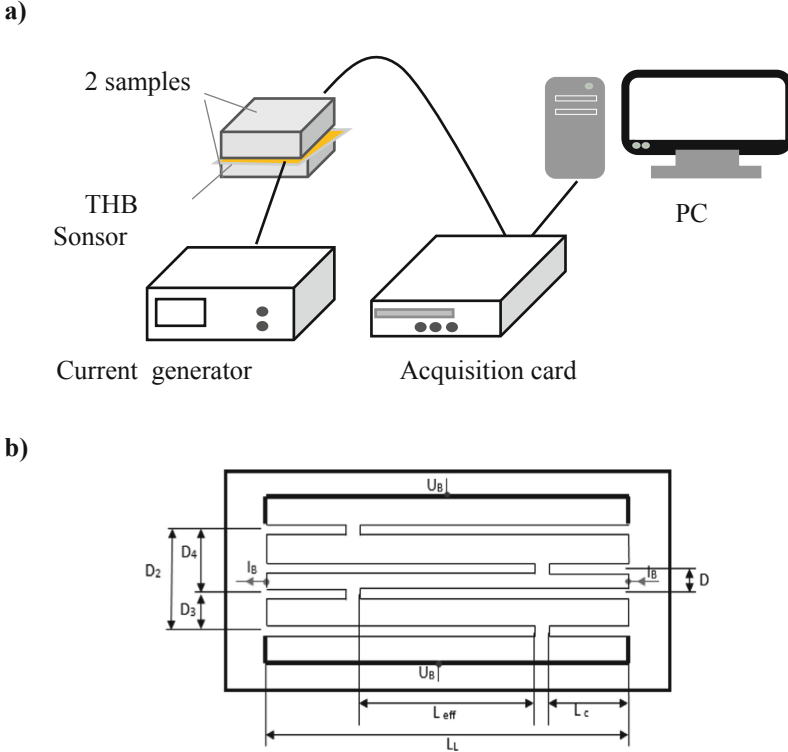
Moulding sand	Composition		
	Silica sand	Additives	
Resin-bonded sand	95%	Resin: 5%	
Green sand	13%	Bentonite: 12%	Water: 5%

Hand mixing was used throughout this step. Then, Samples with dimensions  $110 * 60 * 20 \text{ mm}^3$  were manufactured using a mould specified for this type of sample. A manual hydraulic press machine was used for the green sand samples production. The compaction pressure varies from 3.5 bar to 17.5 bar at ambient temperature.

### 2.2 Experimental Setup

The experiment is based on a thermoelectrical sensor inserted between two identical samples and connected to a current source and an acquisition card which is connected to a microcomputer to record the data using the Benchlink Data Logger software (Fig. 1.a). The THB sensor is composed of a nickel sheet of a  $7.5 \mu\text{m}$  thick cut as a circuit that is composed of four parallel tandem strips (Fig. 1.b). Two of them are in the centre (distant from D1) and the other two are on either side of the end of the sensor (distant from D2). Each strip is considered an electrical resistor. The equivalent circuit consisting of the eight strips forms a Wheatstone weight of equal resistances. This nickel sheet is inserted between two sheets of Kapton with a total dimension of  $120 * 60 * 0.055 \text{ mm}^3$ . The

passage of an electrical current allows the resistors to create a temperature difference between the center and the outside of the sample. This makes the weight unbalanced and an output voltage is measured allowing the determination of the thermal diffusivity and thermal conductivity of the sample.



**Fig. 1.** a) Experiment setup, b) THB sensor

**2.3 Analytical Model**

The temperature difference created between the center and the outside of the sample is experimented with:

$$\Delta T = T_{inn} - T_{out} \tag{1}$$

where  $T_{inn}$  is the temperature rise on the inner strip (K) and  $T_{out}$  is temperature rise on the outer strip (K).

The temperature variation between the inner and outer strips is the sum of the temperature variation of the same strips.

$$T_{inn} = T(D_0) + T(D_1) + T(D_3) + T(D_4) \tag{2}$$

$$T_{out} = T(D_0) + T(D_2) + T(D_3) + T(D_4) \quad (3)$$

where  $D_i$  is the strip width (m).  $i=\{1, 2, 3, 4\}$

The temperature difference is then (Hammerschmidt and Meier 2006):

$$\Delta T(t) = T(D_1) - T(D_2) = \frac{q}{4\pi\lambda} \left[ Ei\left(\frac{-D_2^2}{4\alpha t}\right) - Ei\left(\frac{-D_1^2}{4\alpha t}\right) \right] \quad (4)$$

The signal of the THB is proportional to  $\Delta T$  (Mzali and Meier 2010):

$$U_s = \frac{R_{eff} \cdot I_B \cdot \alpha \cdot \Delta T}{2} \quad (5)$$

where:

$U_s$  is the the sensor output signal (V)

$R_{eff}$  is the effective sensor electrical resistance ( $\Omega$ )

$I_B$  is the sensor current (A)

$\alpha$  is the temperature coefficient of electrical resistance ( $K^{-1}$ ).

The analytical method is based on slope evolution as a function of time.

The expression of the slope ( $m_i$ ) can be written by:

$$m_i = \frac{d(\Delta T(t))}{d(Ln(t))} = \frac{q}{4\pi\lambda} \left[ \exp\left(-\frac{D_1^2}{4\alpha t}\right) - \exp\left(-\frac{D_2^2}{4\alpha t}\right) \right] = \frac{q}{4\pi\lambda} \times m(t) \quad (6)$$

where:

$\lambda$  is the thermal conductivity of the sample ( $W m^{-1} K^{-1}$ )

$q$  is the linear heat flow density ( $W m^{-1}$ )

The maximal slope is detected at  $t = t_{max}$ :

$$\max m_i = \frac{d(\Delta T(t_{max}))}{d(Ln(t_{max}))} = \frac{q}{4\pi\lambda} \times m_{max} \quad (7)$$

where

$$m_{max} = \left(\frac{D_1}{D_2}\right)^{\frac{2D_1^2}{D_2^2-D_1^2}} - \left(\frac{D_1}{D_2}\right)^{\frac{2D_2^2}{D_2^2-D_1^2}} \quad (8)$$

From Eq. (7), we can identify the thermal conductivity:

$$\lambda = \frac{q \cdot Ln(t_{i+1}/t_i)}{4\pi \cdot d(\Delta T_{max})} \cdot m_{max} \quad (9)$$

where

$$q = \frac{R_{eff}}{L_{eff}} \cdot \left(\frac{I_B}{2}\right)^2 \quad (10)$$

where  $L_{eff}$  is the effective strip length (m).

From Eq. 5 the thermal conductivity is then expressed by:

$$\lambda = \frac{\alpha \cdot R_{eff}^2 \cdot Ln\left(\frac{t_{i+1}}{t_i}\right)}{4 \cdot \pi \cdot d(U_{bmax})} \cdot \left(\frac{I_m}{2}\right)^3 \cdot m_{max} \tag{11}$$

By combining the thermal and electrical models, the output voltage is then calculated by (Mzali and Meier 2010).

$$U_B(t) = \frac{\alpha \cdot R_{eff}^2 \cdot I_B^3}{32\Pi\lambda L} \left( Ln(t) + Ln\left(\frac{45\alpha}{16D}\right) \right) \tag{12}$$

The identification of the thermal diffusivity is based on the instantaneous slope  $m_i$  and not influenced by the thermal contact between the sensor and the sample. Indeed, from the expression of the dimensionless slope (Eq. 8) and by cancelling the term in  $D1$  when  $t$  tends towards infinity, we obtain the expression of the instantaneous thermal diffusivity:

$$a_i = \frac{D_2^2}{4 \cdot \pi \cdot Ln\left(\frac{1}{1-m_i}\right)} \tag{13}$$

The thermal diffusivity is then the average of the least values beginning with the maximum value ( $t_i > t_{max}$ ) of the slope.

### 3 Results and Discussion

#### 3.1 Particle Size Analysis

The granulometric analysis was carried out on the dried silica sand, of mass 500 g, poured on a series of sieves nested one on the other, whose diameter of meshes are increasing from the bottom of the column to the top. The classification of grains is obtained by the vibration of the column of sieves for 10 min. The partial refusal of a sieve is the mass of the remaining sand in the sieve. The result of this test is shown in Table 2 and Fig. 2.

**Table 2.** Granulometric analysis

Diameter of meshes (mm)	1.4	0.71	0.5	0.355	0.25	0.18	0.125	0.09	0.063	Bottom
Coefficient	6	15	25	35	45	60	85	120	170	300
Partial refusal	0.06	0.12	0.65	5.3	318.43	102.64	60.97	5.33	1.34	0.78

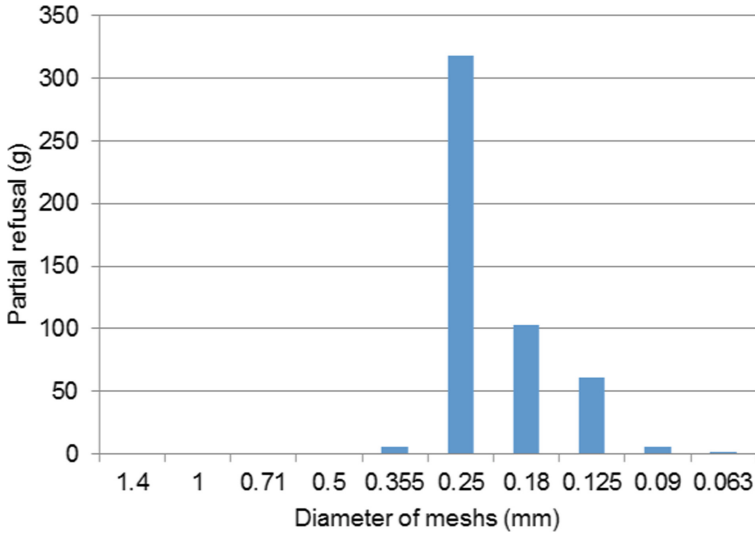


Fig. 2. Granulometric analysis

$$M_f = \frac{\sum_{i=1}^n (\text{coefficient} \times \text{Partial\_refusal})}{\text{sand mass}} \quad (14)$$

$M_f = 54$ . Then the fineness index of this silica sand corresponds to requirements of foundry sand and especially for aluminium casting (PERRIER and JACOB) with  $50 < M_f < 150$

### 3.2 Identification of Thermophysical Properties

Thermal characterization tests were carried out on green sand and resin bonded sand samples. The THB sensor, through which a current  $I_B = 400$  mA is made to flow, is inserted between two identical samples (Fig. 3) and thus generated by a time-dependent tension  $U_s$  with a time step  $\Delta t$  equal to 100 ms (Table 3).

Figure 4 a, b and c present respectively the variation of the thermal conductivity, thermal diffusivity and the heat capacity as a function of density. For a variation of 13% of the density, a significant variation in thermal conductivity of 20%, the thermal diffusivity of 50% and the heat capacity of 30% is observed.

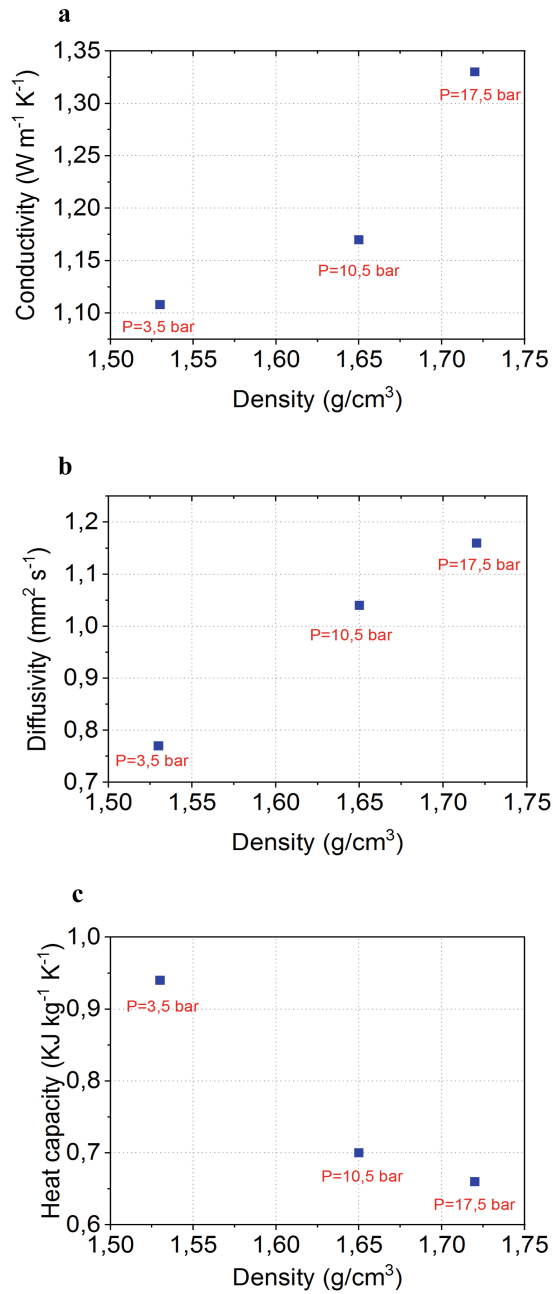


**Fig. 3.** THB sensor inserted between two green sand samples

**Table 3.** Results of characterization

Material	Green sand			Resin-bonded sand	
	P (bar)	10.5	17.5		
$\rho$ (g/cm <sup>3</sup> )	3.5	1.53 ± 0.038	1.65 ± 0.028	1.73 ± 0.02	1.47 ± 0.016
$\lambda$ (W /m.K)		1.108 ± 0.003	1.18 ± 0.008	1.33 ± 0.01	0.385 ± 0.006
$\alpha$ (mm <sup>2</sup> /s)		0.77 ± 0.008	1.04 ± 0.02	1.16 ± 0.07	0.393 ± 0.02
C <sub>P</sub> (KJ/kg.K)		0.941 ± 0.036	0.688 ± 0.029	0.663 ± 0.128	0.666 ± 0.052

The thermal conductivity and the thermal diffusivity are proportional to the variation of the density which is proportional to the compaction. This is related to the fact that compaction multiplies the contacts between particles and thus favors solid conduction. The compaction pressure leads to an increase in density. So it is reasonable to assume that progressive compression of the relatively small spherical particles of silica powders will reduce the particle gap. The pores represent an insulating medium for the passage of heat between particles. The compaction pressure may also lead to an increase in the average number of contacts between the particles and thus an increase in the thermal conduction in the solid matrix. The heat capacity is inverse proportional to the density, this means that a denser object requires more energy to be heated (Oktay et al. 2015). The density of the resin bonded sand is close to that of the green sand for P = 3.4bars with a low difference of 3.9%. However, the thermal conductivity is low by 65% and the thermal diffusivity is also low by 49%. This is explained by the clay content for the green sand is higher than for the resin-bonded sand which acts as a conductor and compensates for the space between the grains.



**Fig. 4.** Variation of thermal conductivity (a), thermal diffusivity(b), and heat capacity(c) as a function of density



## 4 Conclusion

This study illustrates how the thermal properties of green sand samples vary with compaction load and then with density variation. An increase of the thermal conductivity and diffusivity on all the samples, the more important the material is dense. This is due to the decrease in porosity with compaction and the grain-to-grain contact strengths. It is reasonable to assume that progressive compression of the relatively small spherical particles of silica powders will reduce the particle gap. The compaction pressure also leads to an increase in the average number of contacts between the particles and thus an increase in the thermal conduction in the solid matrix. The heat capacity is inversely proportional to the density. The thermal properties of the resin bonded sand are lower than the green sand despite the close density and it is explained by the difference in the clay content. As a continuation of this study, we aim to study the variation of these parameters as a function of mechanical properties and temperature.

**Acknowledgements.** This project is carried out under the MOBIDOC scheme, funded by the EU through the EMORI program and managed by the ANPR.

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