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A simple test method for measurement of the interface thermal resistance of coated and uncoated metal surfaces

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Abstract. Molds for metal casting are often internally coated in order to minimize the interaction between the steel surface of the mold and the melted metal during its pouring and solidification. However, the added coating increases the thermal interface resistance during the cooling process and it can thus affect the process itself. For example, numerical predictions and experimental results are matched only if the interface resistance is even quintupled in the presence of the usual interface coating, compared to the uncoated mold. In order to have a reasonable estimate of the interface thermal resistance, an easy to use measurement approach has been tested. This consists of contacting a cold and a hot samples of metals with known thermal properties, one at ambient temperature and the other one much hotter. The temperatures of the two samples, assumed to be uniform in each sample, are measured by thermocouples placed inside the samples through a hole, and the interface resistance is calculated from the time evolution pattern of those temperatures during the thermal transient that follows the instant in which the samples have been contacted.

1. Introduction

The thermo-fluid-dynamic models for metal casting simulations require to introduce many parameters. Each little uncertainty on such parameters adds an error on the results [1]. In the end, it is not easy to evaluate the reliability of results affected by the interaction of all uncertainties.

The Heat Transfer Coefficient (HTC) between two surfaces in contact is used as a proportionality constant between the heat flux density and the temperature difference between the contacted materials. In the early simulation stage of a design process, the actual HTC values are not known, despite their influence on the accuracy of the results [2]. Rough estimates based on typical HTC values, as available in software databases, are adopted in simulations [3,4]. A cumbersome trial and error process may then lead to more precise results, if required [2,5-8]. The situation can be improved by research work on system identification, that it is an inverse optimization through genetic algorithms [9,10]. Precise HTC values can thus be determined, but specific for the studied phenomenon. Of course a library of such identified HTC values can be reused for simulation in sequential designs. However, an *a priori* calculation of HTC as affected by specific design parameters is missing.

The present work investigates an approach for measurement of the contact heat transfer coefficient under controlled geometric parameters. The results can guide the simulation specialist in the calculation of more precise HTC values.

Standard test methods indeed exist to measure the interface thermal resistance. ASTM D-5470 [11] describes the 1-D reference bar method to measure at steady state conditions the thermal impedance for thermal interface materials such as elastomers, tapes, greases and phase change materials as used in electronics cooling, where the thermal impedance is defined as the sum of thermal resistance of the material layer and thermal resistance of the contact interface [11]. The interface material is placed



between a hot bar and a cold bar, whose temperatures are accurately measured. ASTM E1225 [12] is a steady-state, comparative technique to determine the thermal conductivity of a solid samples through the use of reference pieces with known thermal properties, thus allowing to not measure the heat flow, and it can also be adapted to evaluate the contact thermal conductance/resistance of materials. Both methods require samples with specified geometry and characteristics and, due to their steady-state approach, seem not adequate to measure very low contact resistance values. In general, it is a very challenging task to create and measure a temperature drop across an interface or a thin film since these are as thin as a few nanometers to tens of microns, so the interface contact resistance is arduous to be measured with less than 5% error [13]. Transient methods are also available [14], based on the same 1-D reference bar layout. Several other transient test methods have been developed such as laser flash [15], 3ω [16], photoacoustic [17], thermoreflectance [18,19], and infrared thermography [20]. However, most of them are best suited for studying thin films rather than contact resistances [21]. An alternative test method based on a transient approach is tested here. The method consists of contacting two samples, initially at different temperatures, and then monitoring the temperature transient of both samples (figure 1). The contacted surfaces are perfectly flat as the purpose is to assess the heat transfer at the contact interface as a function of the coating applied to one of the two samples. The approach can be exploited, in molds for metal casting, to assess the heat transfer coefficient between mold and solidified metal as a result of the application of a coating to the mold functional to the casting process.

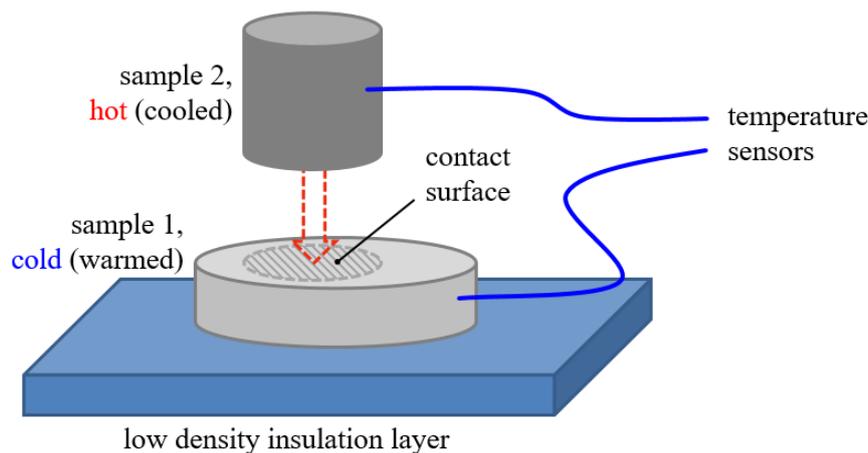


Figure 1. Test layout: sample 2 (initially hot) is contacted with sample 1 (initially at ambient temperature, *i.e.* cold), and then the temperature transient of both samples is measured; the purpose is to assess the heat transfer coefficient at the contact interface, which is flat.

2. Mathematical model

Two samples of the materials to be contacted, identified in the following by subscripts 1 and 2, are selected. The samples have known masses m_1 , m_2 (kg) and specific heats c_1 , c_2 (J/(kg·K)), therefore known heat capacities C_1 , C_2 (J/K):

$$C_1 = m_1 \cdot c_1 \quad C_2 = m_2 \cdot c_2 \quad (1)$$

The temperature in each sample varies in time, but it is assumed to be homogeneous in space. This is a usual approach to thermal analysis based on lumped capacitance calculation, which is considered acceptable if the Biot number associated to the considered thermal problem is very low. In this case, such condition can be expressed as

$$Bi_1 = \frac{h_c \cdot V_1}{\lambda_1 \cdot A_c} \rightarrow 0 \quad Bi_2 = \frac{h_c \cdot V_2}{\lambda_2 \cdot A_c} \rightarrow 0 \quad (2)$$

where $h_c \equiv$ HTC (W/(m²K)) between the two samples, A_c (m²) is the contact interface area, V_1 and V_2 (m³) are the volumes of solid matter in the samples, λ_1 and λ_2 (W/(m·K)) are the thermal conductivities of the sample materials.

2.1. Externally adiabatic samples

As a first approximation, heat transfer with the environment is neglected. This is not unreasonable if two highly conductive samples are contacted over a flat surface, and heat transfer with the surrounding environment is due to natural convection and thermal radiation at the exposed sample surfaces. In this case, the lumped capacitance analysis permits to build the following mass balance for each sample:

$$C_1 \cdot \frac{dT_1}{dt} = h_c \cdot A_c \cdot (T_2 - T_1) \quad (3)$$

$$C_2 \cdot \frac{dT_2}{dt} = h_c \cdot A_c \cdot (T_1 - T_2) \equiv -h_c \cdot A_c \cdot (T_2 - T_1) \quad (4)$$

Different initial temperatures $T_1(t=0) = T_{1,0}$ and $T_2(t=0) = T_{2,0}$ (°C) are imposed in order to start the thermal transient. The balances in equations (3)-(4) are equal, so:

$$C_1 \cdot \frac{dT_1}{dt} + C_2 \cdot \frac{dT_2}{dt} = 0 \quad (5)$$

The following formulation can then be used

$$\mathcal{G}(t) = T_1(t) + \frac{C_2}{C_1} \cdot T_2(t) \quad (6)$$

so that

$$\mathcal{G}(0) = \mathcal{G}_0 = T_{1,0} + \frac{C_2}{C_1} \cdot T_{2,0} \quad (7)$$

From equation (7) one obtains:

$$\frac{d\mathcal{G}}{dt} = 0 \quad \Rightarrow \quad \mathcal{G}(t) = \text{const} = \mathcal{G}_0 \quad (8)$$

In the end, the following equation is obtained:

$$T_1(t) + \frac{C_2}{C_1} \cdot T_2(t) = T_{1,0} + \frac{C_2}{C_1} \cdot T_{2,0} \quad \Leftrightarrow \quad T_1(t) = T_{1,0} + \frac{C_2}{C_1} \cdot [T_{2,0} - T_2(t)] \quad (9)$$

After a virtually infinite time t (s) the temperatures of the two samples converge onto an equilibrium value:

$$T_\infty = T_1(t = \infty) = T_2(t = \infty) \quad (10)$$

Introducing the equation (10) into equation (9), the final equilibrium temperature is equal to the average of the initial temperatures weighted by the heat capacity of the samples:

$$T_\infty = \frac{C_1 \cdot T_{1,0} + C_2 \cdot T_{2,0}}{C_1 + C_2} \quad (11)$$

Equation (9) can then be introduced in equation (4):

$$\frac{dT_2}{dt} = -h_c \cdot A_c \cdot \frac{C_1 + C_2}{C_1 \cdot C_2} \cdot \left[T_2 - \frac{C_1 \cdot T_{1,0} + C_2 \cdot T_{2,0}}{C_1 + C_2} \right] \equiv -\frac{1}{t_c} \cdot (T_2 - T_\infty) \quad (12)$$

where a characteristic time t_c (s) of the thermal process have been identified:

$$\frac{1}{t_c} = h_c \cdot A_c \cdot \frac{C_1 + C_2}{C_1 \cdot C_2} \quad (13)$$

With the position

$$\theta_2(t) = T_2 - T_\infty \Rightarrow \theta_{2,0} = \theta_2(0) = T_{2,0} - T_\infty \quad (14)$$

equation (13) can be solved for a given time t by variable separation

$$\frac{d\theta_2}{dt} = -\frac{1}{t_c} \cdot \theta_2 \Rightarrow \ln\left(\frac{\theta_2}{\theta_{2,0}}\right) = -\frac{t}{t_c} \quad (15)$$

The time evolution patterns of $T_2(t)$ and $T_1(t)$ are eventually described by the following formulas:

$$T_1(t) = T_{1,0} + \frac{C_2}{C_1} \cdot \left(1 - e^{-\frac{t}{t_c}}\right) \cdot (T_{2,0} - T_\infty) \equiv T_{1,0} + \left(1 - e^{-h_c \cdot A_c \cdot \frac{C_1 + C_2}{C_1 \cdot C_2} \cdot t}\right) \left[\frac{C_2 \cdot (T_{2,0} - T_{1,0})}{C_1 + C_2}\right] \quad (16)$$

$$T_2(t) = T_{1,0} + \frac{C_2}{C_1} \cdot \left(1 - e^{-\frac{t}{t_c}}\right) \cdot (T_{2,0} - T_\infty) \equiv T_{1,0} + \left(1 - e^{-h_c \cdot A_c \cdot \frac{C_1 + C_2}{C_1 \cdot C_2} \cdot t}\right) \left[\frac{C_2 \cdot (T_{2,0} - T_{1,0})}{C_1 + C_2}\right] \quad (17)$$

The two formulas can be compared with the measured time evolution patterns of sample temperature to identify t_c and, from that, h_c .

$$\frac{1}{t_c} = -\frac{1}{t} \cdot \ln\left[\frac{T_2(t) - T_\infty}{T_{2,0} - T_\infty}\right] = h_c \cdot A_c \cdot \frac{C_1 + C_2}{C_1 \cdot C_2} \Rightarrow h_c = -\frac{1}{A_c} \cdot \frac{C_1 \cdot C_2}{C_1 + C_2} \cdot \ln\left[\frac{T_2(t) - T_\infty}{T_{2,0} - T_\infty}\right] \cdot \frac{1}{t} \quad (18)$$

or

$$\frac{1}{t_c} = -\frac{1}{t} \cdot \ln\left[1 - \frac{C_1}{C_2} \cdot \frac{T_1(t) - T_{1,0}}{T_{2,0} - T_\infty}\right] \Rightarrow h_c = -\frac{1}{A_c} \cdot \frac{C_1 \cdot C_2}{C_1 + C_2} \cdot \ln\left[1 - \frac{C_1}{C_2} \cdot \frac{T_1(t) - T_{1,0}}{T_{2,0} - T_\infty}\right] \cdot \frac{1}{t} \quad (19)$$

It is interesting to observe that temperature data that are continuously measured along the thermal transient can be fitted to improve the estimate.

2.2. Externally non-adiabatic samples

Heat transfer with a surrounding environment with temperature T_a can be taken into account at the surfaces A_1 and A_2 (m^2) of the two samples different from the contact interface A_c . Two laminar heat transfer coefficients h_1 and h_2 ($\text{W}/(\text{m}^2\text{K})$), resulting from natural convection and thermal radiation processes, can be assumed on the samples surfaces.

The lumped capacitance thermal balances are as follows:

$$C_1 \cdot \frac{dT_1}{dt} = h_c \cdot A_c \cdot (T_2 - T_1) + h_1 \cdot A_1 \cdot (T_a - T_1) \quad (20)$$

$$C_2 \cdot \frac{dT_2}{dt} = -h_c \cdot A_c \cdot (T_2 - T_1) + h_2 \cdot A_2 \cdot (T_a - T_2) \quad (21)$$

An immediate solution for the above equation set is not immediately available. Yet one can observe that the heat transfer at the exposed surfaces causes the warmer sample, be it that with temperature T_2 , to cool down faster than in the externally-adiabatic case, resulting in an apparent heat flow towards the cold sample greater than that forecasted for an adiabatic sample. An overestimated value $h_{c,1}$ would thus be obtained while using equation (18). Instead, the colder sample at temperature T_1 warms up more slowly than in the externally-adiabatic case, so a lower apparent heat flow from the hot sample is obtained and, therefore, equation (19) yields an underestimated value of $h_{c,2}$. An average of the two calculated values may give a more reliable estimate of h_c :

$$h_c = \frac{h_{c,1} + h_{c,2}}{2} \quad (22)$$

The more similar are the two samples in terms of materials, mass and shape, the closer is the average to the real value.

3. Analysis

Equation (18) and equation (19) have been used to estimate the interface heat transfer coefficient from data calculated by means of a 0-D thermal model that takes into account heat transfer with the environment. Metal samples have been considered, and a heat transfer coefficient coherent with natural convection have been set at the exposed surfaces of the samples. Sample 1 was assumed to start the time transient with a temperature equal to that of the surrounding environment, whereas sample 2 was assumed to start at a significantly higher temperature. A given value of h_c was imposed at the contact interface. Conditions in which $Bi_1 < 0.1$ and $Bi_2 < 0.1$ have been considered. Representative results on the time evolution patterns of apparent h_c values along the thermal transient, respectively overestimated and underestimated, as well as the pattern of the average h_c value, are shown in figure 2.

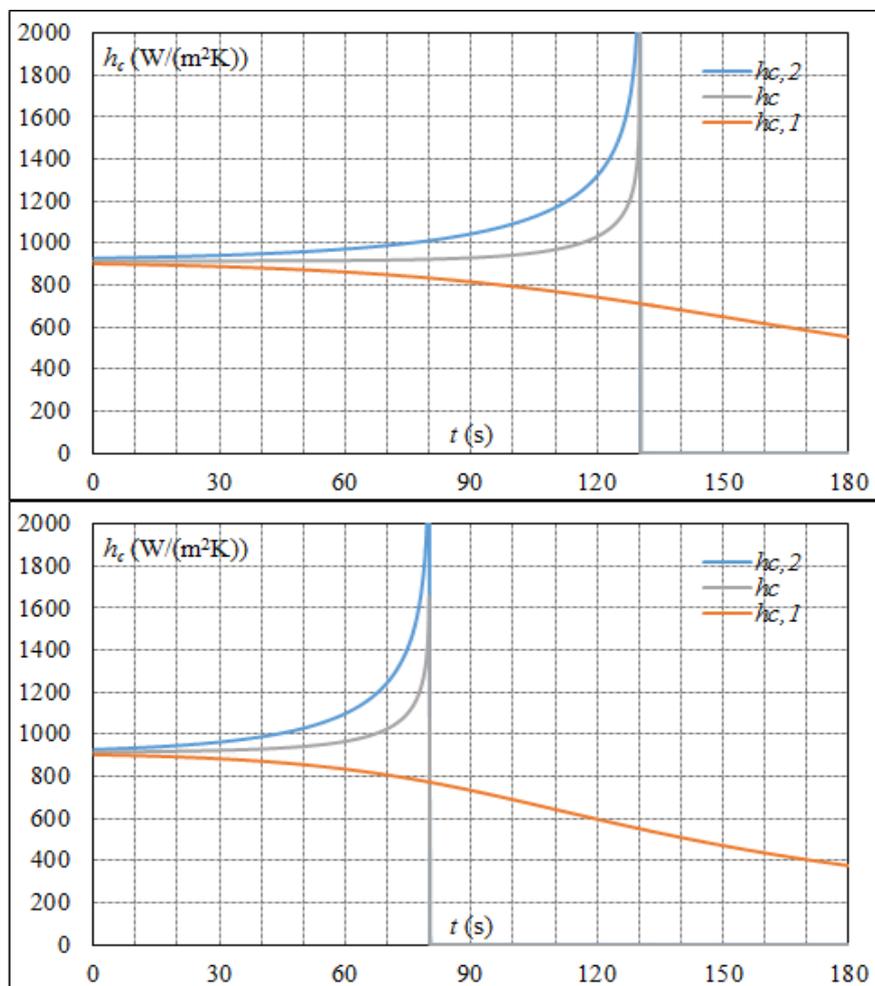


Figure 2. Time evolution patterns of the apparent heat transfer coefficients at the contact interface, $h_{c,1}$ and $h_{c,2}$, calculated from simulated time evolution patterns of sample 1 and sample 2 temperatures, respectively, and time evolution pattern of their average value h_c . For a significant part of the time transient, h_c is quite close to the contact heat transfer coefficient actually imposed in the simulation, equal to $900 \text{ W}/(\text{m}^2\text{K})$. Other simulation data: $h_1 = h_2 = 10 \text{ W}/(\text{m}^2\text{K})$, $T_{1,0} = T_a = 25^\circ\text{C}$, $T_{2,0} = 300^\circ\text{C}$; metal samples have same mass and shape (top), or one has double mass than the other (bottom).

In the time-evolution patterns in figure 2, a first part of the thermal transient is evident, in which the average values of the apparent heat transfer coefficients can be interpolated by a horizontal straight segment. The same can be obtained interpolating noisy measurements as in figure 3.

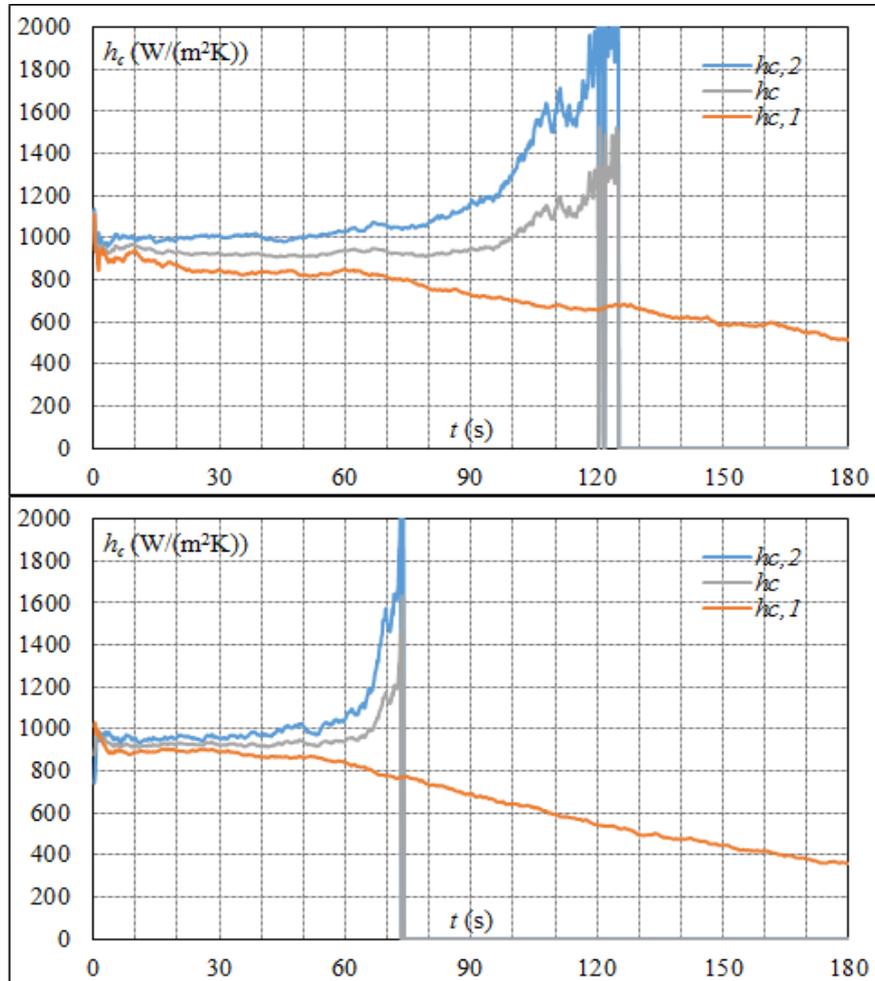


Figure 3. Time evolution patterns of the apparent heat transfer coefficients at the contact interface, $h_{c,1}$ and $h_{c,2}$, calculated from the simulated time evolution patterns of sample 1 and sample 2 temperatures, and time evolution pattern of their average value h_c , with contact heat transfer coefficient actually imposed in the simulation equal to $900 \text{ W/(m}^2\text{K)}$, metal samples with same mass and shape (top), or one with double mass than the other (bottom), and other simulation data as for figure 2, but with white noise up to $\pm 0.5^\circ\text{C}$ added to the sample temperatures.

In view of the positive outcomes of the theoretical analysis, experiments have been performed. Two cylindrical aluminum samples with different mass and dimension have been used. Sample 1, the one initially at ambient temperature, has base diameter 60.0 mm and height 34.1 mm, mass 259 g. Sample 2, initially heated up to a temperature above 200°C in an oven, has base diameter 39.0 mm and height 45.3 mm, mass 145 g. After having been extracted from the oven, the small sample has been placed onto the large one, in turn placed onto and insulating low-density support. The temperature of the samples has been measured by N-type thermocouples with 1 mm probe diameter, inserted in holes drilled in the samples and connected to a computerized data acquisition system with cold junction compensation (PicoLog TC-08). The ambient temperature has also been measured by a thermocouple of the same type. Representative time evolution patterns of the measured temperatures and the calculated apparent and average heat transfer coefficients are shown in figure 4, demonstrating a good agreement between experimental results and expectations.

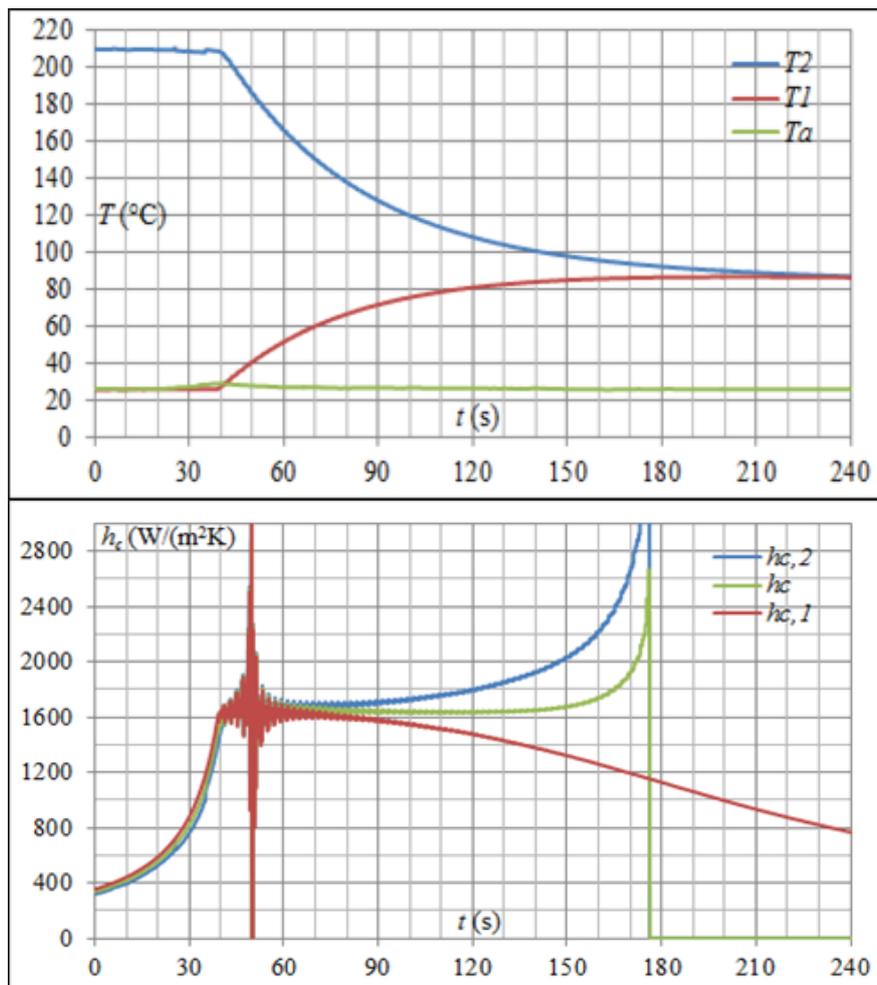


Figure 4. Measured temperatures of the samples (T_1 , T_2) and the ambient (T_a) (top), and time evolution patterns of the apparent heat transfer coefficients at the contact interface, $h_{c,1}$ and $h_{c,2}$, calculated from the measured time evolution patterns of sample 1 and sample 2 temperatures, and time evolution pattern of their average value h_c , (bottom).

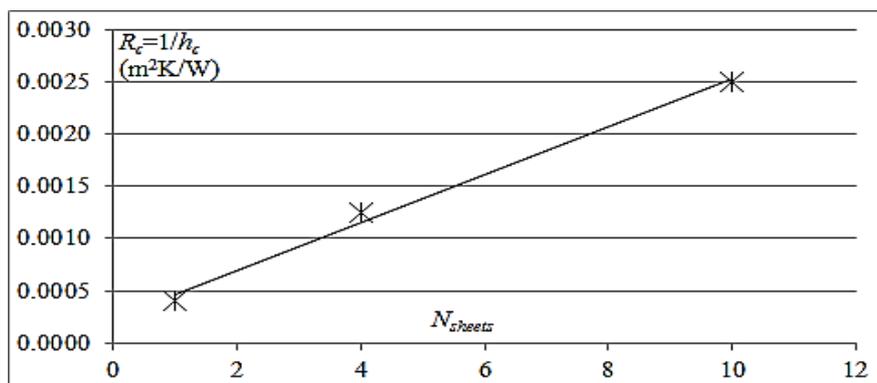


Figure 5. Interface thermal resistance $R_c = 1/h_c$ versus number of dry-paper foils stacked at the interface between samples.

Unfortunately, alternative test methods to crosscheck the measurement results are not yet available to the authors. Therefore, an alternative approach has been developed to obtain a preliminary, implicit confirmation of the reliability of the proposed method: the value of the interface resistance has been modulated by interposing different numbers of oven paper foils, and the contact heat transfer coefficient

has been determined. The paper foils were preventively dried in oven to avoid any latent heat effect due to absorbed humidity. Thereafter, the existence of a correlation between number of stacked foils and contact thermal resistance R_c ($\text{m}^2\text{K}/\text{W}$), *i.e.* the inverse of the heat transfer coefficient h_c at the contact interface, was verified. In agreement with expectations, a linear correlation between R_c and number of foils was found (figure 5).

4. Conclusive remarks

A test method has been developed to test quickly and with relatively low effort the heat transfer coefficient at the contact interface between two conductive samples as resulting from the presence of thermal interface materials coatings, needed in some industrial processes like die casting. The knowledge of such coefficients is necessary to optimize the above mentioned industrial processes. The devised method has provided results in good agreement with expectations.

A preliminary validation has been obtained. A full validation will be achieved by modelling the testing procedure by means of an already validated numerical code, in which the contact heat transfer coefficients will be adjusted until a correspondence with experimental results has been found. Alternatively, samples already measured by a standard test method will be tested.

Further improvement will be sought by using a 1-D thermal model, with the aim of measuring very high values of the contact HTC, which can induce temperature gradients in the sample and, therefore, cannot be assessed by a 0-D lumped capacitance model.

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