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INFLUENCE OF THERMAL CONTACT RESISTANCE IN THERMAL CONDUCTIVITY MEASUREMENTS USING GUARDED HOT PLATE METHOD

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Abstract: A new technique was developed at the Hungarian Metrological Institute (MKEH), devoted to optimising the thermal conductivity measurements by quantifying and minimising the effect of the thermal contact resistance (TCR) arising between a rigid sample and the heated plate of a high temperature guarded hot plate. Due to the existence of the TCR, the calculated thermal conductivity, based on different measurement techniques, could differ with by as much as 5-9 %.

The work was performed in the frame of the European Metrology Research Program (EMRP SIB52) titled “Metrology for Thermal Protection Materials”.

Keywords: Thermal contact resistance, thermal conductivity, guarded hot plate

1. INTRODUCTION

When a junction is formed by pressing two similar or dissimilar metallic materials together, only a small fraction of the nominal surface area is actually in contact because of the nonflatness and roughness of the contacting surfaces. If a heat flux is imposed across the junction, the uniform flow of heat is generally restricted to conduction through the contact spots, as shown in Fig.1. The limited number and size of the contact spots results in an actual contact area which is significantly smaller than the apparent contact area. This limited contact area causes a thermal contact resistance.

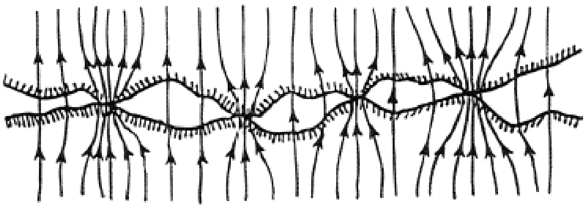

Fig. 1. Magnified view of two materials in contact

When measuring thermal properties with guarded hot plate method, the thermal contact resistance may influence the measurements by inducing systematic errors. A method to control and to minimise thermal contact resistance will be presented.

The guarded hot plate (GHP) method is a standard method to measure the thermal conductivity of solids [1]. The density of heat flow rate is provided by a heating plate on the one side and a cooling plate on the other side of the sample.

One major difficulty with the GHP method is to ensure that there are no lateral heat losses so the density of heat flow rate through the sample is effectively one-dimensional. Another problem is addressed to the potentially great influence of non-vanishing thermal contact resistances (TCR) between the sample and the elements of the measuring instrument on the measurement results. To minimise the errors resulting from TCRs, one can modify the experimental setup or apply mathematical corrections to the measurement results.

In EMRP SIB52 project high temperature guarded hot plates (HTGHP) are developed, working up to 800°C. References samples of high-density and low-density calcium-silicates (HDCaSi and LDCaSi), used as high quality thermal insulation materials, suitable for this wide temperature range were characterised. These types of silicates and ceramics are rigid, having the highest thermal contact resistance as presented in Fig 2 [2].

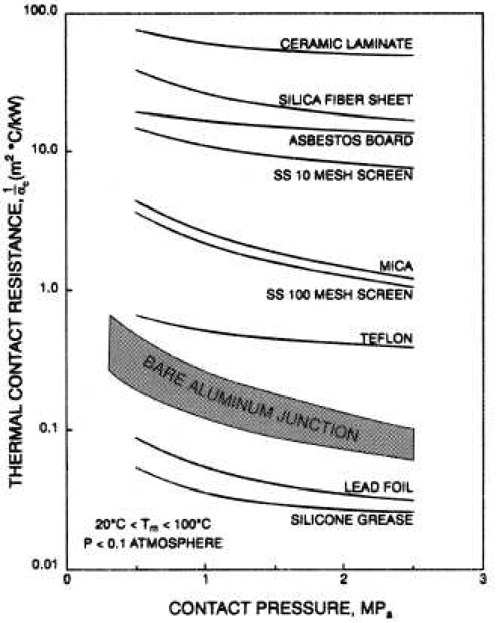

Fig. 2. Contact resistance for selected materials for thermal isolation

2. THERMAL CONTACT RESISTANCE IN GUARDED HOT PLATES

Considering the HTGHP presented in Fig. 3 [1], a thermal contact resistance appears between the rigid test specimen (H) and the metering section surface plates (B), and between the rigid specimen (H) and the cold surface plates (G) respectively. The temperature difference across the specimen is determined by temperature sensors situated inside the hot and cold plate (O and P).

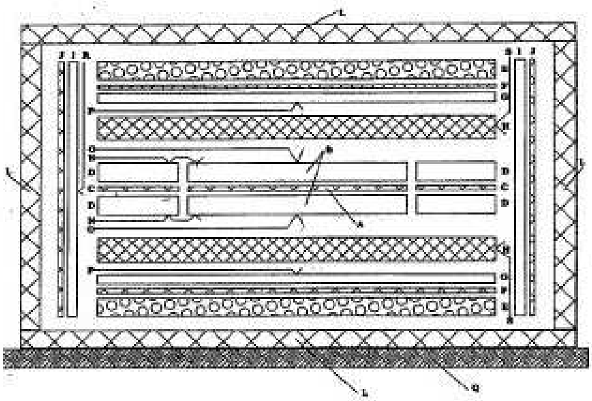

Fig. 3. Schematic design of double specimen guarded hot plate apparatus

This TCR causes a temperature drop between the surfaces in contact (Fig. 2). Therefore the temperatures measured by the sensors presented in Fig.3 will differ from the temperature of the warm and cold surfaces of the specimen (*thw* and *tcw*) defined in the standard [1]. The TCR, *R*, is defined as temperature difference times metering area *A* over the heat flow rate Φ (1):

$$R = \frac{A\cdot(thw - tcw)}{\Phi} \tag{1}$$

3. MEASUREMENT TECHNIQUE USED FOR QUANTIFYING AND MINIMISING THE EFFECT OF THERMAL CONTACT RESISTANCE

The technique applied by MKEH for quantifying the TCR is the most common used technique in case of reference surface temperature apparatus for calibration of surface thermometers. It’s appreciated as the most precise way to determine the temperature of a reference surface and the thermal contact resistance between the heater plate and the heated reference plate respectively [3].

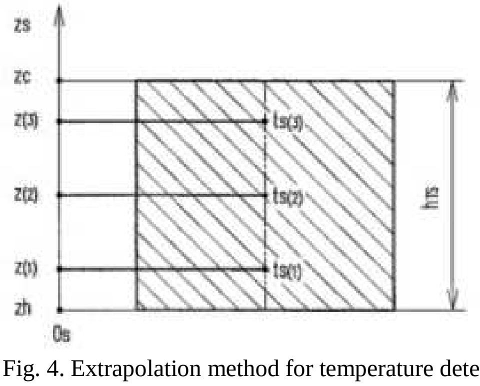

Fig. 4. Extrapolation method for temperature determination

Thin thermocouples are placed along the isotherm inside a solid body, presented in Fig.4. Based on the indications of particular thermocouples, the surface temperature can be determined, without any deformation of the original surface temperature distribution [3]. This technique based on extrapolation method is used at reference apparatus of National Metrology Institutes (NMIs) for determining the temperature of reference surfaces up to 600°C [4]. MKEH has experience in surface temperature measurements, coordinates EURAMET projects in this field [5].

This measurement technique is compatible with the standard for high temperature thermal conductivity measurements CEN/TS 15548-1:2011:E, where is specified: The temperature difference across the specimen, ΔT, is measured by temperature sensors fixed on / or in the surfaces of the plates in contact with the specimen and / or those fixed on / or in the surfaces of the specimens themselves [1].

3.1. Measurement arrengment

The developed set-up for modelling a GHP is presented in Fig. 5. This set-up is compounded from a heat source (HS), hot plate (HP), temperature sensors th1 and th2 inside the hot plate, cold plate (CP), temperature sensors tc1 and tc2 inside the cold plate, insulation (I) and protective cover (PC). Temperature sensors th1 and th2 are used for determination of the surface temperature of the hot plate, while with tc1 and tc2 the surface temperature of the cold plate can be evaluated. On the HP of cylindrical shape with diameter of 100 mm is placed the test specimen (TS) having equivalent shape.

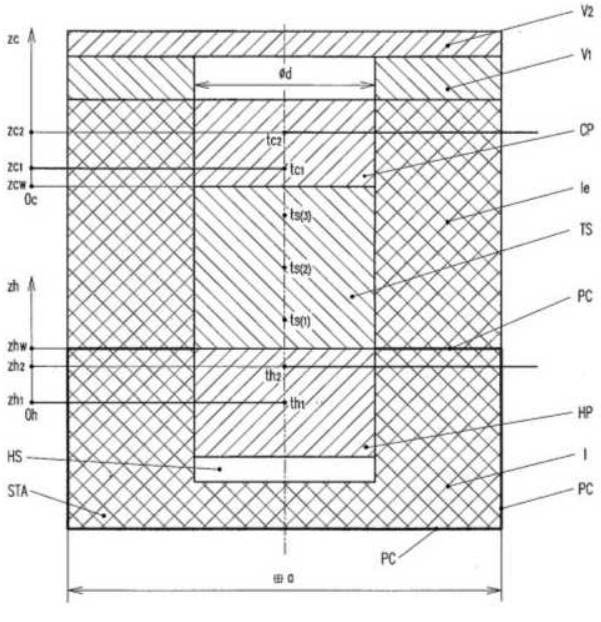

Fig. 5. Schematic design of the developed set-up

The surface temperature of the test specimen can be determined with the aid of three temperature sensors ts(1), ts(2) and ts(3), placed inside the TS. Insulation compounded from more layers having thickness of 10 mm is applied to prevent the heat loss in radial direction.

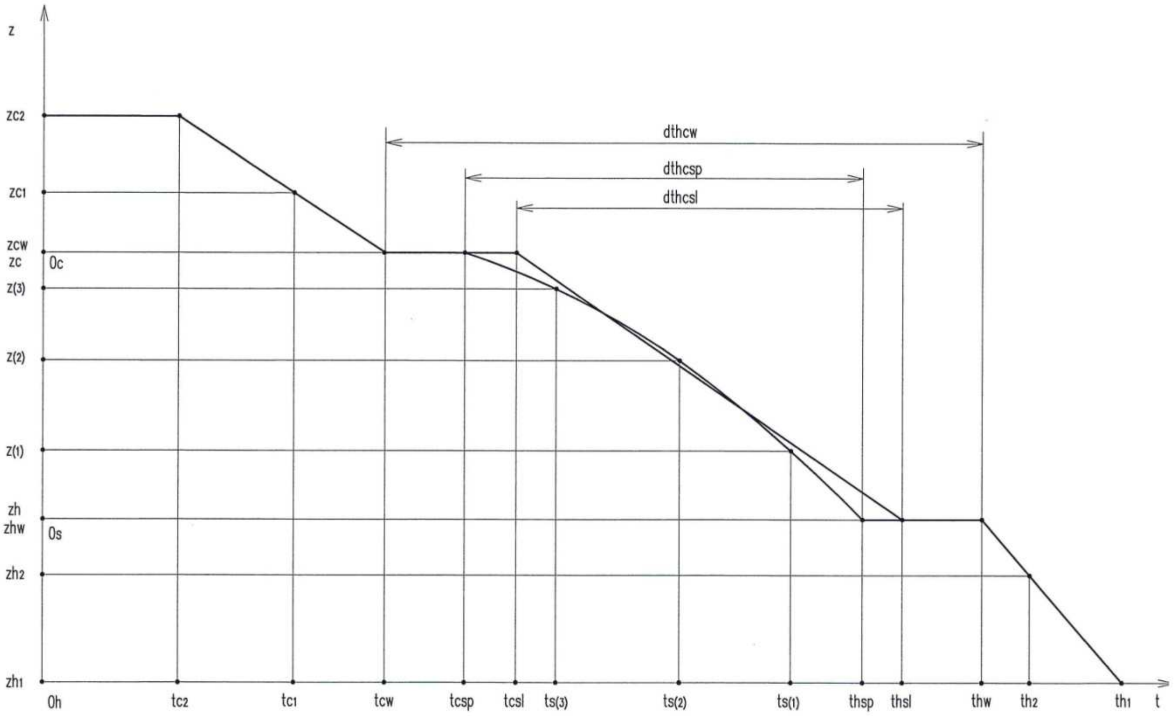

Fig. 6. Temperature drop inside a GHP

3.2. Comparison of different measurement techniques based on the position of the temperature sensors

In Fig. 6 are presented the temperature drops at different parts of a GHP: inside the cold plate, the specimen and the hot plate respectively. The extrapolated surface temperature of the hot and cold plates (*thw* and *tcw*) can be determined with (2) and (3). Notations with *z* are the positions of the different temperature sensors having different *t* temperatures.

$$thw = th1 - \frac{zhw - zh1}{zh2 - zh1} \cdot (th1 - th2) \qquad (2)$$

$$tcw = tc2 - \frac{zc2 - zcw}{zc2 - zc1} \cdot (tc1 - tc2) \qquad (3)$$

The temperature difference between the upper and lower part of the specimen respectively, can be evaluated using different approximations: linear (*dthcsl*) or parabolic (*dthcsp*). Comparing the calculations with the two approximations, it results a difference of less than 1 %.

Considering the measurement technique based on temperature sensors placed inside the hot and cold plate respectively, the temperature difference between the HP and CP can be written:

$$dthcw = thw - tcw \qquad (4)$$

The thermal conductivity of the specimen is calculated with (5),where *d* is the thickness of the specimen.

$$\lambda w = \frac{\emptyset \cdot d}{A \cdot (thw - tcw)} \qquad (5)$$

Considering the new measurement technique based on temperature sensors placed inside the specimen, the temperature drop across the specimen can be written:

$$dthcs = ths - tcs \qquad (6)$$

In this case, the thermal conductivity of the specimen is calculated using the relation (7).

$$\lambda s = \frac{\emptyset \cdot d}{A \cdot (ths - tcs)} \qquad (7)$$

The thermal contact resistance is illustrated in Fig. 6 as the difference between the temperature variations *dthcw* and *dthcs(l,p)*. This difference caused by the discrepancies in the measurement technique applied can be quantified using (8).

$$error(\lambda_{rel}) = \left(1 - \frac{\lambda s}{\lambda w}\right) \cdot 100 \qquad (8)$$

The error in λ resulting from the measurement technique (λw) presented first, can be expressed comparing the temperature drops calculated in each case:

$$error(\lambda_{rel}) = \left(1 - \frac{thw - tcw}{ths - tcs}\right) \cdot 100 \qquad (9)$$

3.3. Measurement results

Thermal conductivity measurements were effectuated using two types of rigid test specimens (HDCaSi and LDCaSi). The effect of the emissivity on the thermal contact resistance was studied changing the materials of the hot and cold plates having different emissivities (Fig. 7, 8).

The relative emissivity of the metal plates was determined experimentally by comparison method between a contact and a non-contact thermometer. First, the surface temperature of the plate was determined with a contact thermometer. Then, the emissivity given by the non-contact thermometer was adjusted until the thermometer indicates the same temperature as the contact thermometer.

In Fig. 7 and 8 are presented the measurement results effectuated in the temperature range from 100 °C to 600 °C. The material of the specimens was LDCaSi and HDCaSi respectively. For hot and cold plates, different types of material were applied, with emissivities ε of 0.2 and 0.8 respectively.

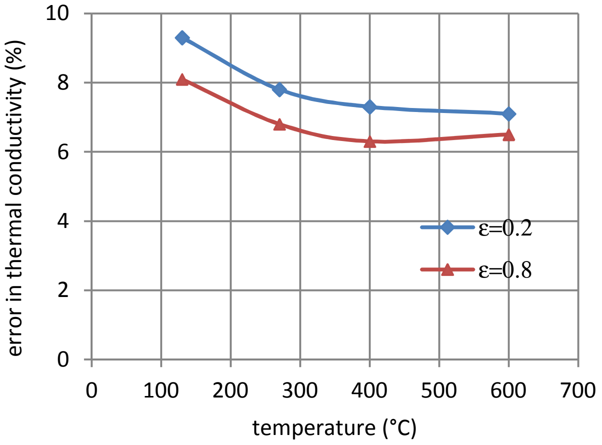

Fig. 7. Errors of λ caused by TCR for LDCaSi specimens

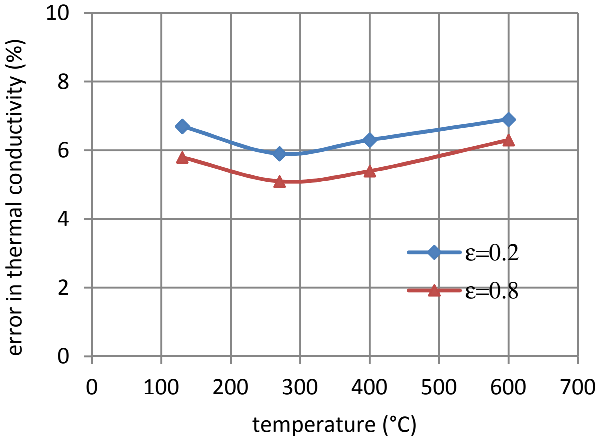

Fig. 8. Errors of λ caused by HDCaSi specimens

The technique for measuring high temperature thermal conductivity, placing the thermometers inside the specimen itself, causes an error of less than 1 %.

In case of the conventional GHP method placing the temperature sensors only in the hot and cold plates, the error in the thermal conductivity (λ) measurements caused by the effect of thermal contact resistance is significantly higher, and can rise from 5 % to 9 %.

4. CONCLUSIONS

The optimisation of methods to evaluate thermal conductivity was the main objective of this study. The measurement results provide solutions to one of the pressing problems associated with thermal conductivity metrology, covering the temperature range from 100 °C to 600 °C. Thermal contact resistance arising between a rigid sample and the heated plate of a high temperature guarded hot plate (HTGHP) can cause significant discrepancies in thermal conductivity measurements.

The alternative technique based on temperature measurement inside a rigid sample from thermal insulation material is suitable for quantifying and minimising the effect of the thermal contact resistance, as well as for accurate determination of the radial heat loss along the sample.

ACKNOLEDGMENTS

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