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DETERMINATION OF THERMAL CONDUCTIVITY IN FOUNDRY MOULD MIXTURES

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For a thorough understanding of the behaviour of foundry mould mixtures, a good knowledge of thermal properties of mould materials is needed. Laboratory determination of thermal conductivity of mould mixtures enables a better control over scabbing defects which are a major problem in green sand mould mixtures. A special instrument has been designed for that purpose and it is described in this work.

Key words: thermal conductivity, granularity of sand, foundry sand

Određivanje koeficijenta toplinske vodljivosti kalupnih mješavina. Za detaljno razumijevanje ponašanja kalupnih mješavina prilikom lijevanja odljevaka potrebno je dobro poznavati toplinska svojstva kalupnih materijala. Laboratorijsko određivanje toplinske vodljivosti kalupnih mješavina omogućava bolju kontrolu nad pojavom odlupljivanja, koja je kao glavni problem vezana za kalupne mješavine s fizikalno očvrstivim vezivima. Određivanje koeficijenta toplinske vodljivosti provedeno je na posebno konstruiranom uređaju koji je opisan ovim radom.

Ključne riječi: toplinska vodljivost, zrnatost pijeska, kaluparski pijesak

INTRODUCTION

For a thorough understanding of the behaviour of foundry mould mixtures, a good knowledge of thermal properties of mould materials [1-3] is required. Thermal conductivity is an important parameter among them. In order to determine the thermal conductivity of real foundry mould mixtures, an instrument for measuring thermal conductivity has been designed [4, 5].

Laboratory determination of thermal conductivity of mould mixtures enables a better control over scabbing defects which are a major problem in green sand mould mixtures [6]. The layer which is responsible for their formation is a part of the mould which has been heated to the temperature higher than the temperature of quartz sand allotropic modification, i.e. the temperature above 570 °C. Such layer is very unstable and is the main cause of internal stresses. As the structure moves and high internal stresses occur, the mixture is being deformed and small parts of the mould mixture break off and fall into the melt, thus causing mould defects.

INSTRUMENT FOR THE DETERMINATION OF THERMAL CONDUCTIVITY

Since the foundry mould mixture consists of the base material (sand), a bond (bentonite), water and mixture additives, the most reliable way of determining thermal properties of the mixture is to do it experimentally. Experimental determination of thermal properties of mould mixtures implies the determination of heat transfer coefficient. A special instrument, shown in Figure 1, has been designed for that purpose.

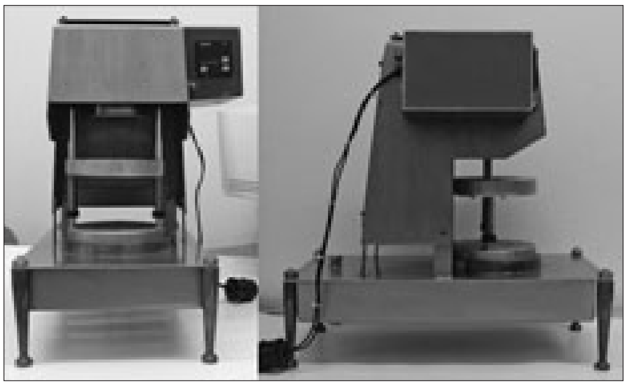

Figure 1. Instrument for determining the heat transfer coefficient

The basic parts of the instrument for determining the heat transfer coefficient of a mould mixture are: a high-temperature reservoir, a low-temperature reservoir, a test sample holder device, a microcontroller-based temperature regulator and the casing.

The high-temperature reservoir is the heat source in the instrument. A 2 kW electric heater with a plate of 90 mm in diameter is used. The contact surface which transfers heat to a test sample is a 6 mm thick steel plate. A Pt100 temperature measuring sensor capable of rec-

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ognizing temperatures from -200 °C to +530 °C is attached to the steel plate. The measuring sensor is directly connected to the microcontroller-based temperature regulator which uses the measured value for maintaining the constant temperature of the high-temperature reservoir plate.

The low-temperature reservoir made of aluminium is used to carry away heat from the test sample. On the lower part of the reservoir there are ducts. A constant input temperature of the water flowing through these ducts ensures a constant temperature of the low-temperature reservoir which takes over the heat flow transferred from the high-temperature reservoir through the sample. The heat quantity transferred to water through the sample in a unit of time, can be calculated from the water flow and the difference between the temperatures at the inlet and outlet of the low-temperature reservoir.

The high-temperature reservoir is fixed to the casing of the instrument, and the low temperature reservoir can be moved up and down and tilted in all directions around the test sample axis. By moving the reservoir up and down, the test sample can be easily positioned and removed from between the two reservoirs. In addition, positioning, holding and removing of non-standard test samples of different heights are made possible. The tilting of low-temperature reservoir enables complete and uniform adherence of the test sample, high-temperature and low-temperature reservoirs. This complete and uniform contact of the test sample with the reservoirs results in measuring accuracy. The mechanism for holding the test sample together with the high-temperature and the low-temperature reservoir is shown in Figure 2.

The heating of samples is controlled by a microcontroller-based temperature regulator which is directly connected to a temperature sensor.

The regulator has the following characteristics:

- Dimensions: 48×48×106 mm (1/16 DIN)
- Power supply: 85 to 264 V , 50/60 Hz, 3 VA maximum
- Operating conditions: 0 °C to 55 °C, humidity from 20 % to 85 %.

The sensor:

- Pt100, measuring flow 170 ìA
- Thermo pair input selection: 10 MÙ
- A/D resolution: 15 000
- Sampling: 10 measurements per second
- Accuracy: 0,2 % for Pt100
- Time constant: 200 to 300 ms.

The base of the instrument is actually a water reservoir with dimensions of 300×500×100 mm. If the volume of the reservoir is not suitable for bigger samples to be measured, it can be expanded by adding one or more external reservoirs. The reservoir water, kept at a constant temperature, is used for maintaining a constant temperature in the low-temperature reservoir.

The water from the reservoir is pumped by a small pump through plastic pipes to the first measuring point placed 100 mm before the water enters the low-temperature reservoir. There, the input water temperature is measured. Passing through the low-temperature reservoir, the water receives a certain quantity of temperature and is heated. The second measuring point is at the low-temperature reservoir outlet where the output water temperature is measured. On the basis of the measurement time, input and output water temperature, and of the quantity of water measured by a measuring cylinder, one can calculate the heat flow through a sample, which is required for calculating the heat flow coefficient.

It has already been stated that temperatures at particular points are measured by means of K-type thermo pairs. The sampling rate during the measuring of the temperature of a mould mixture sample is one second. The measured values are recorded by a computer. Figure 3 shows the measuring equipment used for gathering and processing data obtained by measuring, i.e. by experimental determination of the heat transfer coefficient.

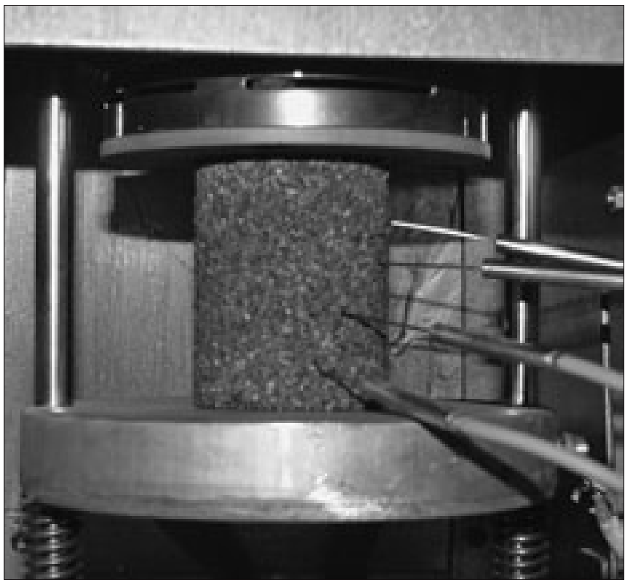

Figure 2. Mechanism for holding test samples

EXPERIMENTAL DETERMINATION OF THE HEAT FLOW COEFFICIENT

Standard test samples with a diameter of 50 mm and a height of 50 mm have been used for experimental determination of the heat flow coefficient. The mould mix-

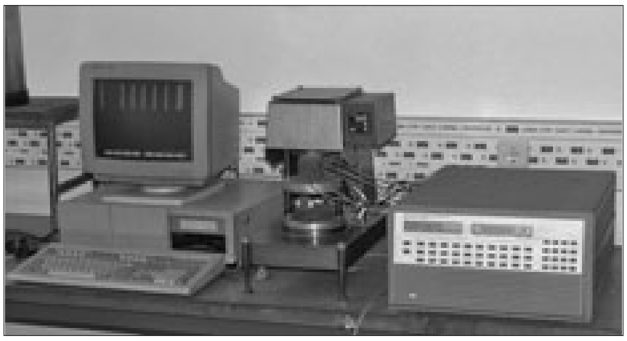

Figure 3. Measuring equipment for experimental determination of the heat transfer coefficient

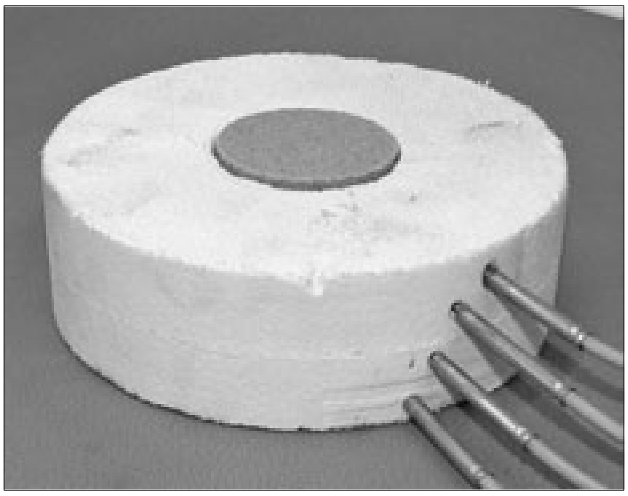

Figure 4. Insulated test sample of mould mixture to be measured for thermal conductivity

ture samples are marked as M1, M2 and M3, and they differ as far as the quartz sand granulation is concerned. The contents of bentonite and water are constant for all three samples and they amount to 6% of bentonite and 4% of water. In order to reduce the heat transfer into the surroundings during measurements, each test sample is insulated by a styrodur shell, Figure 4. Four temperature sensors are fitted through the insulating shell to measure the temperature at the centre of the test sample, but at different heights within the sample.

Figure 5 gives a schematic representation of the mould mixture test sample on the measuring instrument in relation to the high-temperature and low-temperature reservoirs, and the arrangement and position of temperature sensors T2-T5. The measured temperature of the high-temperature reservoir is marked as T1, and the temperature of the low-temperature reservoir as T6.

Table 1 gives the results of measurements carried out on the three basic test samples of mould mixtures M1, M2 and M3:

On the basis of the results of measurements given in Table 1, and using the expression (1) for the total heat flow through the sample, one can calculate the values of the heat transfer coefficient for a particular sample of mould mixture according to expression (2). The calculated values are given in Table 2.

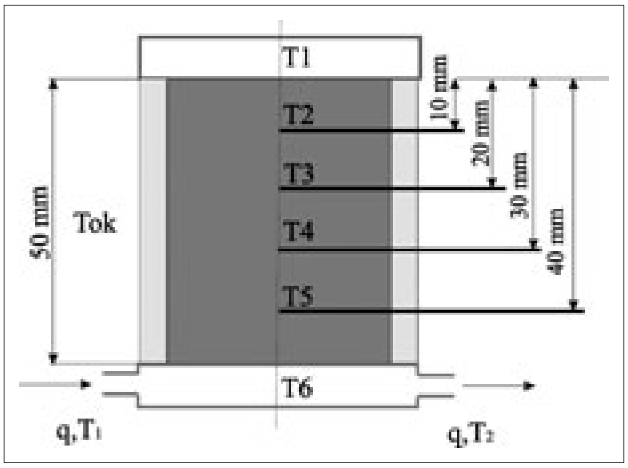

Figure 5. Schematic representation of the test sample on the measuring instrument

Table 1. **Composition of mould mixtures and measured temperatures**

Mould mixtures	M1	M2	M3
Sand granularity	**0.1**	**1**	**0.4**
Mass / kg	0,5	0,5	0,5
Bentonite / g	30	30	30
Water / g	21,5	21,5	21,5
Flow / kg/h	0,45	0,7	0,38
Measured Temperature			
Temperature 1 / °C	300	300	300
Temperature 2 / °C	225	226	211
Temperature 3 / °C	155	171	149
Temperature 4 / °C	98	91	92
Temperature 5 / °C	62	61	62
Temperature 6 / °C	34	32	36
Temperature 7 / °C	6	6	7

$$\phi_{\text{total}} = q_v \cdot c_v \cdot \Delta\vartheta_w \qquad (1)$$

where:

ϕ_{total} – total heat flow through a sample / W,
q_{h} – quantity of humidity / kg/s,
c_{w} - specific thermal capacity of water / J/(kgK),
$\Delta\vartheta_w$ – difference between the water temperatures at the inlet and outlet of low-temperature reservoir / °C.

$$\lambda_i = \frac{\phi_{\text{total}} \cdot (x_{i+1} - x_i)}{(\vartheta_i - \vartheta_{i+1}) \cdot A_s} \qquad (2)$$

where:

λ_i - heat transfer coefficient / W/(mK),
ϕ_{total} – total heat flow through a sample / W,
x – distance between two measuring points / m,
ϑ - temperature of measuring points / °C,
A_{s} – area of the sample cross section / m,
i – number of the measuring point.

The calculated heat transfer coefficients for each sample of mould mixture are indexed from 1 to 5, where the heat transfer coefficients marked by the index 1 are valid for the measuring interval from the measuring point ϑ_1 to ϑ_2 where temperatures are higher. The second row of the table gives the heat transfer coefficients

Table 2. **Values of heat transfer coefficient for three mould mixtures with different quartz sand granulations.**

	λ_{M1} / W/(mK)	λ_{M2} / W/(mK)	λ_{M3} / W/(mK)
1	0,629	0,857	0,664
2	0,489	0,830	0,523
3	0,309	0,372	0,358
4	0,228	0,407	0,279
5	0,149	0,269	0,105

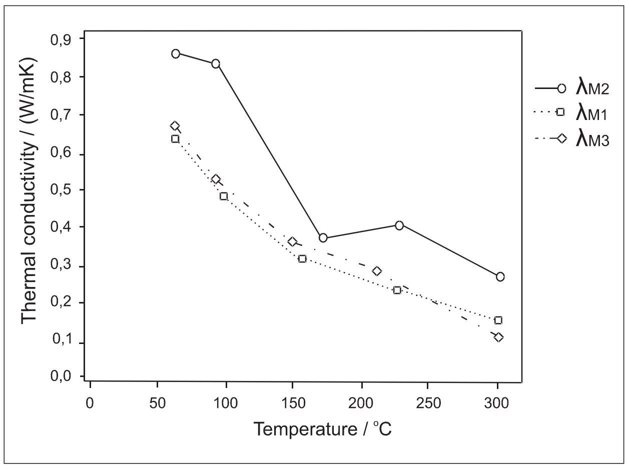

Figure 6. Measurement results of heat transfer coefficients of mould mixtures with different granulometric compositions

marked by the index 2, which are valid for the measuring interval from the point ϑ_2 to ϑ_3, and so on.

For easier reference, the calculated values of the heat transfer coefficient for different mould mixture samples given in Table 2 are graphically presented in Figure 7.

In Figure 6, one can notice that heat transfer coefficients differ significantly with respect to the increase in temperature during the heating of the mould mixture. It is very important that this change has been taken into account of thermal conductivity in the simulation of the process of heating moulds during the process of mould solidification.

ESTIMATION OF THE INSTRUMENT MEASUREMENT UNCERTAINTY

The instrument made for measuring thermal conductivity of mould mixtures, measures the sample temperature with certain measurement accuracy. In order to estimate the measurement accuracy, the instrument measurement uncertainty has to be determined. The total measurement uncertainty can be expressed by equation (3) as the square root of the sum of the squares of individual components of the each instrument.

$$u = \sqrt{\sum u_i^2} \tag{3}$$

where:
u - total measurement uncertainty,
u_i - uncertainty of the i-instrument.

ESTIMATION OF UNCERTAINTY FROM BOUNDARY ERRORS

Specifications of a measuring instrument usually include accuracies, i.e. boundary errors. The information on boundary errors (G) does not contain the information on the real value of the measuring instrument error. Therefore, when the information on the distribution of errors among all measuring instruments (in good working order) from a particular production series is missing, we assume that all measured values (measured by any of measuring instruments from the same series, M) within the range which determines the boundaries of errors (M –G and M +G) are equally probable, and impossible beyond these boundaries. This type of distribution is called rectangular distribution. The standard deviation of individual readings which are equally probable in the interval is expressed as:

$$s = \frac{G}{\sqrt{3}} \tag{4}$$

s - standard deviation of individual read,
G - boundary errors.

Since measurement uncertainty is expressed by a standard deviation, the following is valid:

$$u_B = \frac{G}{\sqrt{3}} \tag{5}$$

s - standard deviation of individual read,
G - boundary errors,
u_B - type of uncertainties.

This is the way B-type uncertainties are estimated when we have at our disposal the information on boundary errors of the instrument, on statistical boundary errors, the hysteresis of the instrument, its resolution, quantization and rounding-off. When defined error boundaries are available, measurement uncertainty is estimated by dividing the defined boundary error by 3. The B-type estimation method is applied in our case to determine the measurement uncertainty of measuring the heat transfer coefficient. Based on the measurement uncertainties u_A = 0,02, u_B = 0,02 and u_C = 0,01 into expression (3), one obtains the total measurement uncertainty of heat transfer coefficient determination of u = 0,1. The instrument measurement uncertainty obtained in this way determines heat transfer coefficient with a sufficient level of accuracy.

CONCLUSION

Different types of mould mixtures have different heat transfer coefficients which change with temperature. The type of sand and its granulometric composition affect thermal properties of the mould. The design and construction of measuring equipment for determining the heat transfer coefficient of mould mixtures enabled measurements on standard test samples of mould mixtures within the temperature range of up to 300 °C. Thus, we obtained different heat transfer coefficients which affect the cooling of the mould during its solidification. The application of this measuring instrument enables the determination of the change in heat transfer coefficient of foundry mould mixtures. The obtained results are then used in computer programs for the purpose of simulating in the green sand moulds solidification process. Such approach results in higher accuracy of simulation results intended to determine the rate at which moulds are heated. Knowing the real heating rates of moulds, one can estimate more precisely the probability of defect occurrence in them, and increase the quality of obtained moulds.

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Note: The responsible translator for English language is B.Tokić, Zagreb, Croatia.