ARCHIVES
of
FOUNDRY ENGINEERING
10.24425/afe.2026.157995
Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences
ISSN (2299-2944)
Volume 2026
Issue 2/2026
106 – 112
12/2

Thermal Properties of the Foundry Sand Mould Material Bonded with Resol Type Resin

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Received 22.12.2025; accepted in revised form 23.02.2026; available online 14.07.2026

Abstract

This study presents a comprehensive analysis of the thermophysical properties of a casting mould based on BK 50 quartz sand and a resol-type phenol-formaldehyde resin. The investigation combines classical laboratory measurements using Differential Scanning Calorimetry (DSC) with in-situ temperature field recording inside a foundry mold during the solidification of a copper plate casting. Based on specific heat capacity data and readings from seven thermocouples, temperature-dependent values of thermal diffusivity (a), heat capacity (b), and thermal conductivity (λ) were determined. The results indicate a low thermal conductivity of the tested material and a strong temperature dependence of its thermophysical properties. A significant influence of residual moisture was observed during the initial heat exchange phase, manifesting as disturbances in the heating curves around 100 °C. The adopted methodology enabled a realistic mapping of thermal conditions during solidification and confirmed the stable course of the process. The identified thermophysical coefficients characterize the material and are crucial for providing accurate input parameters in numerical simulations of casting processes. Furthermore, they support the informed selection of molding materials in industrial applications, contributing to more reliable simulation outcomes and improved process design, material selection, and final casting quality. The findings validate the integration of laboratory measurements with in-situ analysis and point to the necessity of further research involving various binders, sand grain size distributions, and elevated pouring temperatures.

Keywords: Casting mould, Thermophysical properties, Thermal conductivity, DSC analysis, In-situ temperature measurement, Heat transfer, Solidification

1. Introduction

Thermophysical properties of casting mould materials play a key role in the analysis and design of casting processes, as they govern heat extraction from molten metal and directly affect solidification rate, temperature gradients, thermal stresses, and the resulting microstructure of castings [1-6]. Reliable data on thermal conductivity, specific heat capacity, and thermal diffusivity are therefore essential for both process optimization and accurate numerical simulation of casting technologies [7,8].

Mould and core materials based on quartz sand bonded with organic resins exhibit strong temperature-dependent thermophysical behavior, influenced by factors such as compaction, porosity, and binder chemistry [9-11]. In particular, resol-type phenol-formaldehyde resins undergo physicochemical transformations during heating, which can significantly modify heat transfer conditions and the thermal energy storage capacity of the mould [12-17]. These effects alter the thermal boundary conditions at the metal–mould interface and may consequently impact casting quality.

Standard laboratory techniques, including Laser Flash Analysis, Hot Disk methods, and Differential Scanning Calorimetry, provide valuable thermophysical data under controlled conditions [18–20]. However, such measurements alone do not fully reflect the complex thermal conditions occurring during real casting processes. To capture these effects, laboratory measurements should be complemented by in-situ temperature field recording within the mould during metal solidification and cooling, enabling the determination of temperature-dependent thermal diffusivity, heat accumulation coefficient, and thermal conductivity under practical conditions [5,21-24].

The objective of this study is to determine the temperature-dependent thermophysical properties of a moulding sand based on BK 50 quartz sand and a resol-type resin by combining DSC measurements with multi-point in-situ temperature field analysis during the solidification of a copper plate casting. The proposed approach aims to provide reliable input data for numerical casting simulations and to improve the understanding of heat transfer phenomena in mould-casting systems under conditions representative of industrial practice.

2. Materials and methodology

The experimental studies were conducted using dried BK 50 quartz sand supplied by Sibelco and a resol-type phenolic resin. A batch of 11 kg of sand was mixed with the resin and hardener in the following proportions: 100 parts by weight of sand, 1.5 parts by weight of resol resin, and 0.38 parts by weight of hardener. The prepared molding mixture was poured into a flask with external dimensions of 188 × 190 × 198 mm, containing a pattern in the shape of a plate measuring 150 × 150 × 15 mm. The dimensions of the copper plate casting were chosen to satisfy the infinite plate condition, as a classical body. To achieve this condition, the plate's length and height must be ten times greater than the plate's thickness. These specific dimensions were chosen to ensure appropriate mold conditions. Heat during solidification spreads perpendicularly from the flat surfaces of the plate, heating the mold. The thickness of the mold material must be sufficient to prevent overheating during solidification, the period during which data for further calculations are collected. Considering the plate's dimensions and the dimensions of the box, this condition is met, which was also measured and confirmed during the experiment. The mold was compacted using a vibrating table. The final mold, ready for pouring, is shown in Figure 1. The initial bulk density of the compacted mold was ρ_2 = 1644.58 kg/m³. During mold preparation, type K thermocouples were embedded at distances of 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, and 14 mm from the casting–mold interface. The thermocouple measuring the temperature at the center of the copper plate was placed in a ceramic guide, which was then placed in a mounting arm to ensure the established position of the measuring joint was maintained throughout the entire pouring and cooling process. Thermocouples placed in the mold and at the casting-mold interface were prepared as a flat package. At a distance of 10 mm from the weld, the thermocouple wires were connected in a single plane. The stiffness of the thermocouple wires maintained their joints at a constant distance. The mold was vibrator-compacted to half the plate height. The thermocouple package was then placed so that the thermocouple, marked *Tw*, was in direct contact with the plate casting pattern. Additionally, the entire thermocouple package was secured with a wire clamp in a deeper layer of the mold. The remaining molding sand was then vibrator-compacted while continuously monitoring the position of the thermocouples. After removing the model, it was checked whether the thermocouple weld *Tw* was positioned adjacent to the mold cavity. This solution allowed for the thermocouples to be placed in fixed, precisely defined positions. Additionally, three samples were extracted from the molding mixture for DSC analysis. The samples were placed directly into aluminum crucibles with a diameter of 6 mm and sealed with a pressed-on lid.

Fig. 1. Casting mould made from the tested molding sand reproducing the shape of a plate meeting the infinite plate condition

2.1. Specific Heat Measurement of the Molding Material

Specific heat is one of the fundamental thermophysical properties of molding materials and plays a significant role throughout the entire casting process. It is a temperature-dependent quantity and serves as input data for calculating other thermophysical coefficients. Samples for specific heat measurement were prepared directly in aluminum crucibles with a diameter of 6 mm, sealed with a press-fitted lid featuring a small vent hole. The measurements were conducted using a *DSC Polyma 214* instrument (Netzsch). A sapphire standard with a mass of 38.6 mg and known heat capacity was used as the reference material. The measurements were performed in accordance with DIN EN ISO 11357-4 and ASTM E1269 standards. The heating rate was set to 5 K/min. An inert nitrogen atmosphere was maintained during the test, with a flow rate of 20 ml/min. For the tested material, three separate measurements were carried out to ensure the highest possible accuracy. Accuracy of the DSC measurement method: +/- 3-5%

2.2. Temperature Field Determination in the Molding Material

Temperature measurements were carried out using type K thermocouples connected to a digital multichannel data logger (Agilent 34980A). The measurement accuracy of thermocouples is estimated to be approximately 2K. This is due to the accuracy of the weld preparation and the connection of the thermocouple ends to the measuring device. The thermocouples were positioned at three key locations: in the geometric center of the copper plate, at the metal–sand mold interface, and within the mold material at distances of 2 mm, 4 mm, 6 mm, 8 mm, 10 mm, 12 mm, and 14 mm from the casting surface. A schematic of the thermocouple arrangement and the overall mold configuration is shown in Figure 2. The recorded temperature data during casting solidification and mold heating were saved in text format for further processing and analysis.

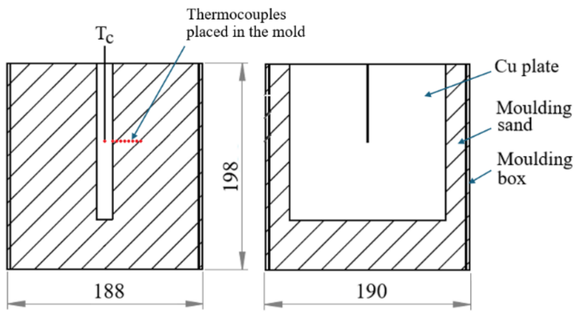

Fig. 2. Schematic diagram of thermocouple arrangement within the mold

The data obtained from the temperature measurements, along with the known density of the mold and the specific heat capacity, were used to calculate the dimensionless temperature, which also corresponds to the value of the Gaussian error function *efr(u)* as expressed in Equation (1)

$$erf(u) = \frac{T_x - T_{surface}}{T_{ambient} - T_{surface}} \tag{1}$$

where:
T_x – measured temperature at a given distance x from the casting surface,
$T_{surface}$ – initial temperature of the mold,
$T_{ambience}$ – constant temperature at the casting–mold interface

By applying the inverse error function, it is possible to determine the value of the argument u (Equation 2), which constitutes a component in the calculation of the thermal diffusivity (a), heat accumulation coefficient (b), and thermal conductivity (λ).

$$u = \frac{x}{2\sqrt{a\tau}}, \tag{2}$$

From this, the following thermophysical coefficients can be directly calculated:
- Thermal diffusivity *a:*

$$a = \left(\frac{x}{2u\sqrt{\tau}}\right)^2 \tag{3}$$

- Heat accumulation coefficient *b:*

$$b = \sqrt{\lambda \cdot C \cdot \rho} \tag{4}$$

- Thermal conductivity *λ:*

$$\lambda = a \cdot \rho \cdot C \tag{5}$$

ρ - density of the foundry sand mould,
C – specific heat capacity of the foundry sand mould [21-24].

3. Results and discussion

3.1. Specific Heat Capacity

The specific heat capacity values were obtained as the average of three measurements conducted on samples of similar mass. The mass of each sample was approximately 39 mg, closely matching that of the sapphire reference sample, which weighed 38.6 mg. The graph showing the variation of the specific heat capacity C with temperature is presented in Figure 3. The plot indicates that the specific heat capacity of the tested molding sand material varies with temperature. A noticeable change in trend is observed in the upper part of the curve, most likely associated with the melting process of the resin. Within the investigated temperature range, the specific heat capacity increased from approximately 750 to 1025 J·(kg·K)$^{-1}$. At room temperature, the value was about 750 J·(kg·K)$^{-1}$, and the most rapid increase occurred up to around 50 °C. At 300 °C, the specific heat capacity C reached approximately 1025 J·(kg·K)$^{-1}$. The obtained specific heat capacity values are consistent with literature data reported for quartz sand-based mould materials bonded with organic resins, for which C typically ranges from approximately 700 to 1100 J·(kg·K)$^{-1}$ within a similar temperature interval [9,12,18]. The observed increase in C with temperature and the change in trend at elevated temperatures are commonly attributed to binder-related thermal transitions and have been reported for phenolic resin systems in previous studies [12–17]. Since specific heat is a key parameter used in calculating other thermophysical coefficients, its variability directly affects the accuracy of those derived values.

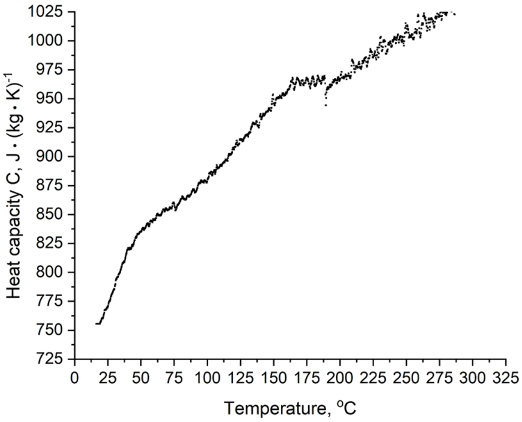

Fig. 3. Specific heat capacity C of the tested molding sand as a function of temperature

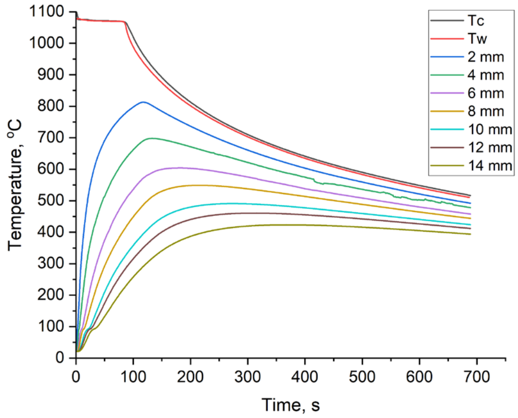

Fig. 4. Cooling curves of the copper plate and heating curves of the sand mold. T_c - temperature at the center of the casting, T_w - temperature at the casting–mold interface

3.2. Thermophysical Coefficients of the Tested Sand Mold Material

The results of the temperature measurements for both the metal and the mold are presented in Figure 4. The cooling curve of technically pure copper exhibits a characteristic profile typical of the solidification and cooling of pure metals (curve *Tc*). At a constant and specific temperature, a horizontal segment appears on the curve, corresponding to the solidification time. Once the final portion of the liquid phase solidifies, the casting begins to cool down. The solidification time determined for the copper plate casting cooled in the mold made from the tested material was τ = 92 seconds. The heating curves of the mold, depending on the distance of the thermocouple from the casting surface, rise with varying intensity. Two characteristic regions can be observed on these curves: The first plateau occurs around 100 °C, which is associated with residual moisture in the mold. Despite using clean and dried sand, some moisture remained and was rapidly evaporated, which is clearly visible in the heating curves. The presence of a temperature plateau around 100 °C is consistent with literature reports for quartz-based moulding sands, where residual moisture evaporation strongly affects early-stage heat transfer and delays temperature rise in the mould material [9,21,22]. Similar moisture-related disturbances in mould heating curves have been widely reported under industrial casting conditions.

The second feature is the inflection point on the curves, which appears near the end of solidification. At this point, the mold is no longer supplied with a constant heat flux, as the casting itself starts to cool down. From this moment onward, the temperature curves recorded in the mold begin to follow the shape of the casting's cooling curve.

Using the recorded temperature changes over time at various distances from the casting surface and applying Equations (1) and (3), the thermal diffusivity coefficient (*a*) was calculated. The resulting curves showing the variation of coefficient a as a function of temperature are presented in Figure 5. These curves can be divided into two distinct regions. The first region, up to approximately 100 °C, reveals a noticeable effect of residual moisture evaporation in the mold. This phenomenon also visibly affects the shape of the thermal diffusivity curves. After this point, a sharp decrease in the value of coefficient a is observed, followed by stabilization at a nearly constant level. The average value of the thermal diffusivity coefficient for the tested molding material is: $2.948 \cdot 10^{-7}\ m^2 \cdot s^{-1}$. The obtained thermal diffusivity values are of the same order of magnitude as those reported in the literature for quartz sand moulds bonded with organic resins, typically ranging around $10^{-7}\ m^2 \cdot s^{-1}$, depending on moisture content and compaction level [9,10,21]. The stabilization of coefficient *a* above 100 °C corresponds to the transition from moisture-affected to dry heat transfer conditions, which has also been observed in previous studies.

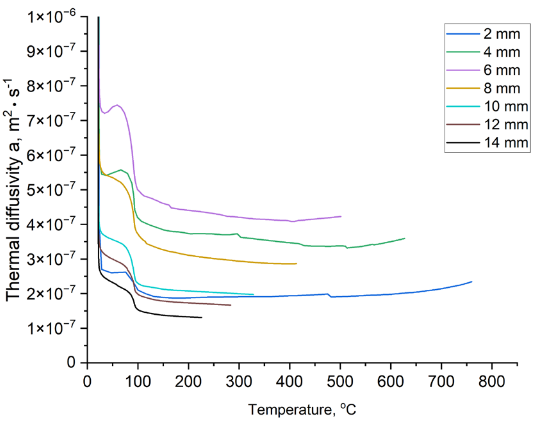

Fig. 5. Thermal diffusivity coefficient a as a function of temperature for measurement points located at various distances from the casting surface

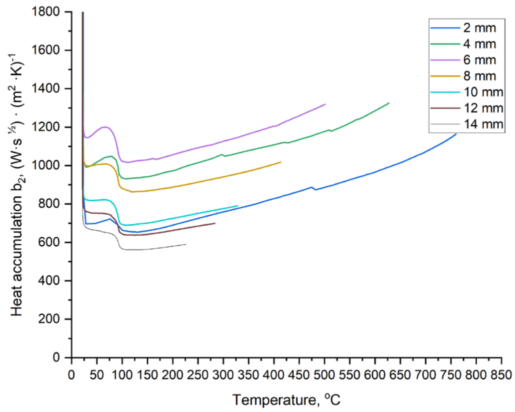

Fig. 6. Heat accumulation coefficient *b* as a function of temperature for measurement points located at various distances from the casting surface

Using the calculated values of thermal diffusivity (*a*), Equation (4), and the measured specific heat capacity (*C*), the heat accumulation coefficient (*b*) of the mold material was determined. The coefficient *b* characterizes the ability of the mold to store thermal energy over a given period. The accumulated heat can later be released, thereby providing stable conditions for the cooling of the casting. Since the considered coefficients are interrelated and reflect the nature of the mold's heating curves, the influence of residual moisture in the mold is also clearly observed in this case (Figure 6). Moisture significantly affects the value of the coefficient in the initial stage immediately after pouring. Analyzing the curve shapes, it appears that the impact of moisture increases with distance from the heat source that is, from the casting surface. This is likely due to the migration of evaporated water vapor into deeper mold layers, which leads to additional re-moistening. This phenomenon alters the behavior of the mold material and directly influences its thermal properties. The average value of the heat accumulation coefficient b = 906.86 $(W \cdot s^{1/2}) \cdot (m^2 \cdot K)^{-1}$. The calculated heat accumulation coefficient is consistent with values reported for moulding sands characterized by low thermal conductivity and high porosity, where b is strongly influenced by moisture migration and binder-related thermal effects [10,22,24]. Similar trends, including increased sensitivity to moisture at greater distances from the casting surface, have been described for sand moulds under real casting conditions.

Using Equation (5), the thermal conductivity coefficient (λ) was calculated for each measurement point located at different distances from the casting surface. The curves showing the variation of λ with temperature are presented in Figure 7. As with the previous coefficients, the moisture content of the mold was also found to significantly influence the behavior of the thermal conductivity curves. A quantitative comparison of the calculated thermal conductivity values showed that in the moisture-affected temperature range (60-100 °C) the mean λ was 0.515 $W \cdot (m \cdot K)^{-1}$, whereas in the stabilized range above the evaporation region (120-200 °C) it decreased to 0.412 $W \cdot (m \cdot K)^{-1}$, corresponding to an approximately 20% difference. This confirms that residual moisture significantly alters heat transfer conditions during the initial mould heating stage. The average value of thermal conductivity λ for the tested material was: 0.5 $W \cdot (m \cdot K)^{-1}$. The obtained thermal conductivity values fall within the typical range reported for quartz sand moulds bonded with organic resins, for which λ usually remains below 1 $W \cdot (m \cdot K)^{-1}$ and commonly stabilizes around 0.4–0.7 $W \cdot (m \cdot K)^{-1}$ after the initial moisture-affected stage [9,10,21]. The observed decrease and stabilization of λ with time and temperature are therefore consistent with literature data. In general, the lower the value of λ, the better the insulating properties of a given material. In the case of a granular and porous material such as molding sand, the thermal conductivity strongly depends on factors such as moisture content, compaction level, and the grain size of the sand matrix. This relationship determines the directions of further research for this type of molding materials, especially the influence of grain size and degree of compaction on thermophysical parameters.

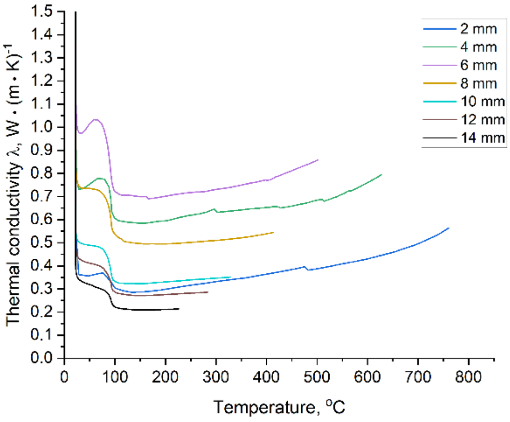

Fig. 7. Thermal conductivity coefficient λ as a function of temperature for measurement points located at various distances from the casting surface

Figure 8 shows the thermal conductivity coefficient λ plotted as a function of casting solidification time.

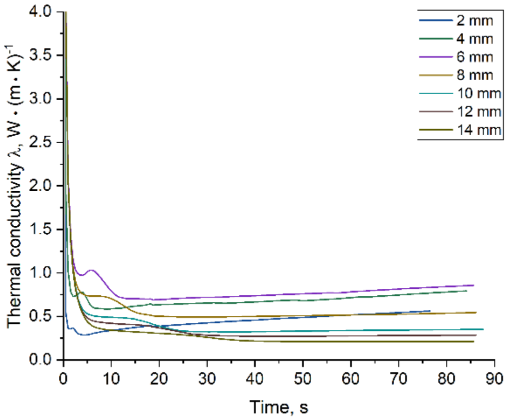

Fig. 8. Thermal conductivity coefficient λ as a function of casting solidification time

The thermal conductivity coefficient (λ) defines how quickly heat is extracted from the casting and transferred into the deeper layers of the mold. All the coefficients determined in this study, together with the specific heat capacity of the mold material, define the complete thermophysical profile of that material. These properties influence how heat is absorbed from the casting and stored within the mold. The individual thermal parameters of the mold material play a critical role in determining the final structure, properties, and quality of the cast product. Of course, the chemical composition and quality of the alloy are also crucial; however, with detailed knowledge of mold parameters, it becomes possible to influence the thermal behavior of the casting itself. In modern casting technology design, thermophysical properties play an increasingly important role. The more accurately they are defined, the more precise the data that can be used in widely applied simulation software. Well-defined boundary conditions, alloy properties, and mold parameters enable realistic and reliable results from virtual experiments. Therefore, accurate determination of thermophysical coefficients, along with a clear understanding of how they vary with temperature, is essential for optimizing casting processes and ensuring repeatable high-quality outcomes.

4. Conclusions

This study demonstrates that the thermophysical properties of molding sands bonded with resol-type resin exhibit a strong temperature dependence and cannot be reliably characterized using laboratory techniques alone. The integration of DSC measurements with multi-point in-situ temperature field recording during metal solidification provides a realistic and reproducible method for determining temperature-dependent thermal diffusivity, heat accumulation coefficient, and thermal conductivity under conditions representative of industrial casting practice.

The investigated molding sand is characterized by low thermal conductivity and distinct temperature-dependent variations of the coefficients a, b, and λ, which directly affect heat extraction from the molten metal and the solidification dynamics of the casting. Residual moisture was identified as a critical factor influencing the initial stage of heat exchange, as evidenced by inflection points in the heating curves around 100 °C and increased variability of the calculated thermophysical parameters.

The obtained thermal coefficients confirmed stable and repeatable solidification conditions of the copper plate casting, including a well-defined solidification plateau. The results constitute a reliable set of thermophysical input data for numerical casting simulations, significantly improving the accuracy of temperature field prediction and defect risk assessment. The proposed methodology supports informed selection and preparation of molding sands, particularly with respect to moisture control and compaction, thereby contributing to improved process stability and casting quality in foundry technology.

Acknowledgements

This work is financially supported by AGH University of Krakow grant number: 16.16.170.654/B507

The experimental apparatus located in the Laboratory of Advanced Thermal Measurements, Department of Fundamental Research in Energy Engineering, AGH University of Krakow, used in the analysis was supported by the program "Excellence Initiative Research University" for the AGH University of Krakow.

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