Modeling capabilities of phenomena in over-moisture zone existing in porous medium using the simplified simulation systems applied in foundry

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The problem described in the paper concerns the thermo-physical properties of the green mould material to which the cast iron most often is poured (about 50% of production). The study described in the paper includes the iron plate casting experiments poured in green bentonite-sand mould. The temperature fields of casting and in different zones of the mould were recorded. The determining of the thermo-physical properties of mould sand containing the over-moisture zone by using simulation tests (inverse problem) was the goal of this study. An originality of the related research is an attempt to take into account the effects of the global thermal phenomena occurring in the quartz sand bonded by bentonite-water binder, applying the apparent thermal coefficients. The majority of foundry simulation systems are not capable of modeling the phase transformation of water into vapor, follow by vapor transport and its condensation in the porous media (mould). In these cases, the application of apparent coefficients is an effective way.

Keywords: green sand mould, over-moisture zone, cast iron, virtualization, validation.

Introduction

About 50% of cast iron castings are made in the moulds from green bentonite sand. The physical properties of the mould material, to which the liquid cast iron is poured, have a decisive influence on the course of the physics–chemical metal–mould reactions and on the time dependent heat transfer rate from the casting especially during initial period of mould-casting thermal contact. The both determine the final casting quality. In the porous mould sand with the bentonite binder, where the amount of water added during the process does not exceed 4%, is used to activate the purely physical mechanism of binding the matrix (quartz grains) using bentonite (type of clay). An important phenomenon accompanying the heating of the green sand mould by poured metal is the production of water vapor and then its condensation in the so-called over-moisture zone (local water content in over-moisture zone exceeds the value of initial process moisture content several times) in the deeper layers of the mould. This zone of moisture condensation, which is formed from the casting–mould interface, is characterized by low strength of mould sand and is the favorable factor to form the special casting defect (scab defect). This zone gets more space and moves into the mould to its external face. Simultaneously the water evaporates increasingly when the temperature of mould is close to 100°C, the vapor is transported (presence of the pressure gradient), and further condenses in more and more distant (from casting) zones of the mould. The water vapor migration into the mould is accompanied by an additional heat transfer (parallel to conduction) related to a mass transfer (vapor). To sum up, the gradually dried and humidified zones of the mould, variable in time and space coordinates, are characterized by different local thermo-physical properties. The phenomena connected with the over-moisture zone affect obviously the dynamics of the heat transfer from the casting and the local time of solidification of its different wall sections. Dynamics of the heat transfer from the casting is of particular significance especially in the initial phase of the process of filling the mould cavity with the liquid cast iron, deciding on parameters of flow through the gating system, filling the mould cavity and distribution of temperature in the casting-mould system.

State of art – phenomena in over-moisture zone

The phenomena in the over-moisture zone were a subject of numerous studies[1,2,3,4]. These studies were mostly aimed at development of methods of measurement of humidity and temperature in the mould manufactured out of multi-component porous material, which is the mould sand. The process of simultaneous, zonal forming, movement and condensation of the water vapor in a moist, porous material is a complex problem – these phenomena should be comprised by a model of simultaneous heat and mass transfer, with taking the laws of fluid penetration through the porous medium into account. Unsteady processes of heat and moisture transfer cause local (in terms of time and space) variations of processing properties of the green sand, which in extreme cases can lead to uncapping of the sand near

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moving condensation zone. Forming and movement of the over-moisture zone is described in the publications [5,6], where the authors distinguished three zones in the heated green sand: dry sand zone, transitory zone (evaporation, movement and condensation of the water vapor) and fresh (primary, external) sand zone. These zones are separated with the apparent surfaces of evaporation and condensation. On these surfaces, the characteristic temperatures correspond to phase transitions occurring in the mould space (only water boiling temperature is considered). The transient location of these surfaces are expressed as a time function (1) and (2)[5], (look Fig.1).

$$X_1^2 = K_1 \cdot t \tag{1}$$

$$X_2^2 = K_2 \cdot t \tag{2}$$

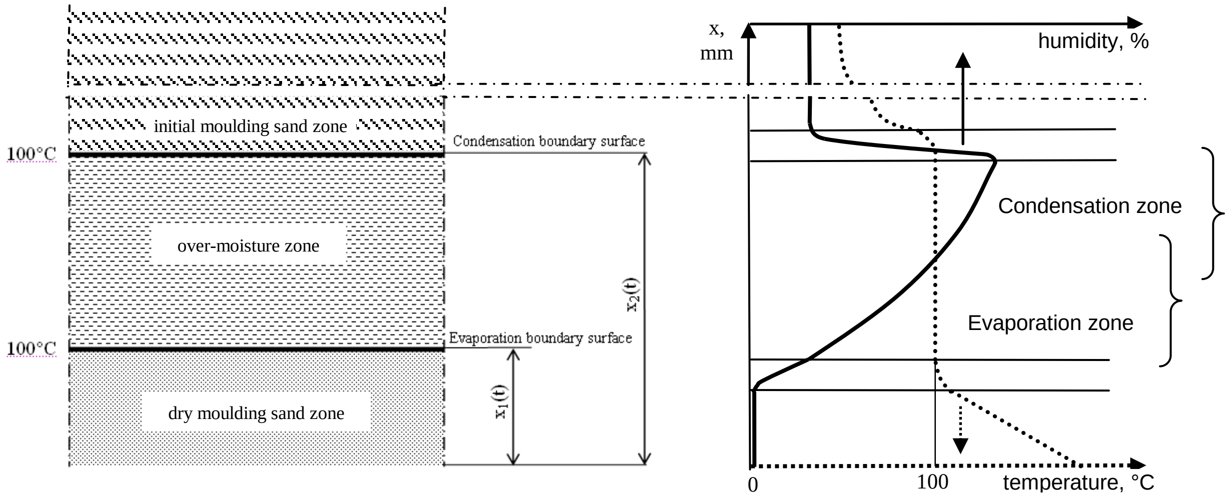

Fig.1: Cross-section through the green sand mould containing the over-moisture zone (based on [5])

However, the authors analyze only a movement of the over-moisture zone (the boundary between the dry zone and the transition zone), omitting the humidity accumulation in the transition zone. The similar relations are proposed in the [3]. Presence of water also influences the dynamics of the heat transfer out of the casting, which is of big significance especially during pouring and for thinner walls, when the decrease of temperature in canals of the gating system and the mould cavity during its filling is considered and modeled. That is why studies of the alloy castability, besides the viscosity parameter, need to take changing properties of the moist mould in the initial stage of period of its filling with liquid metal into account. In studies carried out by Pirowski and Pysz[7], the process castability test is used to determine thermo-physical properties of an alloy, including relation between viscosity and the temperature. In the cited work, influence of the alloy overheating temperature on the castability is analyzed. The authors made castings in moulds of furan sand, in which the phenomena accompanying forming of the over-moisture zone do not occur. It means that influence of the thermal and physical parameters of the mould, including the initial humidity of the sand on the castability, was not analyzed.

In the green sands, changes in amount of moisture in particular zones of the mould are possible to identify on the basis of measurement of the sand temperature in these zones. Studies conducted in [8,9], according to the methodology shown there, allowed to trace the changes of humidity and water vapor pressure in the over-moisture zone since the first contact of metal with the mould. It also creates possibilities in the indirect way, to obtain thermo-physical characteristics of the moulding sands. Forming and movement of the water vapor in the moist, porous bodies subjected to the thermal shock (contact with the liquid cast iron) are a complex problem in terms of phenomena description using a model. The models can be formulated by expressing source of evaporation heat and water vapor penetration separately, which boils down to coupling of the fields: temperature (Fourier-Kirchhoff model) and humidity distribution (Darcy model). Also, a substitute coefficient of heat transfer in the porous body can be introduced and the problem can be reduced to the temperature field modified by the presence of the humidity. The knowledge about amounts of the water vapor flowing through the mould (stream of mass) and transferring a defined amount of heat has become a base for balanced expression of the stream of energy.

Formally, the coupled model of phenomena of appearance and movement of the over-moisture zone should include phenomena of the energy flow in the presence of negative – evaporation – and positive – condensation – sources of heat (the Fourier-Kirchhoff equation), along with equation of movement (penetration) of fluid, i.e. water vapor and water in the porous medium, caused by the pressure difference (the Darcy equation).

In the simplified approach presented in the paper, substitute thermo-physical parameters of the porous medium (moulding sand) in function of temperature were introduced. In case of the foundry simulation systems, based upon the heat model in their "hard modeling" part, there is a possibility to enter modified thermo-physical parameters of the mould sand in function of temperature. These modifications concern considering the heat of water evaporation by changing values of apparent specific heat of the mould sand.

In the databases of the foundry simulation systems, such as Procast[10] and Nova Flow & Solid Control Volume[11] (NF&S CV), phenomena related to forming of the over-moisture zone are not considered in the simulation models. The Magmasoft[12] software allows to define the initial humidity of the mould sand and in the database, the value of the specific heat in a temperature range of approx. 100°C is increased by value of the evaporation heat of water contained in the sand. The value of the considered evaporation heat is not related to the initial humidity, which determines the amount of the water in the mould sand. The simulations performed in the Magmasoft system allow formal representation of phenomena related to forming of the over-moisture zone, while the results obtained for the various initial humidity values are not compatible with intuitive prediction. The deviations of simulated times of solidification of cast iron plates from real times determined by experiment are approximately 50% higher, which means that the energetic validation was not achieved.

Experimental Procedure

The experiment was performed in the real conditions of a cast iron casting – mould system, by casting the plates of thicknesses 16, 30 and 40 mm in a mould made out of green sand. Arrangement of the castings in the mould is shown in the Fig.2. Grey cast iron EN-GJL-250 was used. The cast iron and green sand parameters are shown in Table 1.
The aim of the experiment was to measure and record the temperature in selected points of the casting and the sand mould. To conduct the experiment, special measuring cores needed to be prepared out of the studied greensand (Fig.3). In the cores, the mineral insulated thermocouples of type K were placed, in the distances of 6 mm, 15 mm, 35 mm, 75 mm and in the geometrical center of each casting. The measurement results were recorded using the CASTOR 2 – data acquisition system.

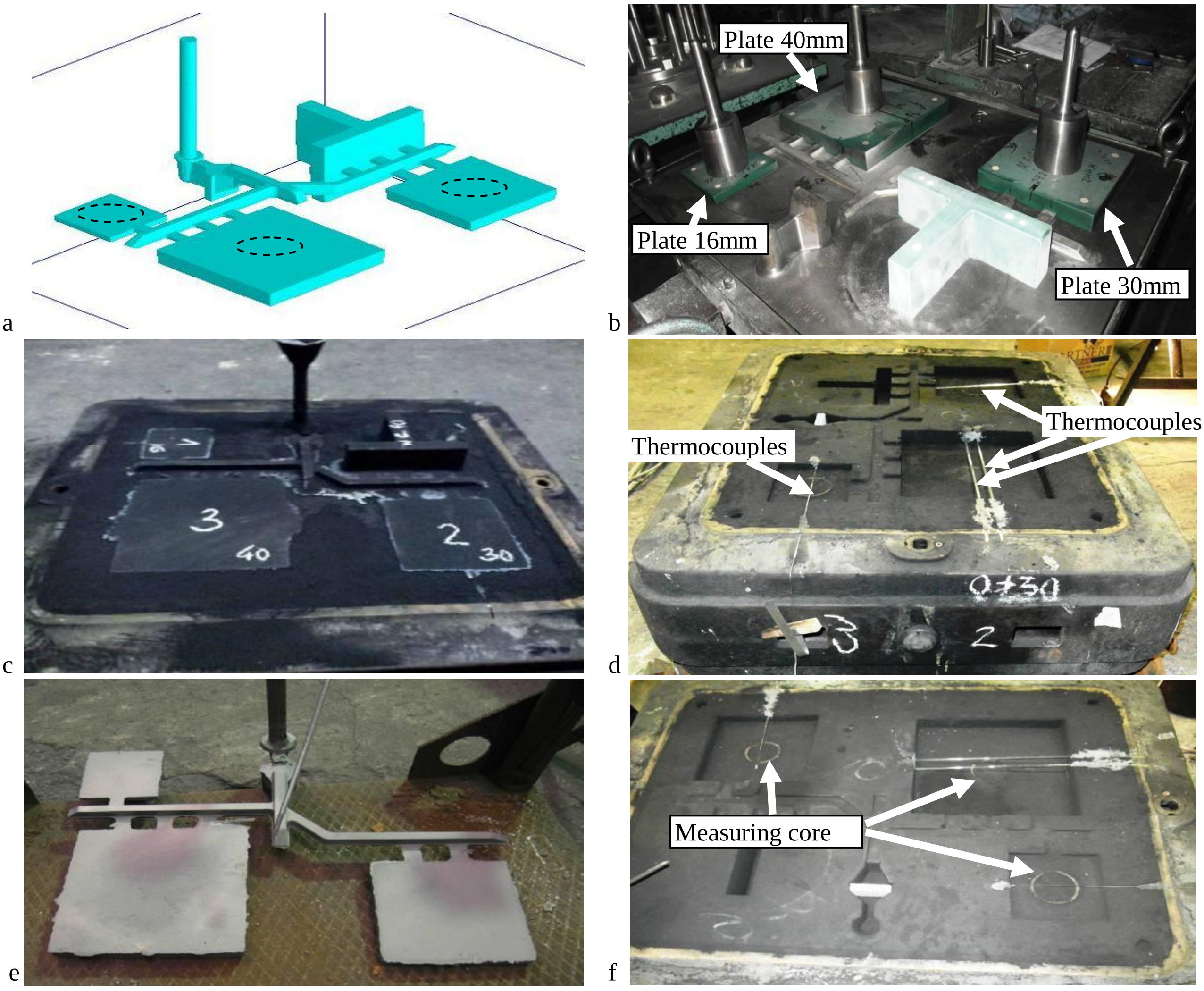

Fig.2: Casting arrangement in the mould. a – CAD model, b – pattern plate, c,d – mould instrumentation, e – mould disassembly, f – raw casting knocking out

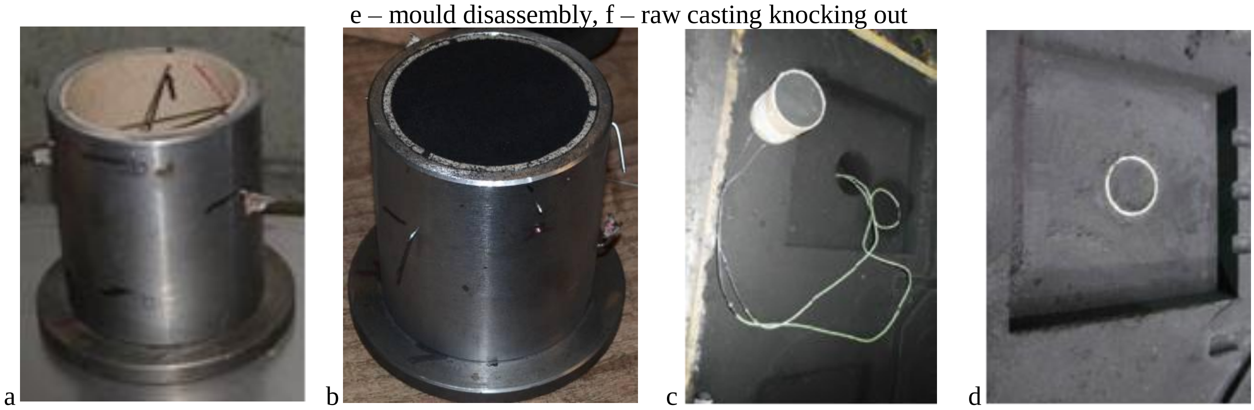

Fig.3: Measuring core – preparation procedure: a – core box with thermocouple positioning pins (6–15–35–75 mm), b – compacted core, c,d – core before and after installation in the mould cavity

Table 1: The cast iron and green sand parameters

Cast iron– final composition															
C	Si	Mn	P	S	Cr	Cu	V	Mo	Ni	Ti	Al	Co	Sn	Te	Mg
3,51	1,99	0,53	0,18	0,09	0,13	0,39	0,02	0,01	0,06	0,02	0,004	0,01	0,008	0	0

Fusion and pouring parameters		
Furnace charge: pig iron 30%, steel scrap 35%, recycle scrap 35% Ladle capacity (over lip) – 1500 kg	Superheating temperature T_{sh} = 1505°C Pouring temperature T_p = 1345°C	Tapping temperature T_{tapp} = 1450°C Pouring time T_z = 11 s

Green bentonite-sand parameters		
Dry components: silica sand 92%, active bentonite 7,0% coal dust 1,0% + water 3,5%	Density (wet state): ρ = 1540 kg/m^3	Mechanical/technological parameters: compression strength 0,24 MPa, permeability 195 10^{-8} m^2/Pa/s, humidity 3,5%, compactibility 40%, calcination losses 3,55%

The simulation studies were conducted using the NF&S CV system, according to the following scheme:
- virtual thermocouples were placed as in the experiment,
- simulation of filling, solidification and cooling to the 600°C was carried out,
- validation was based on assumptions resulting from the scheme presented in the Fig.4:
  - energetic validation – on the basis of comparative analysis of solidification times determined from the cooling curves of the casting,
  - dynamic validation of temperature, based on comparative analysis of the heating curves, recorded in the mould sand.

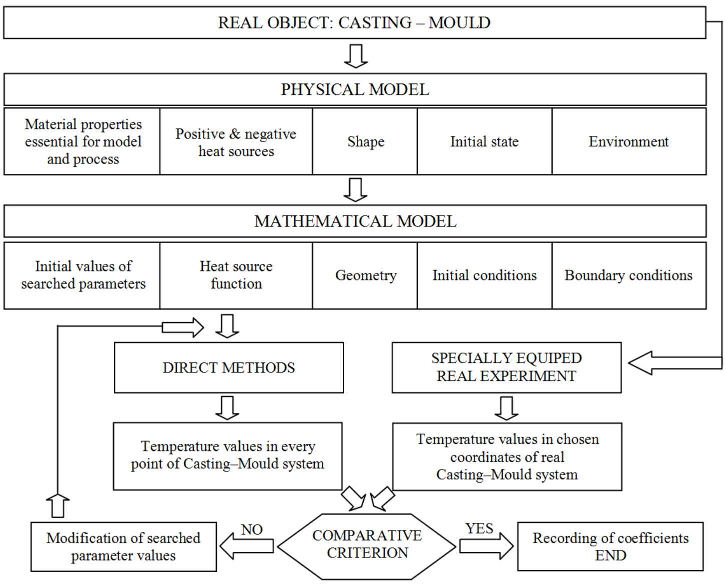

Fig.4: Scheme of validation with the comparison criterion

Results

Results of experimental studies in form of cooling curves of castings and their derivatives, along with curves of heating in the mould are presented in the Fig.5. On the basis of the minimum of the first derivative, the plate solidification times were determined. Times of solidification were used to carry out the energetic validation. On the basis of the measurements of the real thermocouple locations in the mould sand, appropriate corrections were made after casting knocking out. It was taken into consideration during the simulation calculations.

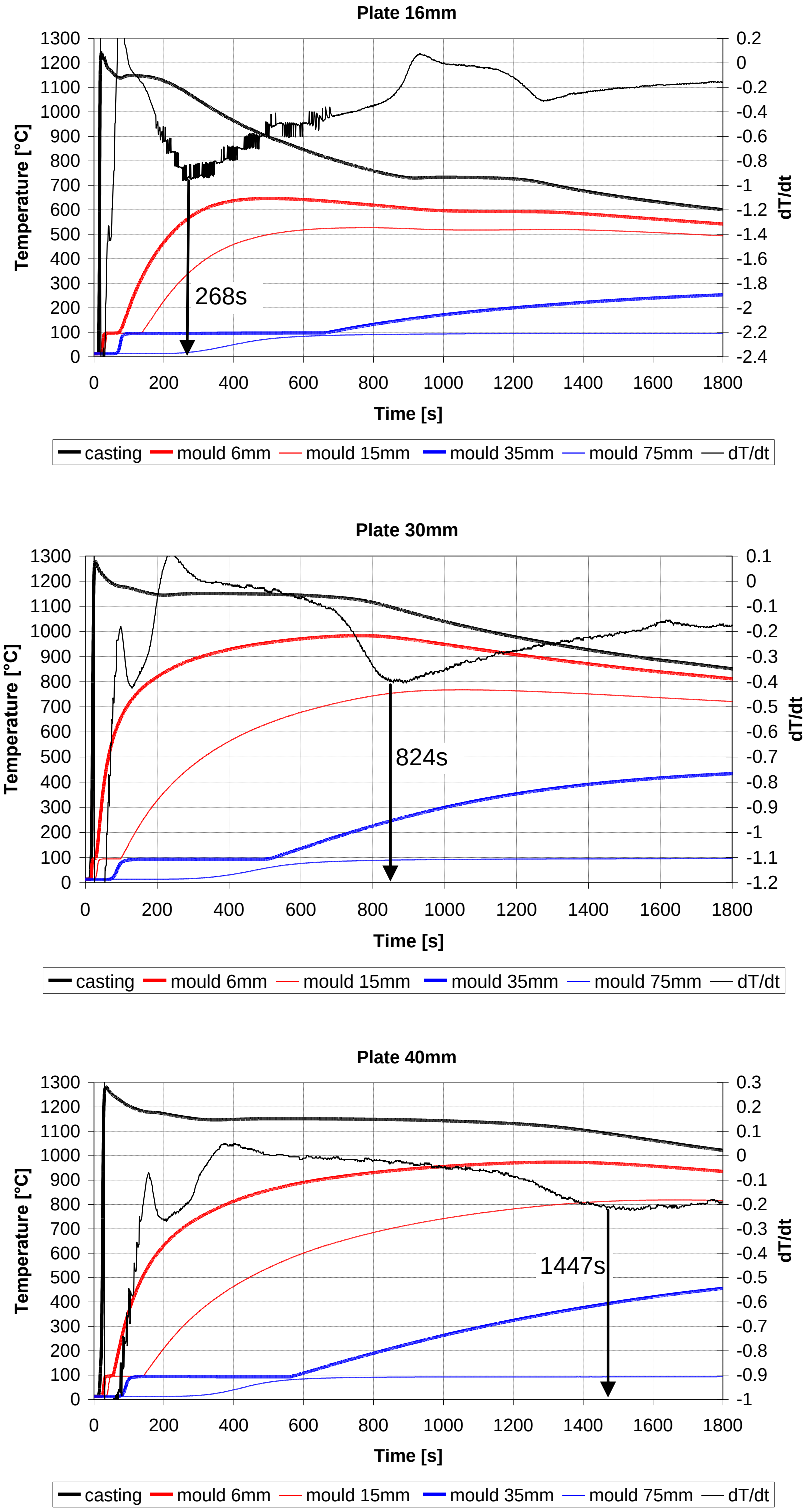

Fig.5: Results of the experimental studies (with solidification times identified by minimum of cooling curves first derivative)

As a result of the validation studies, carried out according to the scheme shown in the Fig.4, satisfying compatibility between curves from the simulation and from the experiment was achieved. The results of the simulation are shown in the Fig.6. The good agreement between times of solidification in the experiment and in the simulation was obtained. The values of obtained solidification times are shown in the graphs.

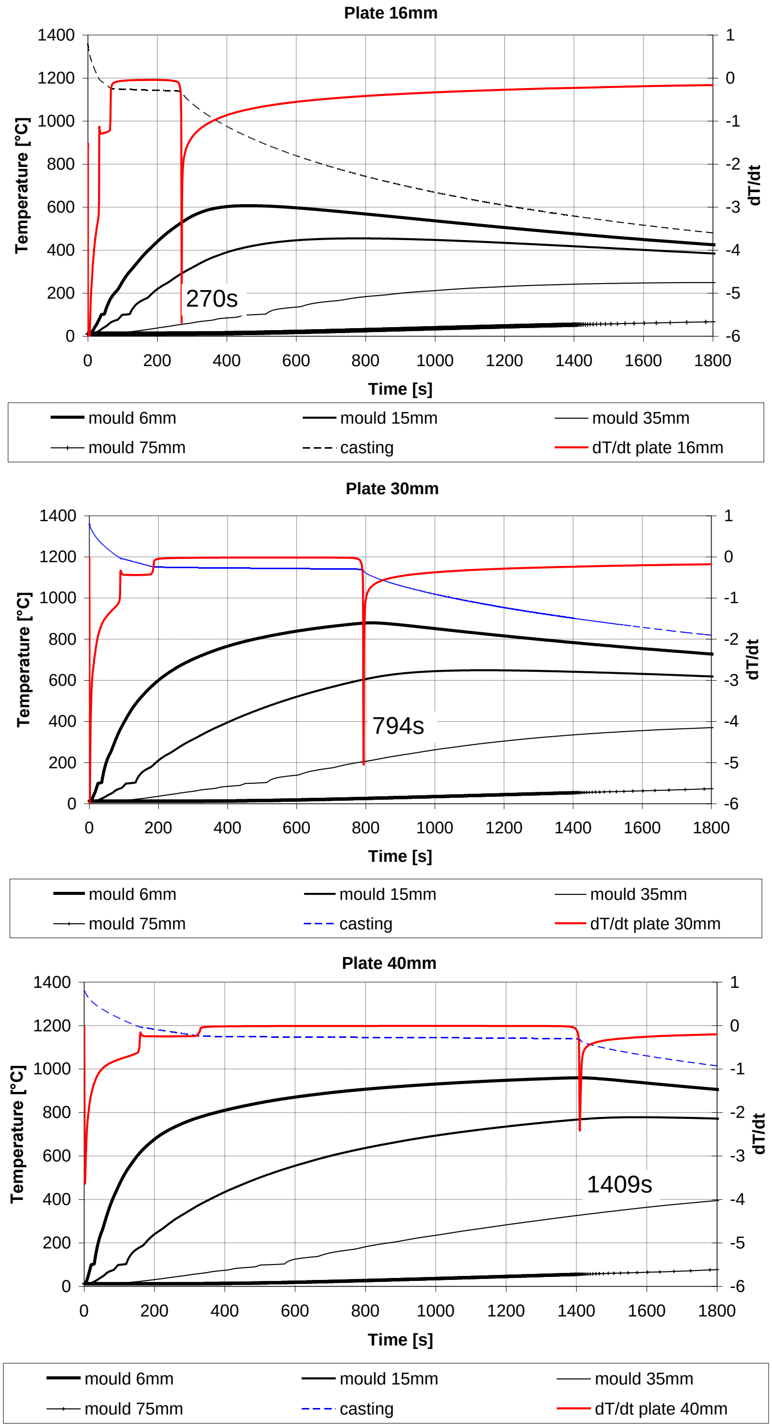

Fig.6: Results of the simulation studies (with solidification times identified by minimum of cooling curves first derivative)

Applying the rule resulting from the scheme presented in the Fig.4, thermo-physical parameters of the moist mould sand were determined. In these parameters, phenomena of appearance and movement of the over-moisture zone in the mould sand are taken into account. The specific heat was modified, considering heat of evaporation of the water contained in the sand, assuming temperature range of 98-102°C. It is presented in the graph of relation between the specific heat and the temperature for the tested sand mould (Fig.7). The thermal conductivity was adopted from NF&S and others databases as λ=f(T) – selected values: λ=1,05 W/m/K for 20 ºC, λ=0,96W/m/K for 100ºC, λ=0,67 W/m/K for 500ºC, λ=1,04W/m/K for 1000ºC.

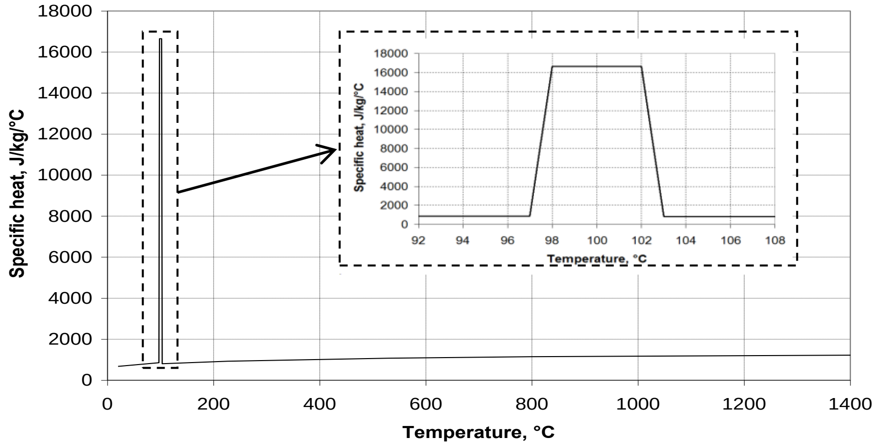

Fig.7: Substitute specific heat parameter of green sand mould determined by simplified inverse problem solution.

The thermo-physical parameters of the green mould sand determined on the basis of the validation studies were used in a simulation of castability trial[13] for cast iron EN-GJL-250 (look Table 1 – casting process parameters). The castability depends on fluidity of metal poured into standard mould cavity made of tested sand. In foundry practice this is the ability of alloy to flow through the gating system and filling the casting walls. The castability value as complex property combining both alloy and mould characteristics, is quantitatively defined by maximum length of the obtained casting (often on spiral shape). The filling of spiral canal is done without a refresh of stream front which is stopped by the local crystallization process. The results of two simulations of pouring process were compared; in the first one, data for the green sand was taken from the database of the NF&S CV system, in the second one – data determined in the described validation studies was used. The results of simulation are presented in the Fig.8 witch show an evident influence of presence of the over-moisture zone in the mould sand on filling of the castability trial.

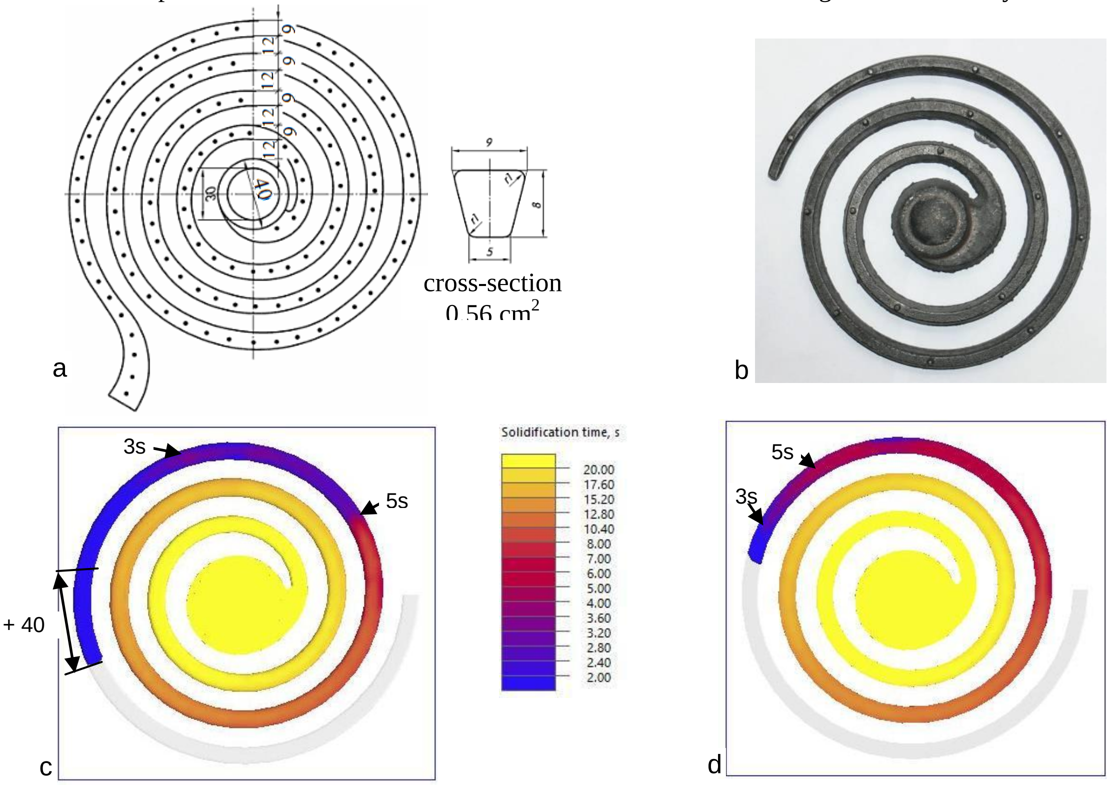

Fig.8: The comparison of filling process results: a – castability trial (spiral shape), b – result as real casting c – simulation using mould sand parameters from the NF&S CV database, d – simulation using mould sand parameters (specific heat) determined by the validation studies

Conclusions

1. The described simulation-experimental studies allowed to estimate the thermo-physical properties of the moist mould sand, according to assumptions made in the paper. The presence of the over-moisture zone was taken into consideration (the specific heat data was modified by increasing its value about heat of evaporation of the water contained in the mould sand in the assumed temperature range of 98 – 102°C).
2. The results of simulation calculations using the determined thermo-physical data of the mould sand are similar to the experiment results.
3. The good compatibility of times of solidification of the plates castings was obtained (energetic validation condition was fulfilled). Also, a proper shape of heating curves was obtained from the simulation, in comparison with those recorded in the mould. On the heating curves from the simulation, the effect of presence of the over-moisture zone was obtained in form of short arrest in the temperature range around 100°C. The length of simulated arrest is significantly shorter than obtained in real experiment. This is caused by doesn't taking into consideration of vapor transfer and its condensation (assumed model simplification).
4. The handled data allowed to conduct a virtual experiment of castability trial. In such a way, a necessity of taking the parameters allowing re-creation of the over-moisture zone in the model into consideration was confirmed, when the cast iron casting is manufactured in the green sand. It is of great significance especially during simulation of filling of the canals of the gating system and thin walls of the casting.

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