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# OPTIMIZATION CASTING OF CERAMIC MATERIAL USING MODEL OF THE TEMPERATURE FIELD

**Josef Štětina[1], Jaromír Heger[2], František Kavička[3], Pavel Ramík[4]**

**Abstract**

EUCOR, a corundo-badelleyit material, which is not only resistant to wear but also to extremely high temperatures, is seldom discussed in literature. The solidification and cooling of this ceramic material in a non-metallic mould is a very complicated problem of heat and mass transfer with a phase and structure change. Investigation of the temperature field, which can be described by the 3D Fourier equation, is not possible without the engagement of a numerical model of the temperature field of the entire system—comprising the casting, the mould and the surroundings.
A temperature field had been investigated on a 350x200x400 mm block casting—the so-called "stone"—with a riser of 400 mm using a numerical model with graphical input and output. The computation included the automatic generation of the network, and the successive display of the temperature field using iso-zones or iso-lines. The thermophysical properties of the cast, as well as the mould materials, were gathered and the initial derivation of the boundary conditions was conducted on all boundaries of the system. The initial measurements were conducted using thermocouples in a limited number of points. The paper provides results of the initial computation of the temperature field, which prove that the transfer of heat is solvable, and also that using the numerical model it is possible to optimise the technology of production of this ceramic material, which enhances its utilisation. The results are complemented with an approximated measurement of the chemical heterogeneity of EUCOR.

***Keywords***: *ceramic material, EUCOR, casting, temperature field, numerical model*

## Introduction

Corundo-badelleyit material (CBM) is a modern electrically cast heat- and wear-resistant material. It is resistant to corrosion and to wear even at very high temperatures. This material belongs to the not too well known area of the $Al2O_3$-$SiO_2$-$ZrO_2$ system. This material is produced in several plants throughout the world under different trademarks—in three types, differing mainly in the $ZrO_2$ content. In the Czech Republic this material is produced with a 32-33% $ZrO_2$ content

CBMs are used mainly in the construction of glass furnaces, in certain steel-works aggregates and, especially, in heating furnaces, etc. They have a high resistance to

[1]Ing. Josef Štětina, VUT FSI Brno, Technická 2, 61669 Brno, email:stetina@eu.fme.vutbr.cz
[2] Ing. Jaromír Heger, CSc., ALSTOM Power technology Centre, Cambridge Road, Whetstone, Leicester, UK
[3] Prof. Ing. František Kavička, CSc., VUT FSI Brno, Technická 2, 61669 Brno, email:kavicka@eu.fme.vutbr.cz
[4] Ing. Pavel Ramík, VUT FSI Brno, Technická 2, 61669 Brno, email:ramik@udt.fme.vutbr.cz

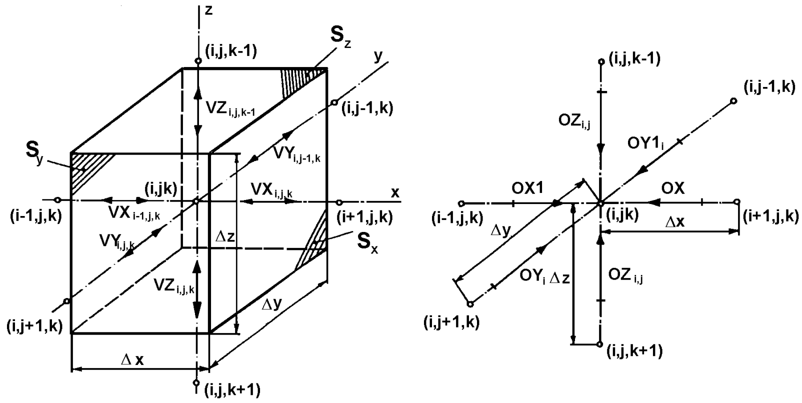


**Fig. 1** The thermal equilibrium diagram of a general nodal point of the network

liquid glass as well as metal, and are also suitable for great temperature changes. Slabs from this material are therefore very suitable for the walls and floors of melting aggregates, linings, pouring filters, insulation plates and for a number of other uses, which can be accessible after optimising the technology of their production and utility properties.

The requirements on the properties of CBM are usually determined:

a) For the internal walls of glass furnaces: the resistance to liquid glass and the creation of bubbles when in contact with liquid glass.
b) For the production of wear-resistant products: resistance to wear, low porousness, crystalline structure, and resistance to temperature shocks.

From the foundry viewpoint, it is possible to compare the properties of EUCOR with those of commonly cast metals, especially steels and cast steel. In a sand mould, the solidification coefficient of steel is approximately 0.07 [$m.h^{1/2}$] and that of EUCOR is 0.065 [$m.h^{1/2}$]; in a cast-iron mould it is 0.13 [$m.h^{1/2}$] and that of EUCOR is 0.163 [$m.h^{1/2}$], etc.

## A numerical model of solidification, cooling and heating

Solidification—crystallization—and cooling belong to the most important technological processes. They are cases of one-to-three-dimensional transfer of heat and also mass. In systems, comprising the casting, the mould and surroundings, all three kinds of heat transfer take place. Since these problems cannot be solved analytically—even with the second-order partial differential Fourier equation (1) (where, mass transfer is neglected and conduction is considered the most important of the three kinds of heat transfer)—it is necessary to engage numerical methods.

$$\frac{dt}{d\tau} = \frac{k}{\rho \cdot c}\left(\frac{\delta^2 t}{\delta x^2} + \frac{\delta^2 t}{\delta y^2} + \frac{\delta^2 t}{\delta z^2}\right) + \frac{Q_{SOURCE}}{\rho \cdot c} \tag{1}$$

A numerical model of solidification, cooling and heating had been developed for investigating one-to-three-dimensional stationary and transient temperature fields of systems comprising the casting, the mould and the surroundings. It is possible to investigate either the system as a whole or any of its parts—during any industrial technological process whose individual sub-processes can be solidification, cooling, heating, refrigerating and others—in any sequence or singly. The model also enables the simulation of traditional and non-traditional technologies of casting in foundries, metallurgical plants, forging operations, heat-treatment processes, etc.

Equation (1), which describes the three-dimensional (3D) transient temperature field of a gravitationally cast casting, was used for the application of the numerical model. Upon reaching the stationary state, the derivative of the temperature by time becomes zero. Equation (1) includes the temperature field of a casting in all its three phases: in the melt, in the mushy zone and in the solid phase. Here it is necessary to introduce the specific volume enthalpy $h_v = c.\rho.T$, which is dependent on temperature. Equation (1) then takes on the form

$$\frac{\partial h_v}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial t}{\partial z}\right) \tag{2}$$

The specific heat capacity $c$, density $\rho$ and heat conductivity $k$ are also functions of temperature.

The 3D transient temperature field of the mould is described by equation (1) without the member $Q_{SOURCE}/\rho.c$. Figure 1 illustrates the thermal equilibrium of an elementary volume—a general nodal point $i,j,k$. The unitary heat conductivities and heat flows, in the directions of all the main axes, are also indicated here. In the z-direction it is

$$VZ_{i,j,k} = k(t)\frac{S_z}{\Delta z} \quad \text{or} \quad VZ_{i,j,k-1} = k(t)\frac{S_z}{\Delta z} \tag{3}$$

The heat flows through the point $i,j,k$ in the z-direction are

$$\dot{Q}Z1_{i,j} = VZ_{i,j,k}(t^{(\tau)}_{i,j,k-1} - t^{(\tau)}_{i,j,k}) \tag{4}$$

$$\dot{Q}Z_{i,j} = VZ_{i,j,k+1}(t^{(\tau)}_{i,j,k+1} - t^{(\tau)}_{i,j,k}) \tag{5}$$

The unknown temperature in the general nodal point of the mould, in the course of a time step of $\Delta\tau$, is

$$t^{(\tau+\Delta\tau)}_{i,j,k} = t^{(\tau)}_{i,j,k} + (\dot{Q}Z1_{i,j} + \dot{Q}Z_{i,j} + \dot{Q}Y1_i + \dot{Q}Y_i + \dot{Q}X1 + \dot{Q}X)\frac{\Delta\tau}{c.\Delta x.\Delta y.\Delta z} \tag{6}$$

where $t^{\tau}_{i,j,k}$ is the temperature in the previous time.

The unknown enthalpy in the general nodal point of the casting in the course of Δt is

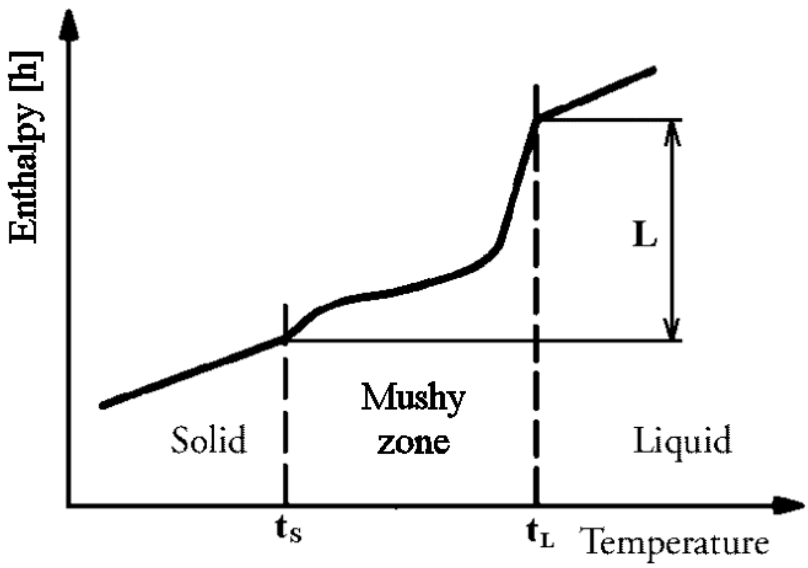


**Fig. 2** Enthalpy as a function of temperature

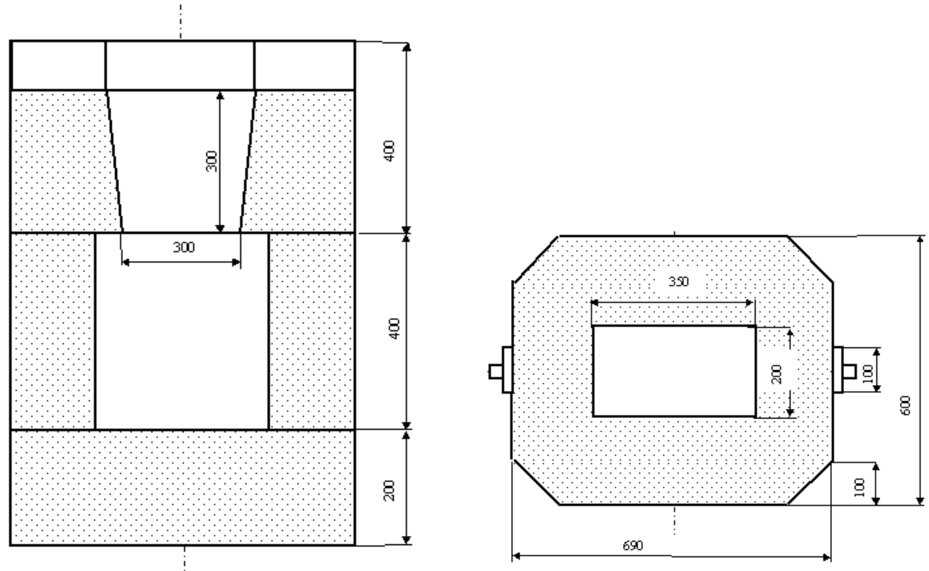


**Fig. 3** The casting-riser-mould system

$$h_{v_{i,j,k}}^{(\tau+\Delta\tau)} = h_{v_{i,j,k}}^{(\tau)} + (\dot{Q}Z1_{i,j} + \dot{Q}Z_{i,j} + \dot{Q}Y1_i + \dot{Q}Y_i + \dot{Q}X1 + \dot{Q}X)\frac{\Delta\tau}{c.\Delta x.\Delta y.\Delta z} \qquad (7)$$

where $h^{\tau}_{v,i,j,k}$ is the enthalpy in the previous time.

The temperature of the general nodal point of the casting is obtained from the enthalpy-temperature dependence, which must be known for the relevant metallic material.

The explicit difference method had been chosen for this investigation because it enables the application of the most convenient method of numerical simulation of the release of latent heat of phase and structural changes using the thermodynamic enthalpy function (Fig. 2).

The susceptibility of the explicit method to oscillations is minimized by a series of longer and shorter time steps. Another modification is one that evaluates the attained stationary state of the modeled process via three shorter time steps.

The program also considers the non-linearity of the task, i.e.:

- The dependence of the thermophysical properties of all materials entering the system, and
- The dependence of the heat-transfer coefficients (on all boundaries of the system) on the temperature of the surface—of the casting and mould.

The software performs all the necessary tasks—from the automatic generation of the net, through the

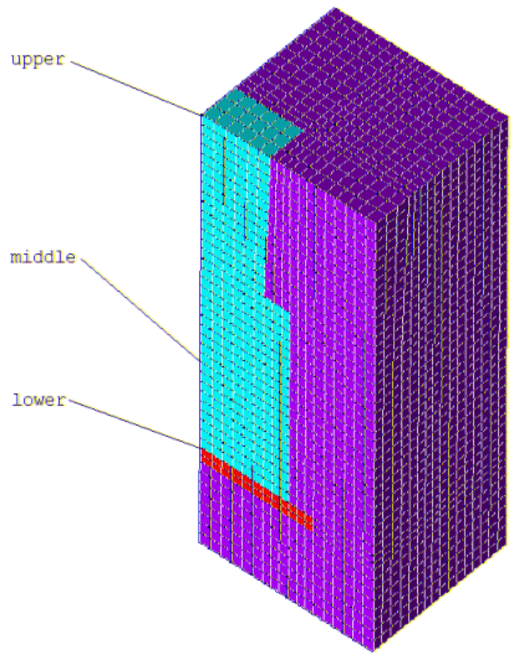


**Fig.4** The 3D computational network

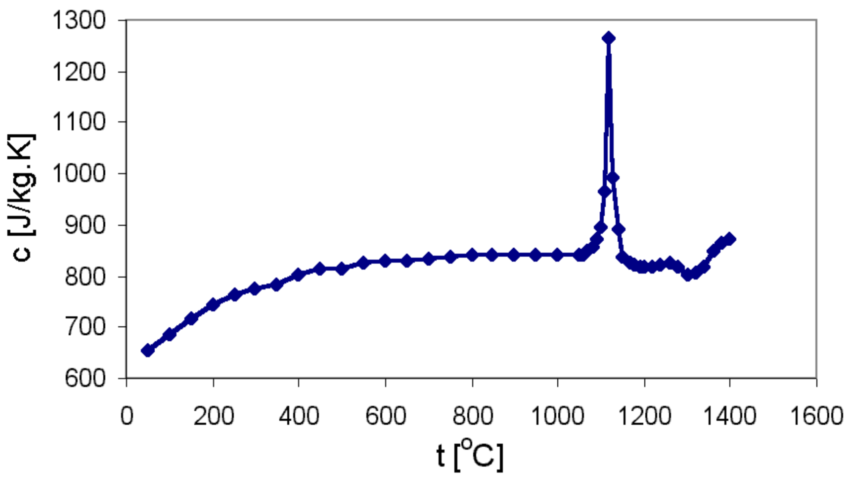


**Fig. 5** The heat capacity-temperature dependence

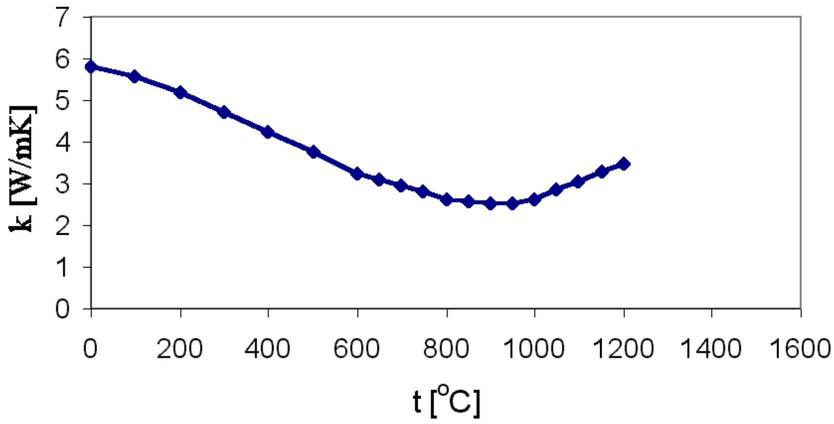


**Fig. 6** The heat conductivity-temperature dependence

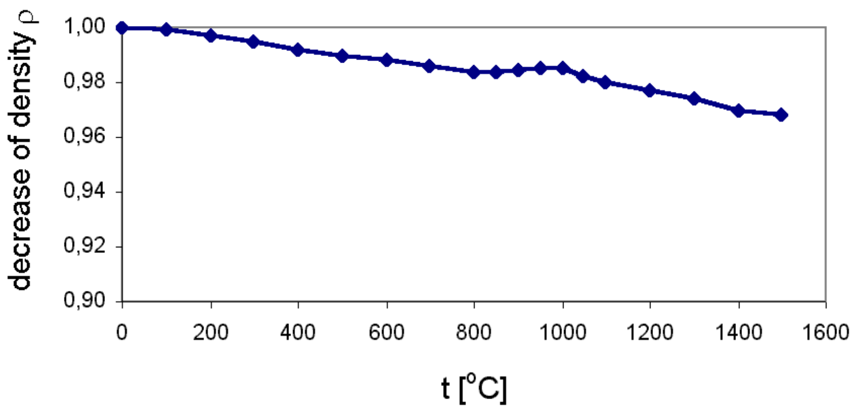


**Fig. 7** The decrease of density-temperature dependence

computation of the thermophysical properties and the definition of boundary conditions, to the actual numerical simulation of the temperature field.

## The assignment

The assignment was aimed at investigating a transient 3D temperature field of a system comprising a casting-and-riser, the mould and the surroundings, using a numerical model. Figure 3 illustrates the main dimensions. The dimensions of the actual casting—the “stone” of the special ceramic material EUCOR—were 400 x 350 x 200 mm, the riser comprised a 300-mm-high truncated four-sided pyramid, where the base was 123 x 250 mm and the top 150 x 270 mm. The initial temperature of the mould was 20°C, which equalled the room temperature. The pouring temperature was 1800°C, the pouring time was 10 s, the liquidus temperature was 1775°C and the solidus 1765°C. The mould material was made from a CT-mixture and the bottom of the mould was made from a layer of magnesite of a thickness of 50 mm. The level of the riser remained untreated. It was necessary to compare the results of the calculation with the temperatures measured within the casting and the mould using thermocouples. It was also necessary to prepare the numerical model and the network in order to successively monitor the effects of the pouring temperature, the shape of the riser, the insulation of its level, etc., in order to optimise the technology of the pouring of the stone.

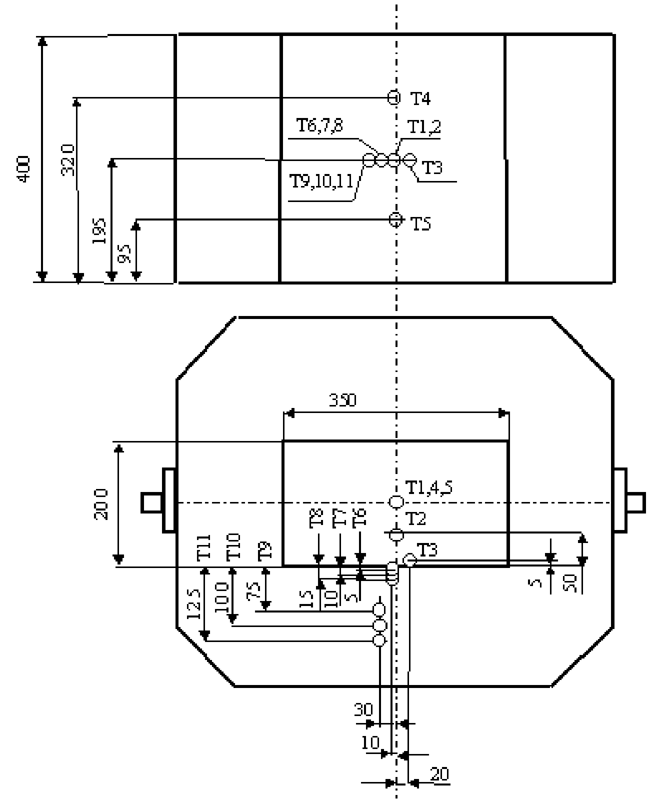


**Fig. 8** The measurement points

## The preparation for simulation

The network is generated automatically—with nodes 20 mm apart. The temperature field is symmetrical along the axes, i.e. it is sufficient to investigate the temperature field of one quadrant only. Figure 4 shows the network for the casting-riser-mould system. The resultant heat flow through both longitudinal sections is equal to zero. The time step was selected at 10 s.

The thermophysical properties of the ceramic material were considered with their dependence on temperature. The dependence of the heat capacity on temperature is shown in Fig. 5, heat conductivity in Fig. 6 and decrease of density in Fig. 7. The density of the mould material was considered 1600 kg/m$^3$. The heat conductivity was 3.3 W/mK within the temperature range 0-100°C and 0.88 W/mK above 100°C; the heat capacity was 800 J/kgK within the temperature range 0-100°C and 1000 J/kgK above 100°C.

The boundary conditions were defined in all planes bordering the system. Heat transfer by radiation and convection into the surroundings was considered from the top of the mould and also from the level of the riser after pouring, from the base and the

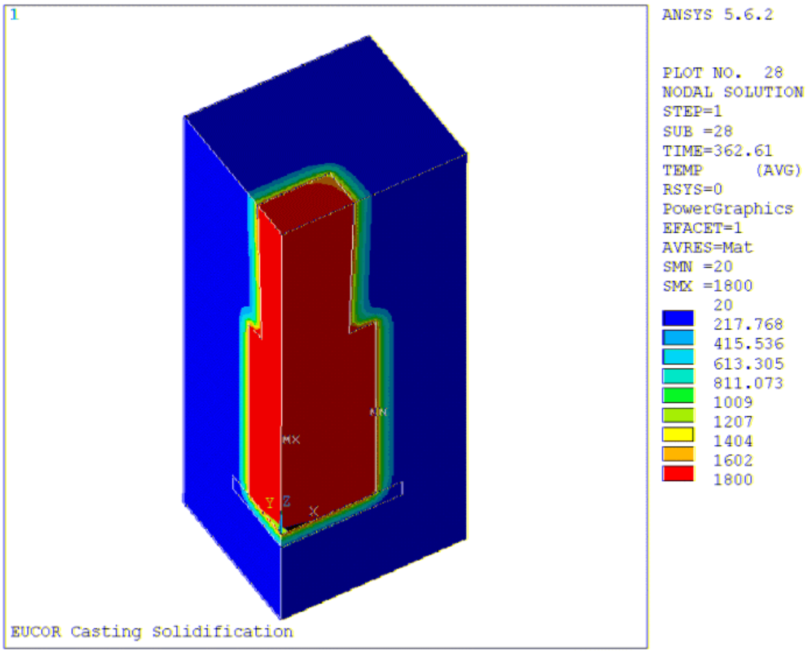


**Fig. 9** The 3D temperature field of the system after 6 min

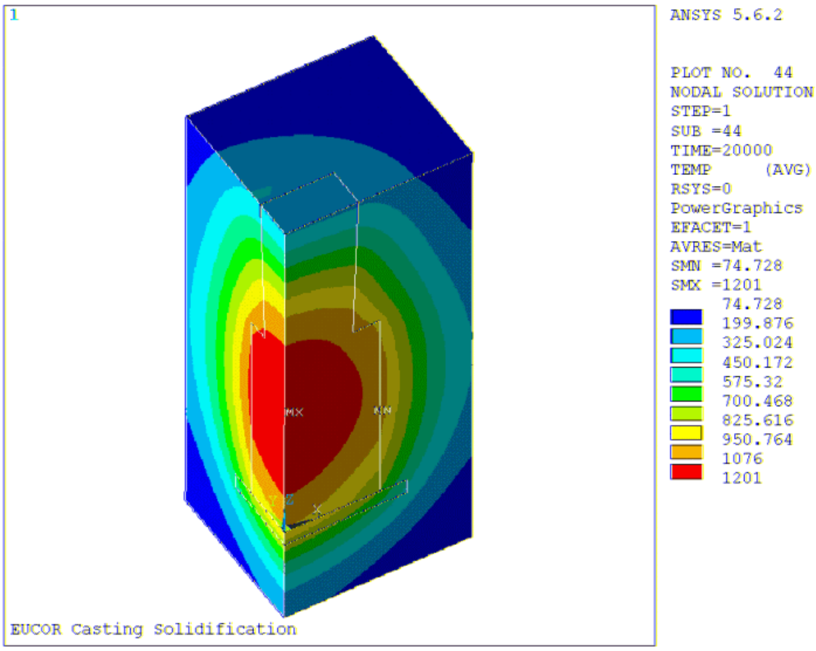


**Fig. 10** The 3D temperature field of the system after 5.6 hours

frame. The resultant heat-transfer coefficients were defined using general procedures, including the engagement of the similarity theory. Ideal physical contact was presumed between the mould and the casting, and between the mould and the riser.

## The experiment

The numerical model of the temperature field of the casting was confronted with experimental measurements and corrected. The temperatures were measured in the actual casting and also in the mould. Special tungsten-rhenium thermocouples had to be used for the measurement within the actual casting, in order to withstand the high pouring temperature, which is approximately 300°C higher than, for example, the

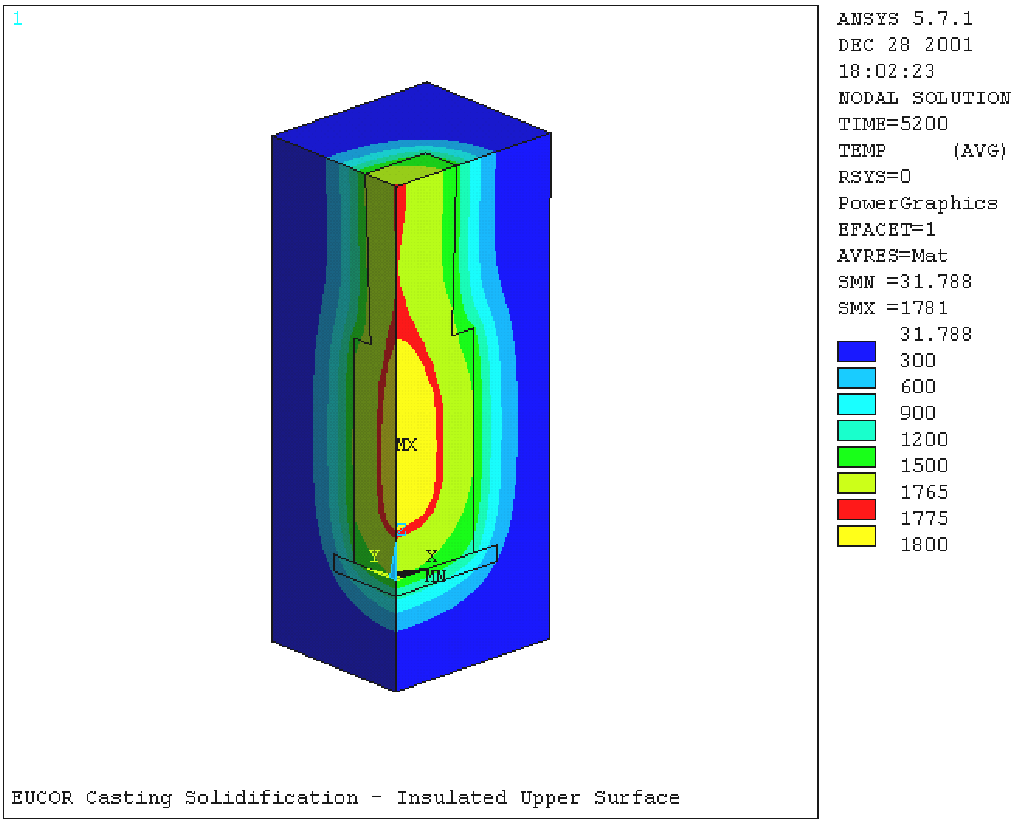


**Fig. 11** The 3D temperature field of the system after 5200s

pouring temperature of steel. The measurement lasted as long as 19 hours. The measurement points are shown in Fig. 8. Three GRANT-type measurement stations were used for the recording of data throughout the process.

## Results

The results attained from the analysis of the temperature field of a solidifying casting and the heating of the mould represent only one quadrant of the system in question. The thermokinetics of the phenomenon were monitored over a five-day period when the casting was kept inside the mould in order to cool completely.

Fig. 9-10 show the temperature field after 6 min and 5.6 hours respectively. Fig. 12 shows the temperature curves of the points along the heat and geometrical axis of the system illustrated in Fig. 4. The primary condition for a healthy casting is directed solidification. Fig. 11 shows that the current casting of EUCOR is not optimal, because the 'refilling' of the casting from the riser is cut off. The riser was the first to solidify – it froze at 5200s.

## Conclusions

The investigation of the temperature field had two goals:

1. Directed solidification as the primary condition for a healthy casting.
2. Optimisation of the technology of casting, together with the preservation of optimum utility properties of the product.

The achievement of these goals depends on the ability to analyse and, successively, control the effect of the main factors which characterise the solidification process or

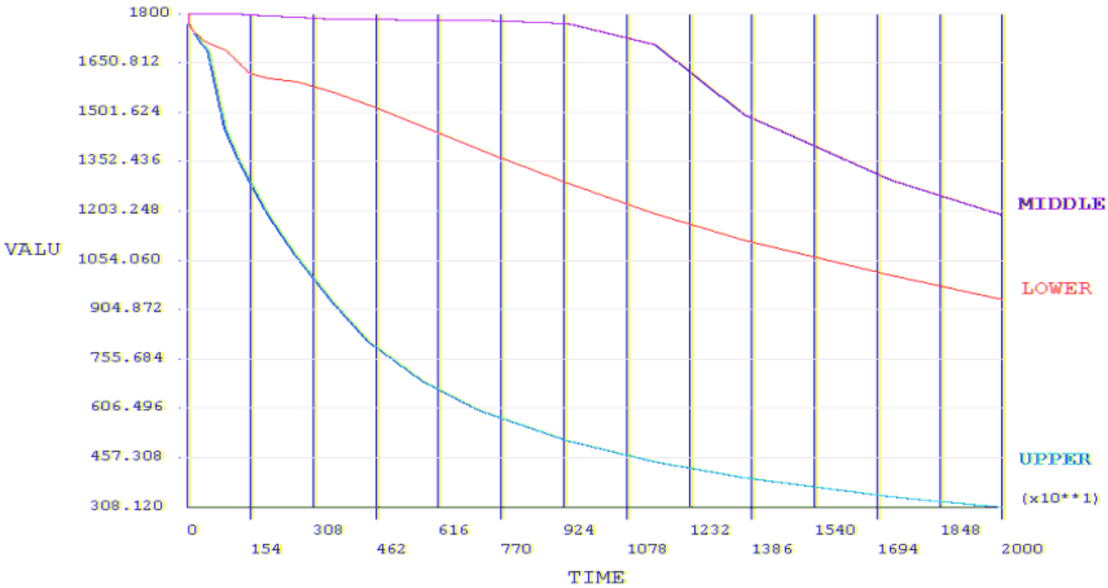


**Fig. 12** The temperature-time dependence in 3 points on the heat axis

accompany it.

The results of the investigation of the quantities should reveal the causes of heterogeneities in the casting with respect to phase and structural changes. It should also be aimed at thermokinetics of the creation of shrinkage porosities and cavities and at the prediction of their creation and, therefore, to control the optimisation of the shape and sizes of the risers, the method of insulation, the treatment of the level, etc. The main economic criteria to be observed are the saving of liquid material, mould and insulation materials, the saving of energy and the optimisation of the casting process and the properties of the cast product.

The paper provides results of the initial computation of the temperature field, which prove that the transfer of heat is solvable, and also that, using the numerical model, it is possible to optimise the technology of production of this ceramic material, which enhances its utilisation.

The mastering of an advanced technology for the casting of EUCOR contributes to the optimisation of a number of industries, namely the glass, energy, foundry and metallurgical.

## Nomenclature

| | | |
|---|---|---|
| $c$ | specific heat capacity | [J.kg$^{-1}$.K$^{-1}$] |
| $c_v$ | specific volume heat capacity $c_v$=c.ρ | [J.m$^{-3}$ .K$^{-1}$] |
| *htc* | heat transfer coefficient | [W. m$^{-2}$.K$^{-1}$] |
| $h$ | specific enthalpy | [J.kg$^{-1}$] |
| $h_v$ | specific volume enthalpy $h_v=h.\ \rho$ | [J.m$^{-3}$] |
| $k$ | heat conductivity | [W. m$^{-1}$.K$^{-1}$] |
| $L$ | latent heat | [J.kg$^{-1}$] |
| $\tau$ | time | [s] |
| $x,y,z$ | axes in given directions | |
| $Q$ | heat flow in given direction | [W] |
| $Q_{SOURCE}$ | latent heat of the phase or structural change | [W.m$^{-3}$] |

| | | |
|---|---|---|
| *V* | volume | [$m^3$] |
| *VX,VY,VZ* | unitary heat conductivity | [$W.K^{-1}$] |
| *t* | temperature | [K] |
| Δ | Laplace operator | [-] |
| ρ | density | [$kg.m^{-3}$] |

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