MODEL OF BODY FORMATION AND SOLIDIFICATION INVOLVING LIQUID TRANSFER IN THE POROUS MOULD

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A mathematical model of body formation and solidification during slip casting into porous moulds, also including transfer of liquid by the porous mould, was prepared with the aim to control and optimize the process. Experimental verification of the model on an aqueous suspension of $\alpha - Al_2O_3$ showed that the model allows the course of body forming and solidification, and the state of saturation of the porous mould with the liquid, to be predicted. The assumptions introduced in formulating the model were proved correct because the model describes the course of the slip-casting technology with an error smaller than 9%.

INTRODUCTION

The models of body formation and solidification during pouring of ceramic suspensions (slips) into porous moulds describe the processes taking place in the suspension and in the green body. In order to be able to control and optimize the slip-casting technology, one also has to know continuously the state of the porous mould. This state is primarily associated with the suction ability of the mould, which determines the reproducibility of the operation and the number of working cycles the mould can be used for without having to be dried. It is also directly related to the service life of the moulds.

The present paper is concerned with resolving the processes taking place in the porous mould during body formation and solidification. On the basis of preparing a model of transmission of the liquid in the mould, calculating the development of concentration profiles and the mean concentration in the mould, it is possible to obtain the necessary data for assessment of the instantaneous state of the mould.

INITIAL CONCEPTS IN THE CREATION OF THE MODEL

Let us start with the concept represented schematically in Fig. 1. A homogeneous distribution of liquid throughout the suspension and the mould is assumed at the beginning. At time $t > 0$, the liquid passes into the porous mould and the transfer brings about formation of the body. The liquid being transported is accumulated in the porous mould. The transfer of liquid phase at the body-porous mould boundary is described by the boundary condition of the second type, i.e. surface flow, which is identical for the porous mould and for the body. If no liquid flow takes place at the suspension-environment and porous-form-environment boundaries (the body-environment boudary in the course of solidification), the state at the boundaries is described by the boundary condition of zero liquid flow. The conditions can be expressed mathematically as follows:

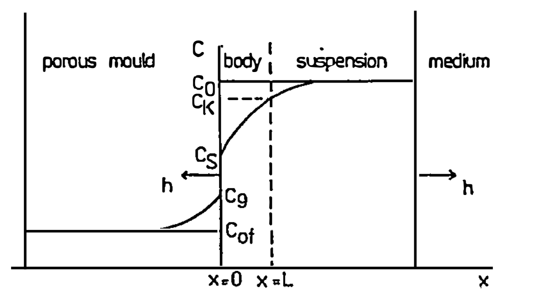

Fig. 1. Schematic representation of body formation and solidification including transmission of liquid through the porous mould.

(i) Initial condition:

$$t = 0 \quad x \in (0; H> \quad C = C_0; \tag{1}$$

$$x \in (0; L> \quad C = C(x)$$

$$x \in (0; -H_f> \quad C = C_{0f}$$

(ii) Boundary conditions:

$$t > 0 \quad x = 0 \quad h = -D_{ef}\delta_x C$$

$$x = 0 \quad h = D_{eff}\delta_x C \tag{2}$$

$$x = H \quad \delta_x C = 0 \tag{3}$$

$$x = L \quad \delta_x C = 0$$

$$x = -H_f \quad \delta_x C = 0$$

where x is the coordinate, H the suspension head (level height), H_f the thickness of the porous mould, D_{ef} the effective diffusion coefficient in the suspension-body system and D_{eff} in the porous mould, C the volume concentration, C_0 and C_{0f} the initial concentration of liquid in the suspension and in the porous mould respectively, and L is the body thickness.

On using the concept that the transmission of the liquid can be described phenomenologically as diffusion in binary mixture not only in the suspension and in the body during its formation and solidification, but also in the porous mould, the weight balance in the following form will hold:

$$\delta_t C = D_{\mathrm{ef}} X^{-m} \delta_x \left(X^m \delta_x C \right) \qquad (4)$$

where x is the coordinate in the direction of liquid transfer and m is a coefficient determining the shape of the body, i.e. $m = 0$ for a plate, $m = 1$ a cylinder and $m = 2$ for a sphere. Resolving of equation (4) for initial conditions (1) and boundary conditions (2), (3), based on knowledge of the effective diffusion coefficient of the liquid in the body and in the porous mould, allows the time development of concentration profiles in the entire system, the kinetics of body formation and the time course of the mean liquid concentration in the body and in the porous mould to be calculated. Compared to the models developed so far [1], the model including transmission of liquid in the porous mould also provides information on the instantaneous state of the suction ability of the porous mould. This parameter can likewise be evaluated from the calculated time course of the mean liquid concentration of liquid in the mould, or directly from the liquid flow. The suction capability of the mould determines the reproducibility of the slip-casting technology and the number of working cycles the porous mould can be used in without having to be dried while maintaining the required rate of body formation.

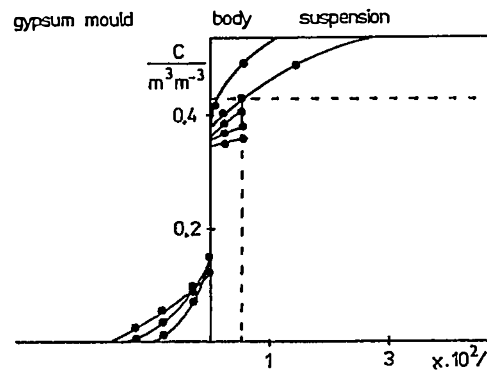

Fig. 3. Experimentally established time development of concentration profiles.

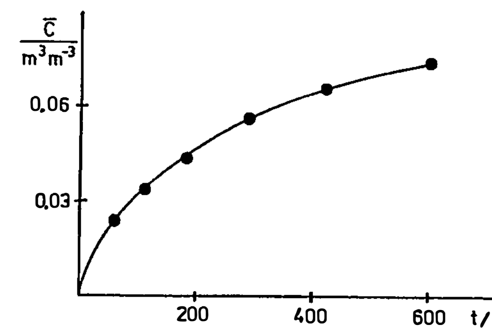

Fig. 4. Experimentally established time dependence of mean concentration of liquid in the gypsum.

EXPERIMENTAL

In the experimental verification, use was made of findings achieved in working out procedures for measuring the boundary conditions, while observing the input assumptions formulated in [2, 3]. For the aqueous suspension of Al_2O_3, use was made of the time dependence of surface flow derived in [2] while respecting the direction of flow indicated in Fig. 2. The time dependence of the moisture profile in the system suspension-body-porous mould and the time dependence of mean concentration in the gypsum mould were established experimentally and are plotted in Figs. 3 and 4. The kinetics of body formation, the time of body solidification and the time dependence of the mean concentration of the body, corresponding to the above relationships, are presented in [2].

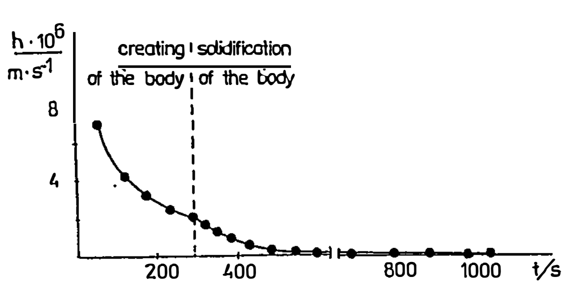

Fig. 2 Time dependence of the surface flow of the liquid.

Verification of the model

The relationships being seeked were calculated by means of the mathematical model by resolving numerically the weight balance equation (1), using the procedure described in [1] for the boundary conditions given in Fig. 2, and the following values [3, 4]:

$C_0 = 0.53\,\mathrm{m^3m^{-3}}$; $C_k = 0.425\,\mathrm{m^3m^{-3}}$;
$C_z = 0.3384\,\mathrm{m^3m^{-3}}$;
$D_{\mathrm{ef}} = 2 \times 10^{-2}\,\mathrm{m^2s^{-1}}$; $D_{\mathrm{eff}} = 2.7 \times 10^{-7}\,\mathrm{m^2s^{-1}}$.

On substituting the above values into the model [1], the relationships given in Figs. 5 and 6 were calculated.

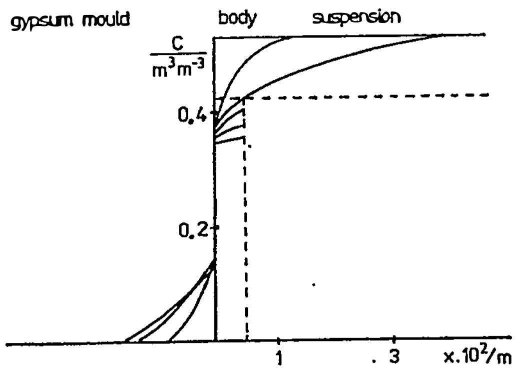

Fig. 5. Calculated time dependence of concentration profiles.

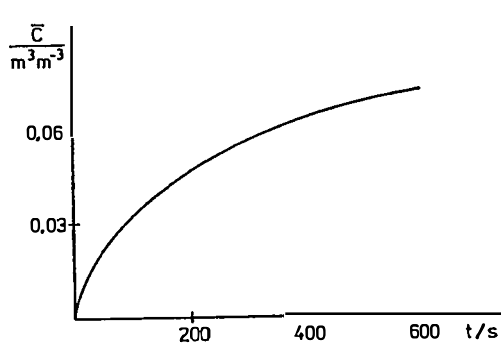

Fig. 6. Calculated time dependence of mean concentration of liquid in the gypsum.

CONCLUSION

A comparison of the time dependences of concentration profiles and the mean concentrations in gypsum calculated from the model (cf. Figs. 5 and 6) to the relationships established experimentally (cf. Figs. 3 and 4) shows a very satisfactory agreement. The error determined from a comparison of the courses of the relationships does not exceed 9% for the model including transmission of liquid through the porous mould.

The suction capability of the porous mould can be assessed on the basis of calculating the time dependence of mean concentration and the time development of the concentration profile in the porous mould for changing intial conditions in the gypsum mould following each concluded body formation and solidification, i.e. for the known $C(x, t = 0)$ in the gypsum, while maintaining the original boundary condition. In comparing the results of the model with experiment, errors exceeding that of the model indicate failure to maintain surface flow in the real system as a result of high saturation of the mould with the liquid. The time dependence of mean concentration in the gypsum mould then allows the mean concentration of liquid, still ensuring reproducible body formation and solidification, to be established. In the case of further using the mould without drying, the model permits the necessary protraction of the time of body formation and solidification to be calculated for the changed conditions in the gypsum.

References

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MODEL TVORBY A ZATUHOVÁNÍ STŘEPU S PŘENOSEM KAPALINY V PORÉZNÍ FORMĚ

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K řízení a optimalizaci lití suspenze do porézní formy byl vypracován matematický model tvorby a zatuhování střepu zahrnující i přenos kapaliny porézní formou. Experimentálním ověřením modelu pro vodnou suspenzi α-Al_2O_3 a sádrovou formu bylo zjištěno, že model umožňuje předpovídat průběh tvorby a zatuhování střepu a stav nasycenosti porézní formy kapalinou. Potvrdila se oprávněnost předpokladů zavedených při formulaci modelu neboť model popisuje průběh technologie lití s chybou menší než 9%.

Obr. 1. Schématické znázornění tvorby a zatuhování střepu včetně přenosu kapaliny porézní formou.
Obr. 2. Časová závislost povrchového toku kapaliny.
Obr. 3. Naměřený časový vývoj koncentračních profilů.
Obr. 4. Naměřená závislost střední koncentrace kapaliny v sádře na čase.
Obr. 5. Vypočtený časový vývoj koncentračních profilů.
Obr. 6. Vypočtená závislost střední koncentrace kapaliny v sádře na čase.