

UDC 532.542

## Peculiarities of controlled forming of porous structure



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### Abstract

The article presents a mathematical model of the porous structure of the equilibrium state at the time of its formation. The dependencies that allow to control this process are obtained.

Keywords: MATHEMATICAL MODEL, HEAT FLUX, VAPOR, PORES, POROSITY

**Introduction.** The process porous material structure formation is realized by allocating the gas in the plastic medium, for example, by evaporation of the heated water contained in the gel mixture. Duration of heating and heat flux determines

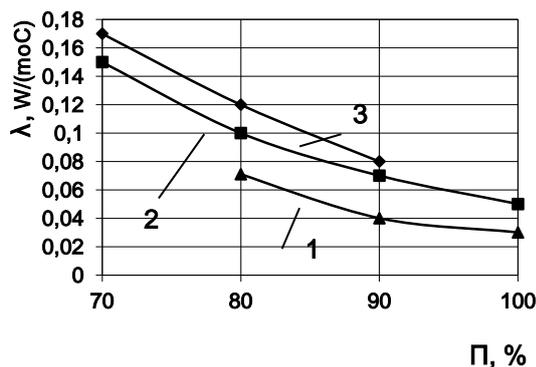
evaporation rate and the amount of released vapor (1,2).

The complexity of observed phenomena, as well as their understanding causes great interest, as by studying of kinetics of phase transitions may create a theoretical basis for the development of

new high-intensity technologies in various industries, in particular the production technology of porous insulating materials. And because the average pore size, porosity is mainly determined by the thermal conductivity and strength of the material (3,4), one can assume that by varying the thermal processing modes, a raw material mixture composition and the prescription can create specific porous structure of the material with the projected thermophysical ones.

**Statement of the problem.** Basing on the results of research it is supposed to develop mathematical model of equilibrium state of the porous structure at the time of its formation.

**The results of the work.** The thermal characteristics of porous materials in the general case are determined by their structure, size, type and shape of the pores, their mutual location in the material. For materials with different structures there defined common pattern: the thermal conductivity varies inversely with the total porosity decreases with the increase that is presented in Fig. 1.



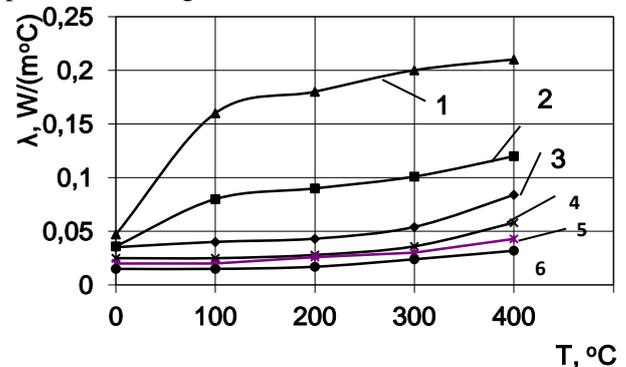
**Figure 1.** Influence of porosity of the material on the thermal conductivity: 1 - grain structure; 2 - fibrous; 3 - cellular.

On these graphs it is not difficult to determine the optimal values of the porosity and pore shape that achieves maximum effect of suppressing heat transfer. But the influence of the other parameters on thermal conductivity of these dependencies is not reflected. Meanwhile, the shape and size not only affect the thermal conductivity, but also change the nature of given dependence, even qualitatively.

Fig. 1 shows that with increase of porosity, thermal conductivity decreases. However, such characteristic, in our opinion, is not complete and unambiguous, as thermal conductivity depends not only on the material properties and porosity, but the pore size, temperature, type of porosity. Obviously, the equal values of porosity can be

achieved, by increasing of amount of small pores. However, thermal conductivity at various temperatures of the material will depend on the porosity at certain pore sizes but such dependences in literary sources are not encountered.

Influence of pore size on the growth of thermal conductivity coefficient at high temperatures is presented in Figure 2.



**Figure 2.** Influence of temperature on the value of the equivalent thermal conductivity coefficient of air in the pores of diameter: 1 - 5 mm.; 2 - 2 mm.; 3 - 1 mm.; 4 - 0.5 mm.; 5 - 0.1 mm.; 6 - 0.05 mm.

The figure shows that with the increase of the pore diameter and the temperature coefficient of thermal conductivity ( $\lambda$ ) of air in the pores also increases. And the larger the pores, the more significant these changes both qualitatively and quantitatively. The upper graph of changing of nature of the curves can be explained by the occurrence of convective component of heat transfer.

Heat transfer by convection, as one of the components of the internal heat transfer in the fine pores is excluded, as the temperature difference in the pores are too small for the occurrence of the heat flow. It can also be seen in the graphs (lines 3, 4, 5). Therefore, the internal heat transfer to the finely porous material takes place mainly by thermal conductivity.

Thus, the main parameter affecting the thermal conductivity, is the pore size. If the porosity rate technologically provide a certain mean value of the pore diameter, it can be assumed to be a thermal conductivity of the resulting material. The size of the pores is given by the corresponding energy parameters of technology free-swelling. We assume that the swelling of raw mixture happens due to the formation and growth of the vapor phase during heating of wet mixture [1,2,5,6].

As the dynamic characteristic, determining the direction of changes in the size of steam pores, let us take the difference of stresses caused by the

pressure of the steam in the area and the resistance of the boundary surface pores.

The equation of Rayleigh - Plesset characterizes the dynamics of growth or decrease of the vapor bubble. Let us display the equation as follows:

$$\frac{dw}{d\tau} = -\frac{1,5\rho w^2 + P_n - P_2(T)}{\rho_2 R} = -\frac{1,5\rho w^2}{\rho_2 R} + \frac{P_n(T) - P_2}{\rho_2 R} \quad (1)$$

After transformations we obtain:

$$\frac{dw}{w^2 - \frac{P_n(T) - P_2}{1,5\rho}} = \frac{1,5\rho d\tau}{\rho_2 R}, \quad (2)$$

where  $\frac{P_n(T) - P_2}{1,5\rho} = b,$

$w$  – the rate of growth of a vapor bubble;  $\tau$  – the growth time of the bubble;  $\rho$  – density;  $P_n$  – the pressure inside the vapor cavity;  $P_2$  – the pressure in the surrounding fluid;  $T$  – temperature;  $R$  – radius of the vapor bubble.

Increase, decrease or stabilization of the size of the bubble can be represented respectively by three cases:

$$\begin{cases} b > 0, & \frac{\sqrt{1,5\rho}}{2\sqrt{P_n(T) - P_2}} \ln \left| \frac{w - \sqrt{b}}{w + \sqrt{b}} \right| = -\frac{1,5\rho\tau}{\rho_2 R} + C, \\ b < 0, & \frac{1}{\sqrt{b}} \operatorname{arctg} \sqrt{\frac{1}{b}} w = -\frac{1,5\rho\tau}{\rho_2 R} + C, \\ b = 0, & \frac{1}{w} = -\frac{1,5\rho\tau}{\rho_2 R} + C. \end{cases} \quad (3)$$

$$\begin{cases} C = \frac{1}{2\sqrt{b}} \ln \left| \frac{w_0 - \sqrt{b}}{w_0 + \sqrt{b}} \right|; & b > 0, \\ C = \frac{1}{\sqrt{b}} \operatorname{arctg} \sqrt{\frac{1}{b}} w_0; & b < 0, \\ C = -\frac{1}{w_0}; & b = 0. \end{cases} \quad (4)$$

At  $P_n(T) - P > 0$  vapor bubble increases,  $P_n(T) - P < 0$  – decreases; in case  $P_n(T) - P = 0$  its size is stabilized.  $P_n(T)$  depends on the magnitude of the external heat flux (the

temperature). Consequently, the process of pore formation can be controlled.

Transform the system of equations (3) to the form

$$\begin{cases} \ln \left| \frac{w - \sqrt{b}}{w + \sqrt{b}} \right| = \left( -\frac{1,5\rho\tau}{\rho_2 R} + C \right) 2\sqrt{b}, & b > 0; \\ \operatorname{arctg} \sqrt{\frac{1}{b}} w = \left( -\frac{1,5\rho\tau}{\rho_2 R} + C \right) 2\sqrt{b}, & b < 0; \\ w = \frac{\rho_2 R}{1,5\rho\tau - \rho_2 RC}, & b = 0. \end{cases} \quad (4)$$

$$\begin{cases} \frac{w - \sqrt{b}}{w + \sqrt{b}} = \exp 2\sqrt{b} \left( C - \frac{1,5\rho\tau}{\rho_2 R} \right), & b > 0; \\ w = \sqrt{|b|} \operatorname{tg} \sqrt{|b|} \left( C - \frac{1,5\rho\tau}{\rho_2 R} \right), & b < 0; \\ w = \frac{\rho_2 R}{1,5\rho\tau - \rho_2 RC}, & b = 0. \end{cases} \quad (5)$$

We denote  $k(\tau) = \exp 2\sqrt{b} \left( C - \frac{1,5\rho\tau}{\rho_2 R} \right)$  (6)

$$w - \sqrt{b} = (w + \sqrt{b}) k(\tau);$$

$$w(1 - k(\tau)) = \sqrt{b}(1 + k(\tau)) \quad (7)$$

$$w = \sqrt{b} \frac{1 + k(\tau)}{1 - k(\tau)}. \quad (8)$$

Thus, the rate of change of the size of the vapor bubble can be determined by the equations:

$$w(\tau) = \begin{cases} \sqrt{b} \frac{1 + k(\tau)}{1 - k(\tau)}, & b > 0, \\ \sqrt{|b|} \operatorname{tg} \sqrt{|b|} \left( C - \frac{1,5\rho\tau}{\rho_2 R} \right), & b < 0, \\ b = 0, & \frac{\rho_2 R}{1,5\rho\tau - \rho_2 RC}; \quad b = 0. \end{cases} \quad (9)$$

Consider last case  $P_n(T) - P_2 = 0$ , given that

$$w = \frac{w_0 \rho_2 R}{1,5\rho w_0 \tau - \rho_2 R}. \quad (10)$$

When the pressure difference  $P_n(T) - P_2$  becomes small, the velocity boundary layer, calculated on the first equation converge the initial value, and in particular - to zero. If  $w_0 \neq 0$ , the last expression loses its physical meaning, as in this case  $w = 0$ .

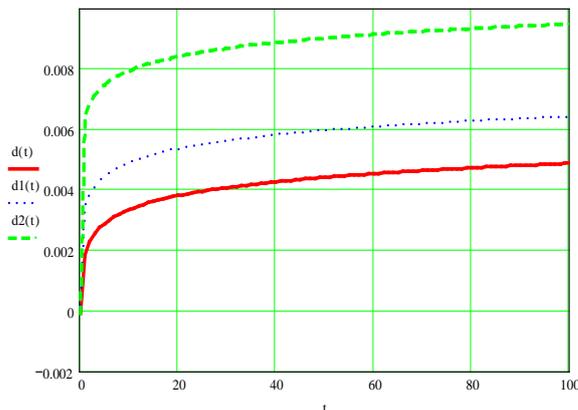
Equation (10) can be written as follows:

$$\frac{dR}{d\tau} = \frac{w_0 \rho_z R}{1,5 \rho w_0 \tau - \rho_z R}$$

Then, after integration, we obtain

$$R(\tau) = \frac{R_0}{1,5} \ln |1,5 w_0 \tau + \rho_z R_0|. \quad (11)$$

The last expression allows to determine the duration of the process of swelling to achieve certain pore size (Fig. 1).



**Figure 1.** The dependence of the radius of the pores of the steam from the heat treatment at a blistering speed: 1-  $w=10$  m/s; 2-  $w=100$  m/s; 3-  $w=1000$  m/s

Graphs show the calculated dependences of increasing of pores diameter. Equation (1) shows the qualitative characteristic of the process of swelling and, in general, one can predict the change in the size of the pores in time. For this it is necessary to know the laws of variation of the growth rate and density of the pores of the raw mix, which will be determined by the temperature of the heat treatment, the composition and properties of the mixture and the duration of its heating. It is assumed that these dependencies will be of more complicated character but generally quite predictable. The equations obtained allow to estimate the expected pore size (mean values) for any production technologies.

### Conclusions

The proposed equations of mathematical model of dynamics of the vapor phase, emerged

and develop in the volume of raw gelatinous mass when heated, provide an opportunity to study in details these processes.

Thus, the size of the pores in porous materials significantly affects the heat transfer indicators. In this case, pores large heat transfer is carried out by conduction, radiation, convection, and in small pores convection is negligible.

For many high-temperature thermal insulation materials there are gases in the pores of relatively small volume, and thermal conductivity of gases abruptly decreases when the pore size becomes smaller than the mean free path of the gas molecules. This conclusion may be of great practical value if obtain quantitative values depending on the value of the pore size on the rate of heat transfer. Under production conditions, the simplest embodiment of this decision - production materials with defined pore size, depending on the temperature of work these materials.

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