The calculating study of the moisture transfer influence at the temperature field in a porous wet medium with internal heat sources

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Abstract. A porous wet medium with solid and gaseous components, with distributed or localized heat sources was considered. The regimes of temperature changes at the heating at various initial material moisture were studied. Mathematical model was developed applied to the investigated wet porous multicomponent medium with internal heat sources, taking into account the transfer of the heat by heat conductivity with variable thermal parameters and porosity, heat transfer by radiation, chemical reactions, drying and moistening of solids, heat and mass transfer of volatile products of chemical reactions by flows filtration, transfer of moisture. The algorithm of numerical calculation and the computer program that implements the proposed mathematical model, allowing to study the dynamics of warming up at a local or distributed heat release, in particular the impact of the transfer of moisture in the medium on the temperature field were created. Graphs of temperature change were obtained at different points of the graphics with different initial moisture. Conclusions about the possible control of the regimes of heating a solid porous body by the initial moisture distribution were made.

1. Introduction
Processes of heat- and mass transfer in porous multicomponent media taking place in the process of the internal heating are very complicated. These processes can be accompanied by changing of the chemical consist of the media, porosity and humidity. Such kind of changings make an influence on physical processes of heat- and mass transfer, they identify specific features of the nonstationary constitution process of the temperature field.

As there is no criteria of the experimental data transfer from the media model of changing parameters to the real object, so we've got a matter about the appropriateness of the laboratory modeling. Moreover, laboratory research at high temperature of the real (industrial) process can't be carried out.

There are industrial productions, where technological process is directly connected to the heat- and mass transfer in the porous media. Scientists need industrial experiments to improve them. Taking into consideration that such kind of experimental work at plants as a rule is risky and expensive these experiments can be few.
When we choose from large amount of variants of changing of the technological process only variants with the best economical effect, there is an interest to verified computational models of similar processes.

In our article we describe exactly such a type of the model. The results of the calculations of temperature fields in the model are compared to the industrial experiments.

2. Equations of heat conductivity and filtration
General heat- and mass transfer process in the humid media with solid (index number "1") and gas (index number "2") components is given as a superposition of two processes: thermal conductivity without mass transfer and energy transfer because of gas filtration.

The nonstationary thermal conductivity equation for continuous medium with variables thermophysical parameters without mass transfer is given as [1]:

$$\frac{\partial}{\partial \tau} (\rho h) = -div \mathbf{q} + q_v$$

where $\rho$ – is density; $h$ - enthalpy; $q_v$ - total density of all internal sources of heat, including generation of heat during the passage of an electric current, the heat of a liquid-vapor phase transition, and the thermal effect of chemical reactions.

The energy transfer because of the gas filtration through the system of interconnected pores is taken into account by the model presented in paper [2]. There we have an equation system for definition of the pressure field $P$ of the gas component in the area of interconnected finite dimensional pores at determined mass flows of gas products of chemical reactions and densities of steam mass flows generated during the drying process or condensed at pores surface. Energy transfer by filtration flow at an arbitrary point of the media at any time in the development of the process at the pressure field calculated at any time is defined as:

$$q_{v,\phi} = \varepsilon \sum_{r} \left( \frac{P k C_p}{\mu R} \right) \frac{\partial P}{\partial \chi_r}$$

where $l$ – is the characteristic size (the average length of the conditional communication channel of the pores); $r$ - index of the direction of filtration; $\sigma$ – is the mass flow source index; $\varepsilon$ – is the porosity of the medium; $\mu$ – is the dynamic viscosity; $C_p$ – is the specific isobaric heat capacity; $k$ – is the permeability coefficient of the porous medium; $R$ – is the gas constant of the gas mixture.

The superposition of the processes of non-stationary thermal conductivity and the transfer of the thermal energy by the filtering flow in the determination of the temperature field $T$ means the simultaneous solution of the equations:

$$\Phi_1 \frac{\partial T}{\partial \tau} = -div \mathbf{q} + q_v + q_{v,\phi}$$

and

$$q_{v,\phi} = \varepsilon \Phi_2$$

where $\Phi_1$ - the function of the heat capacity and density of all components of the solid and gas components and the porosity of the medium; $\Phi_2$ - the function of the temperature and pressure of gas component, properties of gas components.

In this case, for each particular problem, the constituent functions $q_v$ in the right-hand side of equation (1) must be further defined.

3. Model representations of the components of volumetric energy release $q_v$
In [3], an expression for calculating the volume flow of heat during the drying of a moist material was obtained:

$$q_{v,\text{cysh}} = -r \tilde{\rho}_{b,o} s_o e^{-s_o \tau},$$

where $r$ – is the latent heat of vaporization; $\tilde{\rho}_{b,o}$ – is the partial density of the water component, the index "o" indicates the initial state;
\[ S_0 = S_0^0 + S_{01} \frac{\partial T}{\partial \tau}, \] 
\[ S_{00} \text{ and } S_{01} \text{ - constants.} \]

If there are no chemical reactions at drying temperatures, the equation (2) can be written as the following:
\[ q_{v, cysh} = -\frac{1}{1+\nu} \rho_{1,0} \frac{\partial x_n}{\partial \tau}. \] (3)

In equation (3), \( x_n \) is the moisture content of the solid constituent of the medium; \( \nu \) is the fraction of the volume of the solid component attributable to the moisture.

The energy release function due to the condensation of water vapor on the supercooled pore surface \( q_{v, ko} \) coincides with the function (3), but with the inverse sign.

To describe the effect of the thermal effect "m" of the chemical reactions, a semiempirical relation is used [1]:
\[ q_{v, xim} = M_o \sum_{j=1}^{m} e_j \beta_j \left( \int_{v_p} \Delta \tau_j dV \right)^{-1}, \]

where \( e_j \) is the heat of a chemical reaction of the type "j"; \( \beta_j \) - fraction of volatile components of the reaction "j" in the total amount of the formed gaseous products; \( M_o \) - is the total number of volatiles formed of all chemical reactions during the control time \( \tau_k \); \( \Delta \tau_j = \tau_k - \tau_j \), where \( \tau_j \) is the start time of the reaction of type "j"; \( V_p \) is the volume of the reaction zone.

Thus, in the general case, \( q \) is defined as
\[ q_v = q_{v, el} + q_{v, ph} + q_{v, xim}. \]

Here, \( q_{v, el} \) is the energy release during the electric heating; \( q_{v, ph} \) - sources (sinks) of heat, caused by drying or condensation.

4. Effective coefficient of thermal conductivity
The heat flux density \( \vec{q} \) in equation (1) is represented as
\[ \vec{q} = -\left( \lambda_{ef} + \lambda_{izl} \right) \text{grad} \ T. \] (4)

In the ratio (4), the effective coefficient of the molecular thermal conductivity is calculated according to the dependence [4]:
\[ \lambda_{ef} = \frac{2 \lambda_1 \lambda_2 + \varepsilon (1 - \varepsilon) (\lambda_1 - \lambda_2)^2}{2 [\varepsilon \lambda_1 + (1 - \varepsilon) \lambda_2]} . \]

The term \( \lambda_{izl} \) takes into account the radiation component of the flux density and is defined as:
\[ \lambda_{izl} = 4 \sigma_o \varepsilon_{por} l_{por} \varepsilon (1 - \varepsilon) T^3 , \]
where \( \sigma_o \) - is the Stefan-Boltzmann constant; \( \varepsilon_{por} \) - reduced degree of blackness of the pore surface; \( l_{por} \) - is the characteristic pore size.

5. The porosity of the medium
The change in the porosity of the medium \( \varepsilon \) is taken into account in the general model. It is assumed that \( \varepsilon \) can vary not only due to the chemical reactions with the appearance of the volatile components, but also due to the possible mechanical deformation of the medium during the precipitation of the solid component (index "oc").

Then
\[ \frac{\partial \varepsilon}{\partial \tau} = f_{xim} + f_{oc}. \] (5)

In [1] the first term on the right side is determined (5):
\[ f_{xim} = \frac{1}{\rho_1} \left[ (1 + \nu) \frac{q_{v, xim}}{r} + (1 - \varepsilon) \frac{\partial \rho_1}{\partial \tau} \right]. \]
and in [5], the dependencies for the calculation of the second term and the additional source of heat \( q_{v,oc} \) accompanying the sediment are proposed:

\[
\begin{align*}
    f_{oc} &= f_{oc}[\varepsilon, \bar{\varepsilon}, \kappa(\tau)] \\
    q_{v,oc} &= q_{v,oc}[\varepsilon, \bar{\varepsilon}, \rho_1, C_1, T_F, \nabla T, \kappa(\tau)]
\end{align*}
\]

(6)

In dependences (6), \( \kappa(\tau) \) is the function of changing the position of the free boundary of the medium; \( T_F \) is the temperature at the free boundary.

It is clear that the components of porosity changes are connected to the different processes - the transformation of the solid component into gaseous and the crushing of the porous system.

6. Numerical solution of the nonstationary heat equation and the filtration equation

The set of the above equations is a mathematical model of the processes in a porous moist multicomponent medium with the internal heat sources, built on the basis of a model representation of the basic physical and chemical processes in this medium. On the basis of the mathematical description, an algorithm for calculating the non-stationary temperature field is developed, taking into account, in particular, the processes of filtration, drying and condensation of the water vapor. A calculation program has been developed in the Mathcad.

Calculation studies of the influence of the parameters of the porous medium on the formation of the temperature field have been carried out. The results of revealing the role of the initial moisture of the porous material on the dynamics of temperature growth of the medium for two processes: the industrial production of silicon carbide and the production of tungsten carbide are given.

In the first case, the temperature field in the resistance furnace with an electric heater in the form of a carbon core, intended for the production of silicon carbide, is analyzed. The general dimensions of the porous medium (charge) in the furnace are 3620×3240×17000 mm. The composition is silicon dioxide and petrocoke. The input power is 3 MW. The region in the central cross section of a 1 m long furnace is considered. The lower boundary of the calculation area is thermally insulated and impermeable. The side surfaces provide the possibility of the gas and heat removal. The upper free boundary of the porous medium ensures the gas and heat removal by the thermal conductivity, convection, and filtration flow.

Figure 1. Change in humidity at different points in the furnace during the carbide process 1 - 3 cm from the core; 2 - 15 cm from the core; 3 - 25 cm from the core; 4 - 40 cm from the core.
Figure 1 shows that in the initial period of heating the porous ($\varepsilon = 0.5$) medium in the points removed from the heater, humidity increases. Humidification is explained by the condensation of moisture coming from the drying zone with the filtration flow. Such a rise in humidity stops when the temperature of the medium rises to the boiling point at the gas component pressure in this local area. Then due to high temperature gradients at the boundary of the drying and condensation zones the intensive drying of the material takes place.

Figure 2. Experimental and calculated values of furnace temperatures in the cycle of operation of the furnace.

1 - the thermocouple readings, the distance from the core is 20 cm, 2 - the calculated values taking into account the moisture transfer and condensation, 3 - the calculated values without taking into account the condensation process.

Figure 2 shows the difference in the temperature change at the calculated point 200 mm from the core. It is obtained in calculations taking into account the condensation of the transferred moisture (curve 2) and without such an account (curve 3). The design algorithm describing the condensation practically corresponds to the data of the industrial experiment (curve 1), which indicates the need to take into account the processes of moisture transfer.

In another calculation cycle, a cylindrical reaction zone of dimensions $h \times r = 1200 \times 100$ mm, in the initial state representing a porous ($\varepsilon = 0.6$) medium consisting of a mixture of tungsten dioxide and a carbon material is considered. Electric power of the furnace is 50 kW. Thermal insulation of impermeable walls of the cylinder and the presence of a free surface at the upper end of the cylindrical zone through which gas (vapor) removal and heat removal takes place by thermal conductivity, convection and with a filtration flow are assumed. The process is axially symmetric. The calculated data is presented in the longitudinally axial section of the cylinder.
Figure 3 shows that the active temperature rise is interrupted by the drying process of the material. The growth rate of temperature decreases with the approach to a free surface. The drying time in the peripheral zone due to the moisture recharge from the central zone is somewhat greater than the corresponding drying time of the local volumes of the medium remote from the free surface, Fig. 4.

7. Conclusion
In porous media with central heating, the moisture content of the loading material has a significant effect on the formation of the temperature field. The moving boundary of high humidity is a natural barrier to the warming up the peripheral zone, which affects the rate at which the temperature of the central zone is established.

In addition, it should be expected that the vapor formed during the drying of the material before reaching the temperatures of the onset of chemical reactions affects the formation of the pore bond, improving the kinetics of chemical reactions.

For porous media with a uniform energy release in the volume, the presence of moisture in the material interrupts the constant temperature increase when the medium is heated. A momentary significant moistening of the layer adjacent to the free surface is possible.

8. References
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