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SPECIAL FEATURES OF THE DYNAMICS OF HEATING OF MOVING MEDIA BY ELECTROMAGNETIC RADIATION

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The dynamics of temperature waves in moving media heated by high-frequency electromagnetic radiation has been studied by the methods of numerical simulation with allowance for the dependence of the viscosity and the absorption coefficient of the radiation on temperature.

Special features of the heating of motionless absorbing media by electromagnetic radiation with allowance for nonlinear effects caused by a variation in the degree of absorption of the radiation during the heating were considered in [1]. At the same time, many scientific and engineering problems use the heating of moving media by electromagnetic radiation. Here we can mention such processes as decontamination of materials by the method of zone melting, melting of dielectric media in a wave guide [2, 3], heating and drying of capillary-porous and loose media, conveyor technologies of electromagnetic treatment [4, 5], intensification of the output of mineral resources [6], etc.

The dynamics of a temperature field in simulation of these processes is determined by heat conduction, heat transfer by convection, heat exchange with the environment, and dissipation of the energy of electromagnetic radiation to heat. From the point of view of application, in certain cases, the cyclic (intermittent) mode of an electromagnetic-radiation effect and the discontinuous mode of medium motion – alteration of the periods of motion and rest of the medium or periodic variation in the direction of motion (reciprocating motion) – are of fundamental importance.

In a number of cases, a viscosity decrease in heating is a determining factor. This factor exerts a double reverse effect on the dynamics of heating: first, the velocity of motion and the role of convective heat transfer increase; second, the absorption coefficient of electromagnetic radiation varies; this variation is, as a rule, nonmonotonic, which clearly manifests itself in polar viscous fluids that possess dipole-relaxation dielectric losses. Polar molecules in the field of electromagnetic radiation swing in the viscous medium and cause losses of radiation energy by friction with the liberation of heat. At slow temperatures, i.e., rather high viscosity, the molecules do not succeed in following changes in the field, dipole polarization is insufficient, and the medium has a low absorptivity. Dipole losses and the absorption coefficient are also low at high temperatures when the viscosity is small and orientation of the molecules in the field of radiation occurs virtually without friction. At certain mean values of temperature and viscosity, the dipole losses and the absorption coefficient of electromagnetic radiation are maximum. Thus, in the general case, a nonmonotonic dependence of the absorption coefficient on temperature takes place [1].

The distribution of temperature in the case of plane-one-dimensional geometry is described by the following problem:

$$\frac{\partial \theta}{\partial \tau} = a_0 \frac{\partial^2 \theta}{\partial z^2} - b_0 \varphi(\theta)\, \sigma(\tau_v) \frac{\partial \theta}{\partial z} + 2f(z, \tau)\, \sigma(\tau_e) \exp\left(-\int_0^z f(z', \tau)\, dz' \right), \tag{1}$$

$$\theta(z, 0) = \theta(\infty, t) = 1\,, \tag{2}$$

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$$\frac{\partial \theta(0,\tau)}{\partial z}[1-\sigma(\tau_v)]+[\theta(0,\tau)-\theta_{bound}]\,\sigma(\tau_v)=0\,, \tag{3}$$

$$\theta=T/T_0\,,\quad \theta_{bound}=T_{bound}/T_0\,,\quad z=2\alpha_0 x\,,\quad \tau=t/t_0\,,\quad t_0=\rho c T_0/\alpha_0 q_0\,,$$

$$a_0=4\lambda T_0\alpha_0/q_0\,,\quad b_0=2\rho_f c_f v_0 T_0/q_0\,,\quad f(z,\tau)=\alpha(x,t)/\alpha_0\,.$$

Here T_{bound} and T_0 are the values of the temperature at $x = 0$ and $t = 0$, λ and ρc are the volume-averaged thermal conductivity and heat capacity of the medium, ρ_f, c_f, and v_0 are the density, heat capacity, and initial velocity of the moving fluid, $\alpha(x, t)$ and α_0 are the current and initial values of the absorption coefficient, and $\alpha(x, t) \equiv \alpha(T)$ and $\varphi(\theta)$ are the specified functions that determine the dependences of the absorption coefficient and velocity of motion on temperature.

In the general case, problem (1)-(3) describes the filtration of a liquid in a saturated porous medium with volume-averaged thermophysical and electrophysical parameters; in the absence of a porous body (motion in a free space) $c_f = c$ and $\rho_f = \rho$. The velocity of medium motion is taken to be specified, and its dependence on temperature (in terms of a variation in viscosity as a function of temperature) is also assumed to be known. Unit functions $\sigma(\tau_v)$ and $\sigma(\tau_e)$ allow one to describe the discontinuous character of medium motion and the effect of electromagnetic radiation:

$$\sigma(\tau_{v,e})=1 \text{ when } \tau_{v,e}>0\,;\quad \sigma(\tau_{v,e})=0 \text{ when } \tau_{v,e}<0\,.$$

Here τ_v and τ_e are the time intervals that correspond to the presence of the medium motion and the effect of electromagnetic radiation.

The combined boundary condition for temperature (3) on the surface $x = 0$ means that in heating of a quiescent medium ($\tau_v < 0$), this surface is assumed to be adiabatic, and in heating of a medium that moves at velocity $v > 0$ ($\tau_v > 0$), the temperature of the fluid entering the region of heating from outside ($x > 0$) is specified. On modeling the heating of a liquid moving toward electromagnetic radiation, $v < 0$ and $\tau_v < 0$, and when $x = 0$ the condition $\partial T(0, t)/\partial x = 0$ is set.

The dimensionless parameters t_0, a_0, and b_0 have a distinct physical meaning: t_0 determines the characteristic time of the medium heating by electromagnetic radiation, a_0 is equal to the ratio of the characteristic value of the heat-flux power due to heat conduction $\lambda T_0/h$ ($h = 1/2\alpha_0$) to the density of the flow of the energy (intensity) of electromagnetic radiation, and b_0 determines the ratio of the density of the convective heat flux to the intensity of electromagnetic radiation. It is obvious that b_0/a_0 is the Peclet parameter

$$\mathrm{Pe}=v_0 h\,\frac{\rho_f c_f}{\lambda}\,.$$

We consider results of numerical calculations of problem (1)-(3) for the following basic values of the parameters: T_0 = 300 K, α_0 = 0.1 1/m, $\rho c = \rho_f c_f = 2\cdot10^6$ J/(m^3·K), λ = 1 W/(m·K), $q_0 = 10^5$ W/m^2, and v_0 = 0.0001 m/sec. Here t_0 = 60,000 sec, $a_0 = 1.2\cdot10^{-3}$, b_0 = 1.2, and Pe = 1000. For the nonmonotonic dependence of the absorption coefficient of electromagnetic radiation on temperature we take a piecewise-linear approximation [1]:

$$f=\begin{cases} 1 & \theta\le 1\,,\\ 1+a_1(\theta-1) & 1\le\theta\le\theta_m\,,\\ a_3-a_2(\theta-1) & \theta_m\le\theta\le 1\,,\\ a_4 & \theta\ge\theta_1\,. \end{cases} \tag{4}$$

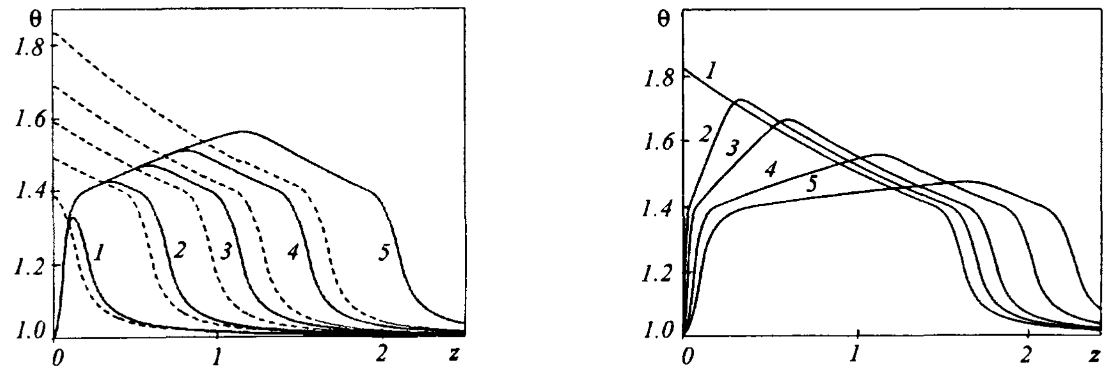


Fig. 1. Dynamics of temperature waves as a function of time for a motionless (dashed lines) and a moving medium (solid lines) at $u = 2$.

Fig. 2. Dynamics of temperature waves as a function of the rate of convection; curve 1, $u = 0$; curves 2-5 correspond to $u = 0.5$, 1, 2, and 3, respectively.

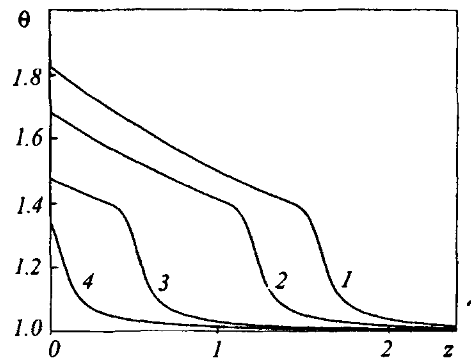
Here $\theta_m = 1.2$, $\theta_1 = 1.4$, $a_1 = 45$, $a_2 = 47.5$, $a_3 = 10$, and $a_4 = 0.5$. These dimensionless parameters correspond to an increase in α from 0.1 to 1.0 1/m within the range of temperatures 300–360 K and to its decrease to 0.05 1/m within the range of temperatures 360–420 K ($\alpha = 0.05$ 1/m when $T > 420$ K).

Figure 1 presents the dynamics of a temperature wave as a function of time. Curves 1-5 correspond to times $\tau = 0.05$, 0.15, 0.25, 0.35, and 0.5. With the motion of the medium the character of heating changes both qualitatively and quantitatively. A temperature wave is nonmonotonic and has a maximum in the depth of the heating zone. The isotherm of the temperature maximum virtually coincides with the coordinate of the front of convective heat transfer $x_c = vt$; actually, some difference occurs due to the effect of molecular heat conduction. For example, for curve 3, $t = 15{,}000$ sec, $x_c = 3$ m, and $x(T_m = 440.93\text{ K}) = 2.94$ m. The characteristic form of the slope of the temperature curves is determined by two competing factors – cooling due to the arrival of a cold liquid at the heating zone and heating of this liquid by electromagnetic radiation in a nonlinear mode when the intensity of the heating constantly changes with time according to (4).

The profile of a temperature wave substantially depends on the velocity of medium motion. The corresponding curves are shown in Fig. 2 for the instant of time $\tau = 0.48$. With increase in the velocity of medium motion the amplitude of the temperature wave decreases and the depth of heating increases. It is obvious that the resulting velocity of the temperature wave in a moving medium is determined by the sum of the rates of convection v and the "proper" velocity of the temperature wave in the quiescent medium that can be found from the expression [1]

$$v_s = \frac{q_0}{\rho c\,(T_1 - T_0) + 2\alpha_1 q_0\,(t - t_s)}\,.$$

Here t_s is the time of formation of the temperature wave determined from the condition $T(0, t_s) = T_1$. By virtue of the above, it becomes obvious that when convection is directed opposite to the propagation of electromagnetic waves, the velocity of the temperature wave decelerates and, in principle, the realization of a "standing" temperature wave is possible. This situation is illustrated in Figs. 3 and 4. Figure 3 presents the curves that describe the distribution of temperature at $\tau = 0.4$. Curves 1-6 in Fig. 4 correspond to the instants of time τ equal to 0.05, 0.15, 0.25, 0.35, 0.45, and 0.5 at the rate of convection $u = -2$. It is seen that at $\tau = 0.5$ virtually a standing temperature wave takes place, i.e., localization of the heating zone is realized. In this case, the basic characteristics of heating – depth and temperature – are determined by the rate of convection, thermophysical and electrophysical parameters of the medium, and intensity of radiation and its frequency (absorptivity of the medium depends on frequency). Thus, it becomes possible to control and to optimize the process of heating by, for example, variation of the rate of convection and the intensity or frequency of radiation.



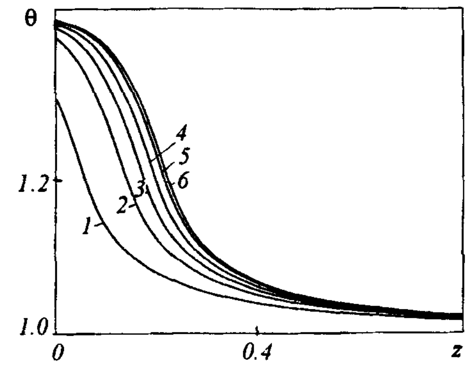


Fig. 3. Dynamics of temperature waves as a function of the absolute value of the rate of convection for $v < 0$: curve 1, $u = 0$; curves 2-4 correspond to $u = -0.5$, -1.5, and -2.5, respectively.

Fig. 4. Dynamics of temperature waves as a function of time at $u = -2$.

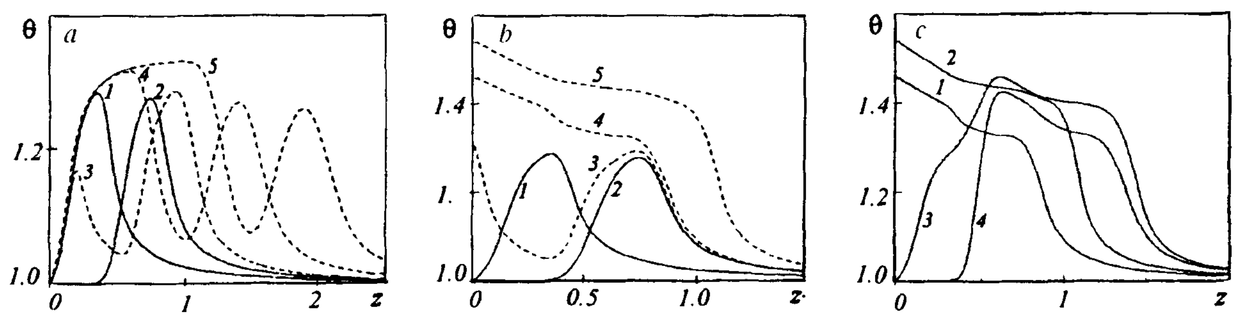


Fig. 5. Dynamics of a temperature wave with allowance for the cyclic character of heating and motion of the medium.

It is seen from a comparison of Figs. 1-4 that the direction of medium motion greatly affects the temperature profiles. This is associated with the fact that when $v > 0$ cold liquid enters the heating zone and when $v < 0$ hot liquid leaves this zone.

Figure 5 shows the profiles of temperature with allowance for the cyclic character of heating and the motion of the heated medium. Curves 1 in Fig. 5a and b correspond to $\tau_1 = 0.0666$, when the heating of the liquid moving at a velocity $u = 5$ halts. Curves 2 show the temperature distribution at $\tau_2 = 2\tau_1$; thus, within the time interval $\tau_2 - \tau_1$ the temperature profile is moved by convection in the absence of heating. Some decrease in the maximum temperature due to molecular heat conduction is noted.

In Fig. 5a, dashed lines 3-5 define the profile of temperature for the instants of time $2.5\tau_1$, $3.95\tau_1$, and $5\tau_1$; here, at $\tau = 2\tau_1$ the heating of the medium begins. As the heating is resumed, a new peak of temperature (curve 3), which is then transformed to a temperature plateau (curves 4 and 5) with an asymptotic value of the amplitude, appears between the "initial" peak (curve 2) and the surface of radiation ($x = 0$). At the same time, the "initial" peak of temperature (curve 2) is carried away by convection to the right with some spreading due to heat conduction.

In Fig. 5b, dashed lines 3-5 define the profiles of temperature for the same values of τ as in Fig. 5a; however, here the situation is represented where at the moment of resumption of heating $2\tau_1$ the motion of the medium halts. The region of radiation penetration is progressively heated and the temperature wave moves backward (curve 3). A temperature wave whose motion becomes noticeable after its formation (when a temperature equal to θ_1 is reached) is generated with time – curves 4 and 5.

Figure 5c depicts the situation describing the evolution of the temperature profile within a time interval from $\tau = 0.25$ (curve 1) to $\tau = 0.333$ (curves 2-4). In this case, curves 2 and 3 correspond to the heating of quiescent and moving media, and curve 4 describes the temperature profile for a medium moving without heat-

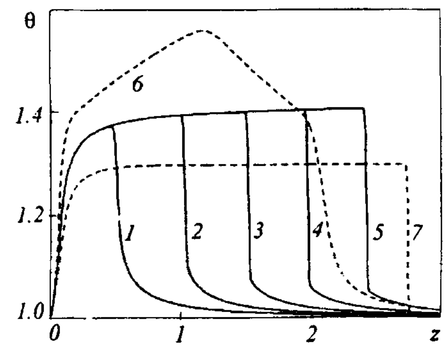


Fig. 6. Dynamics of temperature waves with allowance for the change in viscosity as a function of temperature.

ing. If at $\tau = 0.25$ both the heating and motion of the medium are eliminated, then the evolution of curve 1 with time occurs only due to molecular heat conduction. During the considered interval of time the effect of heat conduction is small (within the scale of the figure the difference in the temperature profiles is not revealed, only a slight difference at the leading front of curve 1 takes place, i.e., some flattening of it is observed).

Figure 6 shows the profiles of temperature as functions of the parameter b which determines the rate of change in the velocity in heating of the medium; the velocity change during the heating was approximated by the following relation: $v = v_0 \exp [b(T - T_0)]$. Curves 1-5 correspond to the instants of time $\tau = 0.1$, 0.2, 0.3, 0.4, and 0.5 at $u_0 \leq 2$ and $b = 0.01$. Dashed lines 6 and 7 show the distribution of temperature at $\tau = 0.5$ for $b = 0$ and $b = 0.02$. The general tendency in the formation of the temperature field with a variable rate of convection is as follows. As the temperature increases, the viscosity decreases and the velocity of motion increases; in this case, the contribution of convective heat transfer, which in turn facilitates a decrease in the temperature, increases. As a result of this self-limitation of growth, the temperature reaches the asymptotics rather quickly, and the asymptotic value of the rate of convection is set with some delay in time. Thus, after a certain interval of time, a quasistationary temperature wave, which has virtually constant amplitude and velocity, is formed. All other things being equal, the amplitude of the temperature wave θ_s decreases and velocity grows with increase in v_0 (the Peclet parameter) and b; a larger region is covered by heating. At $b = 0.01$: $\theta_s = 1.4$, $\bar{x}_s = 2.41$; at $b = 0.05$: $\theta_s = 1/17$, $\bar{x}_s = 3.29$; at $b = 0.1$: $\theta_s = 1.11$, $\bar{x}_s = 3.68$; here $\bar{x}_s$ is a dimensionless coordinate of the front of the temperature wave ($\bar{x}_s = 2\alpha_0 x_s$).

The studied special features of the heating of moving media by electromagnetic radiation make it possible to realize the processes of control and optimization of the heating. For example, varying only the cycles of heating and motion, we can obtain a set of temperature profiles that differ in the temperature, size of the region, and rate of heating.

NOTATION

x, coordinate; t, time; T, temperature; α and q_0, coefficient of absorption and the intensity of electromagnetic radiation; v, velocity of medium motion; v_0, preexponential factor in the formula of temperature dependence of velocity; ρ and c, density and heat capacity of the medium; λ, thermal conductivity; θ, z, τ, and u, dimensionless values of the temperature, coordinates, time, and velocity; σ, Heaviside unit function; Pe, Peclet number; h, initial depth of penetration of electromagnetic radiation into the medium; t_0, characteristic time of heating; x_c, coordinate of the front of convective heat transfer; x_3, coordinate of the front of the temperature wave; v_s, velocity of the front of the temperature wave; t_s, time of formation of the temperature wave. Subscripts: m, maximum value of the absorption index and the corresponding temperature θ_m; f, moving fluid; s, front of the temperature wave; 0, initial value; bound, boundary value; c, front of convective heat transfer; e, presence of electromagnetic radiation; v, presence of medium motion; b, index of the exponential growth in velocity as a function of temperature.

REFERENCES

1. I. L. Khabibullin, *Inzh.-Fiz. Zh.*, **73**, No. 4, 832-838 (2000).
2. A. G. Merzhanov, V. A. Raduchev, and E. N. Rumanov, *Prom. Mekh. Tekh. Fiz.*, No. 1, 7-12 (1985).
3. E. Okress (ed.), *SHF-Energetics* [in Russian], Vol. 2, Moscow (1971).
4. A. V. Luikov, *Theory of Drying* [in Russian], Moscow (1986).
5. A. V. Netushil, B. Ya. Zhukhovitskii, V. N. Kudin, and E. P. Parini, *High-Frequency Heating of Dielectrics and Semiconductors* [in Russian], Moscow–Leningrad (1959).
6. Yu. F. Makogon, F. L. Sayakhov, and I. L. Khabibullin, *Dokl. Akad. Nauk SSSR*, **306**, No. 4, 941-943 (1989).