EXCHANGE OF HEAT IN A REVERSE GAS FLOW WITH A NONMOVING DISPERSED SOLID PHASE

N. I. Gamayunov, R. A. Ispiryan, and A. V. Klinger

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We have arrived at an analytical solution to the problem of convective heat exchange in a reverse gas flow with a disperse solid phase exhibiting high thermal conductivity.

A reverse gas flow, i.e., one which periodically changes its direction, as it penetrates the layer of a disperse material, is used in processes of drying and in certain types of heat exchangers. To ensure the efficiency of the process, it is essential that we analyze the effect of technological and structural parameters on the temperature field for both the solid phase and for the events within the gas flow.

Let us examine a layer of a disperse material having a thickness h, injected by means of a gas flow, at a linear velocity v and a temperature T_l (at the inlet to the layer). Within the time interval $\Delta\tau$ this injection is accomplished in the direction of the 0x axis; over the following time interval $\Delta\tau$, the injection is accomplished in the opposite direction, etc. We will set the coordinate origin at the surface of the layer. We will assume that the thermal conductivity of the solid phase is rather high, and that the dimensions of the dispersed particles are small. When these conditions are satisfied, convective heat transfer occurs within the layer. The system of heat-exchange equations, the boundary and initial conditions of the problem, have the form:

$$\frac{\partial T_1}{\partial \tau} + v\frac{\partial T_1}{\partial x} = m_1 (T_2 - T_1), \tag{1}$$

$$\frac{\partial T_2}{\partial \tau} = m_2 (T_1 - T_2); \tag{2}$$

$$T_1|_{x=0} = T_l;\ T_i|_{\tau=0} = T_{i0}(x),\ i = 1,\ 2. \tag{3}$$

To account for flow reversal, it is expedient, as the half-cycles of duration $\Delta\tau$ change from one to the other, each time to begin anew to count the time τ and to replace the variable x by h–x. The various inlet temperatures for the gas stream in the "direct" and "reverse" directions can be accounted for by specifying various values for T_l in the boundary condition.

The initial temperature distributions $T_{i0}(x)$ are determined from the nature of the temperature fields formed at the instant at which each previous half-cycle is concluded. The preliminary calculations carried out in accordance with the solution derived for problem (1)-(3) with respect to the initial half cycld ($T_{10} = T_{20} = T_0$ = const) demonstrated that when the condition $\Delta\tau > h/v$ is satisfied in actual practice the phase temperature distributions $T_i(x, \Delta\tau)$ are monotonic in nature, nearly exponential, and for the approximation of the initial conditions we will therefore choose functions of the form

$$T_{i0}(x) = A_i + B_i \exp(C_i x). \tag{4}$$

For the initial half cycle $A_i = T_0$ and $B_i = C_i = 0$. For the subsequent half cycles the coefficients of the approximation function can be found as follows:

$$A_i = (\varphi_{i1}\varphi_{i3} - \varphi_{i2}^2)/D_i;\ B_i = (\varphi_{i3} - \varphi_{i2})^2/D_i;$$

$$C_i = \frac{2}{h}\ln\frac{\varphi_{i2} - \varphi_{i1}}{\varphi_{i3} - \varphi_{i2}},$$

where φ_{i1}, φ_{i3}, and φ_{i2} are the values of T_i, respectively, at the inlet, at the outlet, and in the mid-section of the layer, at the instant of cessation in the previous half cycle; $D_i = \varphi_{i1} + \varphi_{i3} - 2\varphi_{i2}$.

The solution of problem (1)-(4) was obtained by an operational method and has the following form:

for the "undisturbed" area ($x \geq v\tau$ or $\tau \leq x/v$)

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$$T_i|_{\tau \le t_x} = A_i + \frac{\Delta A}{m} (-1)^i m_i [1 - \exp(-m\tau)] +$$

$$+ \frac{1}{2} \sum_{j=1}^{2} \frac{1}{\omega_j} B_j f_{ij}(\tau) \exp(C_j x);$$

for the "disturbed" area ($x < v\tau$ or $\tau > x/v$)

$$T_i|_{\tau > t_x} = T_l + \Big\{ (A_i - T_l) \psi_i (m_1 t_x,\ m_2 t) +$$

$$+ \frac{\Delta A}{m} (-1)^i m_i [\psi_i (m_1 t_x,\ m_2 t) - \psi_i (-m_2 t_x,\ -m_1 t)] +$$

$$+ \frac{1}{2} \sum_{j=1}^{2} \frac{1}{\omega_j} B_j g_{ij}(t_x,\ t) \Big\} \exp[-(m_1 t_x + m_2 t)],$$

where

$$t_x = x/v;\ t = \tau - t_x;\ m = m_1 + m_2;\ \Delta A = A_1 - A_2;$$

$$f_{ii}(\tau) = (-1)^i [\nu_{ik} \exp(\varkappa_{i2}\tau) - \nu_{ii} \exp(\varkappa_{i1}\tau)];$$

$$f_{ik}(\tau) = m_i [\exp(\varkappa_{k1}\tau) - \exp(\varkappa_{k2}\tau)];$$

$$k = 3 - i;\ \omega_i = \sqrt{\varepsilon_i^2 - m_2 v C_i};\ \varepsilon_i = \frac{1}{2} (m + v C_i);$$

$$\varkappa_{ij} = -[\varepsilon_i + (-1)^j \omega_i];\ \nu_{ij} = m_2 + \varkappa_{ij};$$

$$g_{ii}(t_x,\ t) = (-1)^i [\nu_{ik} \psi_i (-\nu_{i1} t_x,\ \nu_{i2} t) - \nu_{ii} \psi_i (-\nu_{i2} t_x,\ \nu_{i1} t)];$$

$$g_{ik}(t_x,\ t) = m_i [\psi_i (-\nu_{i2} t_x,\ \nu_{i1} t) - \psi_i (-\nu_{i1} t_x,\ \nu_{i2} t)];$$

$$\psi_i(a,\ b) = \sum_{n=2-i}^{\infty} \frac{a^n}{n!} \sum_{k=0}^{n+i-2} \frac{b^k}{k!}.$$

The derived solution for the problem found practical application in the analysis of the operational regimes of a heat-shielding mask intended to shield human breathing organs against low-temperature supercooling. The heat-exchange mask is filled with a jumble of metal wires; the operational principle involves the heating of the inspired air by the heat accumulated by the wire on expiration. Recommendations based on mathematical modeling were proposed with respect to perfecting the design of the mask.

NOTATION

$T_i(x, \tau)$, the temperature of the i-th phase ($i = 1$ for a gas and $i = 2$ for the solid phase) at the instant of time τ at the cross section with the x coordinate; $m_i = \alpha S/(c_i \rho_i V_i)$, the heating (cooling) rates for the i-th phase; α, heat-transfer coefficient; S, heat-exchange surface area; c_i, ρ_i, and V_i, specific heat capacity, density, and volume of the i-th phase; h, thickness of the disperse layer; T_l, gas temperature on entry to the layer; v, linear flow velocity.