Journal of Engineering Physics and Thermophysics, Vol. 70, No. 4, 1997

ANALYSIS OF THE PROCESSES OF HEAT AND MASS EXCHANGE IN A SLAG-LINED PLASMA REACTOR IN PRODUCTION OF MICROFIBERS FROM POWDER MINERALS

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UDC 532.516:666.1.036.25:531.767

We investigate numerically the dependence of the characteristics of a mineral powder raw-material melt film exposed to a plasma jet on the geometric and operating parameters of the reactor and plasmatron in the process of the production of ultra- and superthin microfibers.

In recent times, electric-arc plasma is finding wider application in the production of mineral fibers [1, 2]. The application of plasma methods of fiber formation makes it possible to raise the quality of the product obtained, decrease the specific energy expenditures and to minimize the amount of the production equipment; this, in turn, leads to a decrease in capital outlays.

Plasma separation of a raw-material-melt jet into superfine fibers [3, 4] has already found industrial application, with the economic feasibility of the method being confirmed.

However, the most promising seems to be a technological process in which melting of the starting raw material occurs as a result of its interaction with a plasma flow and when the melt formed is drawn as fibers by this very flow. In such a case the entire technological process, from the solid phase of the charge up to the fiber, is localized within a small volume of the plasma reactor. This allows one to reduce to a minimum heat fluxes and thus to decrease the energy-output ratio.

As regards the parameters of the generated flow (temperature, velocity, chemical composition), electric-arc low-temperature plasma generators (plasmatrons) are very flexible devices, since they allow one to change these parameters in wide ranges without complex readjustments.

The application of a plasma jet makes it possible to extend the range of minerals to the side of higher-melting ones.

By changing the composition of the plasma-forming gas, it is possible to influence also the chemical composition of the end product (for example, to change the acidity modulus) in the direction needed by the consumer. This is very important in a number of cases and inaccessible by the traditional techniques of the production of fibers. By changing the temperature and velocity of the plasma flow, it is possible to influence the geometric parameters of the fibers obtained.

We should also note the fact that the occurrence of a high-temperature process in a closed space greatly simplifies the protection of the environment from hazardous waste and improves the working conditions of attending personnel.

Application of a powder raw material simplifies its feeding to the reactor and intensifies heat exchange with the plasma jet.

We have developed a number of fiber-forming plasma reactors in which the starting raw material is fed through a pipeline in a powder state in the form of suspension together with a transporting gas [1, 5, 6]. The fibers are formed following the scheme: a suspension of working material is blown into a plasma jet (usually this occurs immediately downstream of the output nozzle of the plasmatron), the material particles and the plasma jet form a

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Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of Belarus," Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 70, No. 4, pp. 621-624, July-August, 1997. Original article submitted January 17, 1996.

 1062-0125/97/7004-0616$18.00

two-phase flow that moves in the cavity of the plasma reactor, the particles of the material are heated and partially melted. At the bottom of the reactor in the melt bath complete melting and homogenization of the material occur. The surface of the melt is subjected to the effect of the subsonic turbulent plasma flow, as a result of which two processes develop that determine the formation of fibers: the appearance of local instabilities (splashes) on the surface of the bath with drawing of separate fibers from them [7] and displacement of the melt, under the action of the forces of friction with the plasma flow, to the side of the reactor nozzle. The balance of these processes greatly determines the effectiveness and stability of functioning of a fiber-forming plasma reactor. When the first process dominates, the bath of the melt becomes shallow and the reactor output decreases; in this case the portion of the reactor hearth not protected by the melt layer is subjected to the high-pressure effect of the plasma jet and begins to erode rapidly. If the second process is dominant, not all of the material has time to transform into fibers; a portion of it is discharged from the nozzle as waste, with the end product turning out to be contaminated with reguli of the starting material.

From the foregoing the necessity is evident for optimization of the initial parameters of the process to attain an effective and stable operation regime of the reactor. These are the consumption of the mineral material, power and capacity of the plasmatron, the flow rate of the plasma-forming gas, the geometric dimensions of the reactor, as well as the thermophysical characteristics of the mineral material and plasma-forming gas.

To carry out the necessary calculations we adopt the following model of flow in the nozzle zone of the plasma reactor: in a rectangular section of the reactor channel of width d and height h a plasma flow moves and the friction force between this flow and the melt surface gives rise to the formation of a viscous flow of the melt film over the reactor hearth with the appearance of large temperature gradients and, correspondingly, of melt viscosity over the film height.

The present work is devoted to the optimization of the regimes and geometric parameters of a mineral fiber-forming plasma reactor when mineral powder is used as the starting material.

Let us consider the problem of the melt film flow over the reactor hearth surface under the action of the "plasma flow – melt surface" friction force in the presence of heat transfer from the plasma to the coolant.

The heat flux density is

$$q = \frac{T_p - T_s}{1/\alpha + h_1/\lambda_{mel} + h_2/\lambda_s}, \tag{1}$$

the temperature of the melt at an arbitrary point x is

$$T_x = T_p - \frac{q}{\alpha} - q\frac{h_1 - X}{\lambda_{mel}}, \tag{2}$$

the stress on the melt surface as a result of the plasma flow friction is

$$\tau = \frac{\xi}{8}\rho_p \bar{V}_p^2 \tag{3}$$

according to Newton's friction law

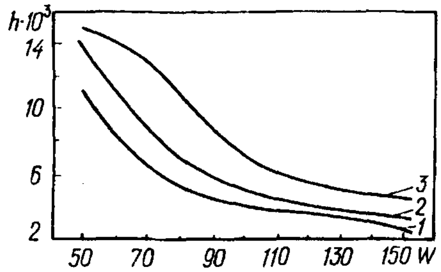
$$\tau = \eta_{mel}\frac{dU}{dX}. \tag{4}$$

We approximate the dependence of the mineral melt viscosity on temperature by the expression

$$\eta_{mel} = A\exp(-BT_{mel}), \tag{5}$$

where A and B are the constants that depend on the kind of the mineral.

Usually [8] the formula $\log\eta = M + (N/T^m_{mel})$ is used (where m, M, and N are constants), which has a smaller error of approximation, but the application of expression (5) allows one to integrate equation (4) analytically.



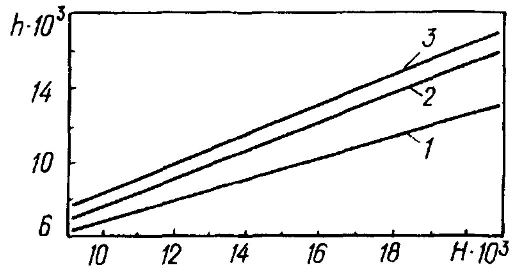


Fig. 1. Dependence of melt-film thickness on plasmatron power ($G_p = 0.01$ kg/sec, $H = 0.015\ \mu$): 1) $G_{mel} = 0.002$ kg/sec; 2) 0.005; 3) 0.008. h, mm.

Fig. 2. Dependence of melt-film thickness on height of working zone of reactor ($G_p = 0.01$ kg/sec, $W = 60$ kW): 1) $G_{mel} = 0.003$ kg/sec; 2) 0.005; 3) 0.006.

Integrating Eq. (3) over X subject to the boundary condition $U = 0$ and $X = 0$, we obtain an expression for the melt particle velocity at the point X:

$$U = \frac{\tau}{A} \exp\left(B\left(T_p - \frac{q}{\alpha} - \frac{qh_1}{\lambda_{mel}}\right)\right) \frac{\lambda_{mel}}{Bq} \left(\exp\left(\frac{Bq}{\lambda_{mel}} X\right) - 1\right). \tag{6}$$

The melt flow rate through an arbitrary cross-section of the reactor is

$$G_{mel} = \int_0^{h_1} \rho_{mel} U L dx. \tag{7}$$

Substituting into Eq. (7) the expression for U from Eq. (6) and integrating, we obtain

$$G_{mel} = \frac{\rho_{mel} L \tau}{\eta_{mel}} \frac{\lambda_{mel}}{Bq} \left(\frac{\lambda_{mel}}{Bq}\left(\exp\left(\frac{Bq}{\lambda_{mel}} h_1\right) - 1\right) - h_1\right). \tag{8}$$

Supplementing the system of equations (3) and (8) with empirical relations $\lambda_p = f(P, T)$, $\eta_p = f(P, T)$, and $\rho_p = f(P, T)$ from [9], determining ξ from the Blasius equation, and then solving the system of equations numerically, we obtain the dependence

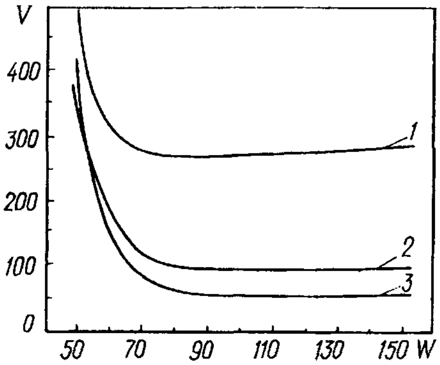
$$h_1 = f(G_p, G_{mel}, T_{mel}, L, h_2). \tag{9}$$

The dependence of the melt film thickness on the plasmatron power is shown in Fig. 1. In the case of low consumption of the material and an increase in the power, the melt film thickness decreases according to a law which is nearly hyperbolic. With an increase in the consumption of the material, this dependence becomes more complex.

As the height of the working zone of the reactor increases, the film thickness increases linearly (Fig. 2). The thickening of the film occurs due to a decrease in the plasma flow velocity above its surface.

As the power is decreased, the curves of the plasma flow velocity tend to approach the vertical asymptotes depending on the power of the plasmatron (Fig. 3). This is due to the fact that on a decrease in power below a certain ultimately admissible value, the plasma jet energy becomes insufficient for complete melting of the material. This leads to solidification of the melt, sharp constriction of the flow area and, as a consequence, the velocity begins to increase infinitely. In practice this is a regime of emergency. On an increase in the power, the velocity attains a certain minimum value, after which it begins to increase insignificantly. This is explained by the fact that the process of increase in velocity due to a rise in temperature and a decrease in the plasma flux density begins to dominate over the process of the decrease in velocity due to the increase in the flow area as a result of melt-film thinning.

Figure 4 presents the viscosity on the melt film surface as a function of the plasmatron power. In practice the viscosity of the melt is one of the determining factors of the fiber quality, since it allows one to calculate the optimal operation regimes of the reactor. Within the range of plasmatron powers of 60–70 kW for a given reactor,



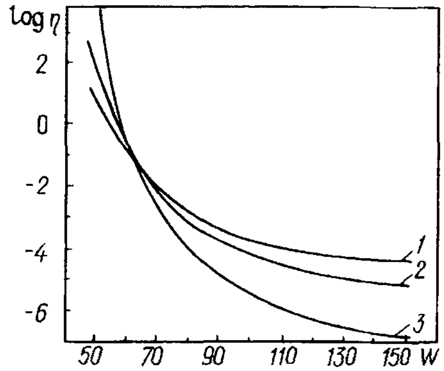


Fig. 3. Dependence of plasma-flow velocity on plasmatron power (G_p = 0.01 kg/sec, H = 0.015 μ): 1) G_{mel} = 0.003 kg/sec; 2) 0.005; 3) 0.006.

Fig. 4. Viscosity on melt-film surface as a function of plasmatron power (G_p = 0.01 kg/sec, H = 0.015 μ): 1) G_{mel} = 0.004 kg/sec; 2) 0.006; 3) 0.008.

the viscosity on the melt-film surface is almost independent of the material consumption. As the latter increases, the decrease in the viscosity of the melt film surface becomes sharper with an increase in the plasmatron power.

NOTATION

η, dynamic viscosity, N·sec/m^2; T, temperature, K; ρ, density, kg/m^3; Nu, Nusselt number; Re, Reynolds number; U, melt flow velocity, m/sec; V, plasma flow velocity, m/sec; X, coordinate in the direction normal to the reactor hearth, m; L, width of the working zone of the reactor, m; H, height of the working zone of the reactor, m; h_1, height of the melt layer in the working zone of the reactor, m; h_2, thickness of the steel hearth, m; q, heat flux density, W/m^2; τ, stress on the melt bath surface due to friction with the plasma flow, kg/m·sec^2; A and B, empirical coefficients; λ, thermal conductivity coefficient, J/m·sec·K; C, heat capacity, J/kg·K; G, flow rate, kg/sec; α, heat transfer coefficient, W/m^2·K; P, pressure, N/m^2; ξ, friction factor; W, power, kW. Subscripts: p, plasma; mel, melt; s, steel; x, at the arbitrary point X.

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