

It is shown theoretically that a jet energy use factor of up to 45% can be obtained in plasma spraying.

The energy use factor (EUF) in the spraying and treatment of a disperse powder in a plasma is very low, 2-10% [1-2]. Therefore, investigators and manufacturers have before them the problem of increasing it. Let us theoretically estimate the ideal EUF for powder heating in a plasma. From simple physical considerations it is clear that heat transfer from the plasma to powder particles will proceed until the heat flux from plasma to particle is no greater than or equal to the heat flux emitted by the powder particles:

$$\alpha_p(T_p' - T_p) \geq \epsilon \sigma T_p^4. \quad (1)$$

It is seen from (1) that heat transfer from the plasma to powder particles will proceed if

$$T_g' \geq T_p \left(\frac{\epsilon \sigma T_p^3}{\alpha_p} + 1 \right). \quad (2)$$

This is one of the necessary conditions.

By analogy with the equation for the efficiency of an ideal heat engine, we write the EUF for powder heating in a plasma jet,

$$\eta_1 = 1 - \frac{T_g'}{T_g}. \quad (3)$$

From (2) and (3) we get

$$\eta_1 \leq \frac{T_p}{T_g} \left(1 - \frac{\epsilon \sigma T_p^3}{\alpha_p} \right). \quad (4)$$

The EUF will always be less than the right side of Eq. (4), since when the amounts of energy emitted and absorbed by a powder particle are equal, the heat flux to it becomes equal to zero. Consequently, one must always keep in mind that

$$\eta_1 < \frac{T_p}{T_g} \left(1 - \frac{\epsilon \sigma r_{pc} T_p^3}{\text{Bi} \lambda_p} \right). \quad (4')$$

Calculations were made from (4) for $T_g = 4000-8000^\circ\text{K}$, $\alpha = 0.1-2.0 \text{ W/cm}^2 \cdot \text{deg}$, and $T_p = 1000-4100^\circ\text{K}$. The results of the calculations are shown in Fig. 1. As seen from the figure, a change in the coefficient of heat transfer does not affect the EUF at a plasma-jet temperature of up to 4000°K for particles of a powder with a melting temperature of less than 2000°K . The jet temperature has considerable influence on the EUF. To increase the EUF one must increase the jet temperature as much as possible and eliminate heat losses. It is also seen from Fig. 1 that low-temperature jets are not suitable for spraying materials with a high melting temperature.

Under actual spraying conditions there is a decrease in EUF owing to the decrease in the average-mass temperature of the jet as it mixes with the cold gas of the surrounding medium

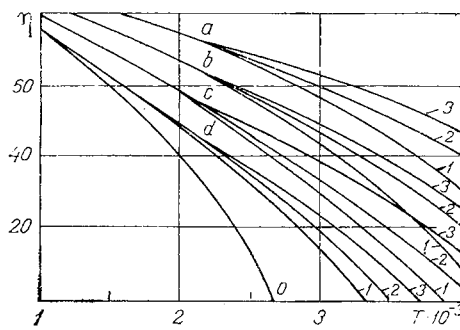


Fig. 1

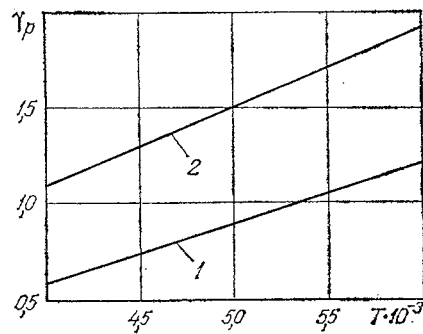


Fig. 2

Fig. 1. Variation of the ideal use factor for jet energy as a function of particle surface temperature for different coefficients of heat transfer at plasma temperatures $T_{pl} = 8, 6, 5, \text{ and } 4 \cdot 10^3 \text{ }^\circ\text{K}$ ($a, b, c, \text{ and } d$); $0, 1, 2, 3$) $\alpha_p = 0.1, 0.5, 1.0, \text{ and } 2.0 \text{ W/cm}^2 \cdot \text{degK}$; $\eta, \%$; $T, \text{ }^\circ\text{K}$.

Fig. 2. Relative flow rate of Al_2O_3 as a function of air-plasma temperature: 1) calculation from (11); 2) from (12).

and with the gas transporting the powder, and due to heat losses to the walls during discharge into the reactor.

In this case the average plasma temperature can be estimated from the equation

$$T_g = \frac{IU\eta_2 - N_p}{G_g C_{pg} + G_t C_{pt} + G_m C_{pm}} \quad (5)$$

During spraying the flow rate of powder-transporting gas is $G_t = (0.2-0.5)G_g$ and that of the mixing gas is $G_m = (0.5-0.9)G_g$ [7]. Consequently, for an air-plasma jet discharging into the open atmosphere, the temperature decrease due to the mixing gases can reach $\Delta T = 800-1000^\circ\text{K}$ at 4000°K and $\Delta T = 1200-1800^\circ\text{K}$ at $T_g = 5000^\circ\text{K}$. Although in transporting the powder through supply lines one must maintain the gas flow rate at a certain level, one can decrease G_t right at the inlet to the plasma jet by dividing the powder and gas into two streams through their separation.

To decrease the amount of gas mixing into the plasma jet from the surrounding medium it must be "isolated." Such "isolation" can be achieved through a sharp change in viscosity at the jet-gas boundary by organizing the laminar flow or discharging the jet into a plasma reactor with walls heated to $900-1000^\circ\text{C}$, or by creating a comoving stream of hydrocarbon fuel or another protective envelope around the jet.

To clarify the ways of increasing the coefficient of heat transfer, we write [3]

$$\alpha_p = \lambda_0 \bar{U} \gamma n k / \delta \quad (6)$$

As is seen from (6), at a constant pressure δ , \bar{U} , and γ will act most efficiently on α_p . To increase γ one must change to polyatomic gases such as nitrogen, ammonia, air, air + hydrocarbons, water vapor, CO_2 , etc. As is known, increases in \bar{U} can be achieved only with an increase in T_g . Other conditions being equal, a change in δ can act efficiently on α_p . It is possible to decrease δ by imposing acoustical oscillations on the plasma [4-5].

As follows from Fig. 1, α_p has a significant effect on the EUF only in the spraying of powders with a melting temperature of more than 2500°K , i.e., for oxides, carbides, and nitrides. The low EUF in the plasma application of coatings indicates the poor organization of the process in existing plasma sprayers.

In analyzing Fig. 1, one can also conclude that to increase the EUF one must increase the plasma temperature and the coefficient of heat transfer as much as possible. With an increase in the temperature of the plasma jet and the coefficient of heat transfer, the Biot number can considerably exceed unity ($\text{Bi} > 1$).

According to [6], the surfaces of powder particles introduced into such a plasma reach the melting temperature in a time $t \approx 10^{-6} - 10^{-5}$ sec. In this case the melting is determined by the size and by the thermophysical properties of the particle material [7]. For the temperature at the center of a particle to equal $0.9T_{pme}$ for $Bi = 10$ requires that $F_0 = 0.3$. The time such particles spend in the high-temperature zone can be estimated from the formula

$$t = 0.3r_p^2 / \alpha_p. \quad (7)$$

To increase the EUF and the material use factor one can create a high-temperature region with a practically stationary plasma through which the powder passes in the time determined from (7). The substrate for spraying must be located beyond this region. The flow rate of sprayed powder will be determined from the expression

$$G_p = \frac{IU\eta_2}{C_{pg}(T_{pme} - T_{pc}) + L_p}. \quad (8)$$

For values of $Bi < 1$ the average-mass temperature of powder particles at any time up to melting can be determined from the equation

$$T_p = T_g - (T_g - T_{p0}) \exp(-kt).$$

The relative powder flow rate $G_p/G_g = \gamma_p$ can be obtained from the equation of heat balance for powder particles and plasma,

$$\gamma_p = \frac{C_{pg}}{C_{pp}} \cdot \frac{\eta_1}{1 - \exp(-kt)}. \quad (10)$$

As $t \rightarrow \infty$, (10) acquires the form

$$\gamma_p = H_g \eta / T_g C_{pp}. \quad (11)$$

Equation (11) corresponds to the maximum possible value of γ_p for a given plasma temperature.

For the majority of gases C_{pg} depends in a complicated way on temperature. Therefore, for more precise estimates of γ_p one can use the function

$$\gamma_{p2} = H_g \eta / \bar{C}_{pp} T_p. \quad (12)$$

Curves of the relative flow rate of Al_2O_3 powder as a function of the temperature of an air plasma are presented in Fig. 2. Equation (11) gives understated values of γ_p , while Eq. (12) gives overstated values. In the spraying of plasma coatings one can attain a relative powder flow rate lying between curves 1 and 2 of Fig. 2.

NOTATION

ϵ , reduced emissivity of a powder particle relative to the surrounding medium (for a small particle diameter ϵ equals the emissivity of the powder material); σ , Stefan-Boltzmann constant; α_p , coefficient of heat transfer from plasma to particle; T_p , melting temperature of powder material; T_g' , average plasma temperature at which heat transfer from plasma to powder particles is still observed; T_g , average-mass plasma temperature; Bi , Biot number; r_p , radius of a powder particle; λ , coefficient of thermal conductivity of powder material; I , U , η_1 , current, voltage, and efficiency of plasmatron; C_{pg} , C_{pt} , C_{pm} , G_g , G_t , G_m , average heat capacities and mass flow rates of plasma-forming, powder-transporting, and mixing gases, respectively; k , Boltzmann constant; λ_0 , mean free path of gas; δ , thickness of thermal boundary layer; n , particle density; \bar{U} , mean velocity of gas molecules at the temperature T_p ; γ , number of degrees of freedom of a particle; $T_{p\lambda}$, plasma temperature; N_p , power drawn off to reactor walls.

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MODELING REVERSE PROBLEMS OF HEAT CONDUCTION WITH
MOVING PHASE TRANSITION BOUNDARIES

A. A. Kosarev, L. S. Milovskaya,
and P. V. Cherpakov*

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An approximate method of solving some reverse problems of nonlinear heat transfer is considered. A procedure is shown for modeling such problems on grid analogs.

We consider a problem of transient heat transfer or diffusion describable by the equations

$$\rho(U) \frac{\partial U}{\partial t} = [\lambda(U) U_x]_x - c(U) U + f(x, t), \quad 0 < x < \xi(t), \quad (1)$$

$$\bar{\rho}(\bar{U}) \frac{\partial \bar{U}}{\partial t} = [\bar{\lambda}(\bar{U}) \bar{U}_x]_x - \bar{c}(\bar{U}) \bar{U} + \bar{f}(x, t), \quad \xi(t) < x < l \quad (2)$$

(where ρ , $\bar{\rho}$, λ , $\bar{\lambda}$, c , \bar{c} , f , \bar{f} are known functions) with the initial conditions

$$U(x, 0) = \varphi(x), \quad 0 < x < \xi(0) = \xi_0; \quad \bar{U}(x, 0) = \bar{\varphi}(x), \quad \xi_0 < x < l \quad (3)$$

(including the possible case $\xi_0 = 0$) and the boundary condition

$$[\bar{\mu}(\bar{U}) \bar{U}_x + \bar{\nu}(\bar{U}) \bar{U}]_{x=l} = -\bar{q}(t, \bar{U}(l, t)). \quad (4)$$

The law according to which the interphase boundary $\xi(t)$ moves is described by the equation

$$\left\{ \gamma(t, U, \bar{U}) \frac{d\xi}{dt} = \bar{\lambda}(\bar{U}) \bar{U}_x - \lambda(U) U_x + \Phi(x, t, U, \bar{U}) \right\}_{x=\xi(t)}, \quad (5)$$

with $\xi(t)$ a monotonically increasing function. At points on the interphase boundary $\xi(t)$ are stipulated the additional constraints

$$U(\xi(t), t) = \bar{U}(\xi(t), t) = U^0 = \text{const} \quad (6)$$

for the Stefan problem or

$$U(\xi(t), t) = \bar{U}(\xi(t), t), \quad (7)$$

$$\alpha U_x(\xi(t), t) = \bar{\alpha} \bar{U}_x(\xi(t), t) \quad (8)$$

*Deceased.

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