Mathematical modeling and calculation of heating and melting of particles of the polymeric powder in flow channel of the sprayer

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Abstract. Heating and melting of particles of polymeric powder in the central flow channel of spraying gun is investigated. Mathematical models of these processes taking into account convective and radiative-convective heat interaction of particles with environment is represented. Relations for calculating the temperature of the particles depending on the longitudinal coordinate, time of flight, operating and design parameters as well as thermophysical characteristics of the particles material and environment are given.

1. Introduction

When applying polymeric powdered materials (compositions) for retaining powder particles on the treated surface it is preheated to a temperature that ensures melting of the particles at the point of contact with the surface. Particles charging, their deposition on the electrode with subsequent melting and formation of the coating is also produced. In the case of flame spraying the powder particles are fed in the high temperature jet of the fuel combustion products. Thus the probability of material destruction on the particle surface and as a result appearance of the coating imperfections is high [1, 2]. In order to prevent the mentioned undesirable circumstances, taking into account the high thermal inertia of the material of sputtering polymeric powders it is appropriate to carry out heating and melting of the particles stage-by-stage: first in the proportioning feeder then in the first section of the central flow channel of the sprayer by convection through the dividing wall. After that in the second section in the area of direct contact of powder-air mixture with the gases heated up to high temperature the melting of the powder particles should be carried out mainly through the radiant heat exchange.

First section of flow channel of the sprayer consists of a central annular channel of length \( l_1 \) with a helical insert wherein the powder-air mixture is moving and a peripheral annular channel of the same length with a hot gaseous medium flowing in it. In fact, this section represents a recuperative tube-in-tube heat exchanger. Second section is a tube of length \( l_2 \) its inner diameter coincides with the diameter of the peripheral annular channel of the first section. Outer surface of this tube like outer surface of the tube of first section is thermally insulated. In the tube of the second section powder-air...
mixture and heated gaseous medium (air, fuel combustion products) covering the mixture flow are moving at different speeds.

When considering nonisothermal flow of mediums in the cavities of these sections it is assumed that mediums are incompressible and in the first section powder-air mixture is homogeneous. Cylindrical coordinate system $r, \varphi, z$ is introduced; its axis $0z$ is directed along a symmetry axis of the concentric tubes.

2. First section of flow channel

Initial system of equations describing the motion of powder-air mixture in the central annular channel consists of differential equations of conservation of momentum, mass, energy and dependency of powder-air mixture density on the temperature.

At the first section equations of this system are averaged and supplemented by closing phenomenological relations.

In order to find formulas suitable for engineering calculations, the system of averaged equations is simplified as much as possible using the following assumptions. Turbulent nonisothermal flow of the mixture in the channel is considered quasi-stationary, terms containing $z$ coordinate derivatives in the equations of conservation of momentum and continuity are neglected, change of the heat flow density in the longitudinal direction is assumed to be small compared to the change in the radial direction [3].

Thus obtained problem is solved with regard to the weight-average temperature of the mixture

$$\tilde{t}_1 = \tilde{t}_1(z) = \tilde{t}_{01} + 2\pi r_1 q_c z \left( \rho_1 c_1 S \bar{u}_1 \right),$$

where $\tilde{t}_{01}$ is the average temperature of the powder-air mixture at the inlet to the annular channel, $\bar{u}_1$ is the average speed of the mixture flow rate taken relative to the total cross section of the channel $S_1 = \pi \left( r_1^2 - r_0^2 \right)$; $r_0, r_1$ is the radius of the central cylindrical insert; $r_1$ is the radius of the internal surface of the annular channel; $\rho_1$ is the average mixture density, $c_1$ is the average specific heat capacity of the mixture; $q_c$ is the heat flow density from the side of heated gas.

Similar relationship can be found for the weight-average temperature $\tilde{t}_2 = \tilde{t}_2(z)$ of the heated gas in the peripheral annular channel. After a number of transformations of these relationships we get

$$\tilde{t}_1 = \left( \tilde{t}_{01} + k_1 S_1 \tilde{t}_2 \right) / \chi_1,$$

$$\tilde{t}_2 = \left( \tilde{t}_{02} + \left( k_2 S_2 / \chi_2 \right) \tilde{t}_{01} + \tilde{S}_E q_E \right) / \chi_2 .$$

Here $\chi_1 = 1 + k_1 S_1$, $\chi_2 = 1 + k_2 S_2 / \chi_1$, $\tilde{S}_1 = \tilde{S}_1(z) = \pi z / \left( \rho_1 c_1 S_1 \bar{u}_1 \right)$, $\tilde{S}_2 = \tilde{S}_2(z) = \pi z / \left( \rho_2 c_2 S_2 \bar{u}_2 \right)$,

$S_2 = \pi \left( r_2^2 - r_1^2 \right)$ is the area of a total cross section of the peripheral channel, $\tilde{S}_E = \tilde{S}_E(z) = S_E / \left( \rho_2 c_2 S_2 \bar{u}_2 \right)$; $S_E = S_E(z)$ is the lateral surface area of the electric heating element mounted in a gap of the peripheral annular channel; $k_j = 2 \left[ \frac{1}{\alpha_1 r_1} + \frac{1}{\lambda_m \ln \left( \frac{r_2}{r_1} \right)} + \frac{1}{\alpha_2 r_1} \right]$ is the average heat transfer coefficient, $\lambda_m$ average coefficient of thermal conductivity of the material on the dividing wall, $\bar{r}_1 = r_1 + h$, $h$ is the wall thickness; $\alpha_1, \alpha_2$ is the average convective heat exchange coefficients on the inner and outer surfaces of this wall; $\rho_2, c_2, \bar{u}_2, \tilde{t}_{02}$ is the average density, specific heat capacity, speed of the mixture flow rate, inlet temperature of the heated gas in the peripheral annular channel.
In the general case the density, heat capacity, average speed of the gas flow rate in the considered channels are close, $S_1 < S_2$. Taking this into consideration, assuming $q_E = 0$, we find

$$t_1 = \left[1 - k_t S_1\right]t_{01} + k_t S_1 t_2, \quad t_2 = \left[1 + k_t S_2\right]t_{02} + k_t S_2 t_{01},$$

and thus temperature $t_{pl1}$ of the powder particles will be

$$t_{pl1} = t_{01} + k_t t_{02}.$$  \hfill (4)

Temperature of the gaseous medium in the peripheral annular channel

$$\tilde{t}_{2l1} = k_2 t_{02},$$

where $k_1 = k_2 k_t S_1 l_1$, $S_1 l_1 = S_S(z = l_1)$, $S_2 l_1 = S_2(z = l_2)$.

It follows that if $0 t_0 < t_{02}$, then at the channel exit ($z = l_1$) temperature of the powder-air mixture and thus temperature $t_{pl1}$ of the powder particles will be

$$t_{pl1} = t_{01} + k_t t_{02},$$

where $k_t = k_2 k_t S_1 l_1$, $S_1 l_1 = S_S(z = l_1)$, $S_2 l_1 = S_2(z = l_2)$.

We can see that temperature $t_{pl1}$ of the powder-air mixture at the outlet compared with the initial temperature increases by a value proportional to $t_{02}$, heat transfer coefficient $k_t$, length of the first section $l_1$ and decreases proportional to the flow rate of this mixture. Respectively, gas temperature $\tilde{t}_{2l1}$ compared to $t_{02}$ decreases this is consistent with the existing views.

3. Second section of flow channel

At the second section heated powder-air mixture moves in the annular jet of the hot gas. By virtue of stability loss of the boundary line of the flows blurring of this boundary surface and mixing of the mediums occur. However, since the length of the section $l_2$ is relatively small, mixing is not taken into account here. It is assumed that the powder particles of the spherical shape with the same radius are under the uniform effect of radiation of a gas with the temperature approximately equal to $t_G \approx \tilde{t}_{2l1}$, temperature of the inner surface of the tube is close to $t_G$. Under condition that powder particles in powder-air mixture can slow down or accelerate relative to the flow of a carrier medium, for example, under the action of an electrostatic field, coefficient of radiative-convective heat exchange of the particles with an environment can be written as

$$\alpha_G = \alpha_R \left(1 + \frac{\alpha_C}{\alpha_R}\right),$$

where $\alpha_C = \alpha_c (t_{pl1} - t_p) / \left[(T_G / 100)^4 - (T_p / 100)^4\right]$; $t_p$, $T_p$ is the temperature of the particle surface, $\alpha_C$ is the convective heat exchange coefficient of the particle surface, $\alpha_R = e_0 e_c$ is the reduced emissivity, $e_0 = 5.7 \text{ W} / \left(\text{m}^2 \cdot \text{K}^4\right)$ is the blackbody emissivity, $e_c = e' P_c$ is the reduced emissivity factor of the system “body-gas”; $e' P_c = e_p \left[1 + (1 - e_p)(1 - e_G)\right]$, $e_p$ is the emissivity factor of the surface material, $e' G = \left(e_G - A_G(T_p / T_G)^4\right) / \left(1 - (T_p / T_G)^4\right)$ is the effective emissivity factor of the gas; $e_G$, $A_G$ is the emissivity factor, gaseous absorbivity ($A_G \approx e_G$), for furnace gases $e_G \approx 0.63$.

Having $\alpha_G$, heat flow density acting on the powder particles per unit time can be calculated by empirical formula

$$q_p = \alpha_G \left[(T_G / 100)^4 - (T_p / 100)^4\right].$$

Further, assuming that powder particles are thermally thin bodies let us find their temperature in the second section after the time $\tau$ from the beginning of the flight

$$t_p = t_{pl1} + \frac{3 q_p \tau}{\left(\rho c_p R_p\right)}.$$
where $\rho_p, c_p, R_p$ is the density, specific heat capacity and radius of powder particle, respectively.

In the case when particles velocity in the second section is close to $\tilde{u}_1$, flight time in this section \( \tau_l = \frac{l_2}{\tilde{u}_1} \). Consequently, the particles temperature at the outlet of the second section

\[
t_{pl2} = t_{pl1} + 3q_p l_2 \left( \rho_p c_p R_p \tilde{u}_1 \right).
\]

In the simplest case when \( \alpha_G = 0, \ T_p \parallel \ T_G = \text{const}, \ e'_G = e_G \), heat flow density \( q_p \approx c_0 e'_p e_G (T_G/100)^4 \), calculation ratio to estimate the temperature of particles material has the form

\[
t_{pl2} \approx t_{pl1} + 3c_0 e'_p e_G l_2 (T_G/100)^4 \left( \rho_p c_p R_p \tilde{u}_1 \right). \quad \text{(8)}
\]

Using these relations we estimate the length \( l_1 \) of the first and \( l_2 \) of the second sections provided that powder material is polyethylene average thermal and physical characteristics are as follows: density \( \rho_p = 10^3 \text{ kg/m}^3 \), coefficient of thermal conductivity \( \lambda_p = 0.35 \text{ W/(m} \cdot \text{ºC}) \), specific heat capacity \( c_p = 2.4 \cdot 10^3 \text{ J/(kg} \cdot \text{ºC}) \), melting temperature \( T_p = 160 \text{ ºC} \), decomposition temperature \( 290 \text{ ºC} \), average particles diameter \( d_p = 10^{-4} \text{ m} \).

Assuming that the powder sprayer has a relatively small sizes and is intended for manual spraying, the powder mass flow rate \( G_p = 3 \cdot 10^{-3} \text{ kg/s} \), mass flow rate of air that contains the powder \( G_{B1} = 5 \cdot 10^{-3} \text{ kg/s} \), mass flow rate of air in the outer annular channel \( G_{B2} = 1.6 \cdot 10^{-4} \text{ kg/s} \). Cross sectional area of the central annular channel \( S_1 = 1.9 \cdot 10^{-4} \text{ m}^2 \), outer – \( S_2 = 8 \cdot 10^{-4} \text{ m}^2 \); average speed of flow rate, respectively, \( \tilde{u}_1 = 0.25 \text{ m/s} \), \( \tilde{u}_2 = 0.15 \text{ m/s} \).

Inlet temperature of powder-air mixture \( \tilde{t}_{01} = 100 \text{ ºC} \), air inlet temperature in the outer channel \( \tilde{t}_{02} = 20 \text{ ºC} \), heat flux into the air from the helical electrical heating element \( q_E = 2 \cdot 10^3 / l_1 \text{ W/m} \).

On condition that wall of the central tube is ceramic, its thickness \( h = 0.003 \text{ m} \), \( \lambda_m = 0.5 \text{ W/(m} \cdot \text{ºC}) \), radius \( r = 0.008 \text{ m} \), taking into account the twist of powder-air mixture in it, as well as in outer annular channel [3-5], the intensification of heat exchange due to additional turbulization of the flows [6,7], the presence of impurity [8] we find: \( \alpha_1 = 13.7 \text{ W}/\left( \text{m}^2 \cdot \text{ºC} \right), \ \alpha_2 = 3.25 \text{ W}/\left( \text{m}^2 \cdot \text{ºC} \right), \ \frac{1}{\lambda_m} \ln \left( \frac{r}{h} \right) = 0.64 \text{ m} \cdot \text{ºC}/\text{W} \), \( k_i = 0.054 \text{ W/(m} \cdot \text{ºC}) \).

As a result the calculated temperature of the heated air at the outlet of outer annular channel \( \tilde{t}_{21} = 440 \text{ ºC} \), the length of the first section whereby inlet temperature of the powder-air mixture \( \tilde{t}_{u1} = 160 \text{ ºC} \), is \( l_1 = 0.16 \text{ m} \).

It should be noted that, this length can be reduced by increasing the temperature \( \tilde{t}_{01} \), increasing the power of a heating element, increasing the convective heat exchange coefficients \( \alpha_1, \alpha_2 \), increasing the coefficient of thermal conductivity of the wall material \( \lambda_m \), decreasing the powder-air mixture flow rate.

Since it is necessary that at the outlet of the second section the powder particles have been melted, temperature of the material would have been approximately 200 ºC from (8) we will find the length of the second section \( l_2 = 0.09 \text{ m} \).

4. Conclusion
The proposed mathematical models of heating and melting the polymeric powder particles as they move in the flow channel of the spraying gun quite completely reflect the specificity of these
processes, contain all the basic design and operating parameters, allow solving the part of the problems of rational designing and operation of the plants for applying the polymer powder coatings.

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