Deposition of polymer powder particles on the product surface at jet spraying

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Abstract. Gas-thermodynamic processes taking place during spraying of polymer powder materials are considered. Numerical and analytical models describing these processes are proposed. For the case of circular cylinder rotating with a constant angular velocity results of calculations and engineering formulas for estimating the thickness of powder particles layer deposited on the processed surface are present.

1. Introduction

Widespread application of polymeric powder materials for production of coatings on the surface of parts, products, constructions is caused by, on the one hand, the development of chemistry, production of a large variety of synthetic materials that possess valuable properties and performance characteristics, on the other hand, the increasing requirements to coating characteristics [1-3]. In this work among a great number of ways and methods to deposit the polymer powder coatings the jet methods such as flameless gas-thermal spraying are distinguished. When developing the appropriate equipment and technologies we can point out two main problems: to provide proper performance, required quality of the coatings and to minimize the materials loss and energy consumption. One of the effective ways to solve these problems is mathematical modeling of gas thermodynamic processes that take place during the spraying as well as processes of coating formation on the surface of processed bodies.

For the spraying processes of polymer powder on the surface of parts, products and constructions it is characteristic that the jet flowing out of the nozzle, the spraying gun header or the other device can be flat, axisymmetric, circular, conical and etc. Apart from the carrying medium (air fuel combustion products) it contains particles of polymer powder that can be solid, fritted or completely melted. In the presence of temperature drops in the direction of medium motion the heat exchange occurs between powder particles and carrying medium, jet and ambient air.

Particularly complex gas-thermodynamic processes are observed when the jet flows over the processed body. It is very difficult to take fully into account the named and other peculiarities of the

considered processes at mathematical modeling, the corresponding problems can be solved numerically.

2. Calculation of the flow past of the cylinder

Below it is assumed that the body being processed is a lengthy circular cylinder of radius a, rotating counter-clockwise at a constant angular velocity ω, the carrying medium – air, lateral dimensions, volume concentration of polymer powder particles are small. For the mathematical description of a medium flow and particles movement we use the averaged Reynolds equations with closing $k - \varepsilon$ turbulence model and Lagrangian continual approach, respectively. Velocity profile, temperature, turbulence intensity and scale of turbulence are specified at the inlet of computational domain in the jet zone. The symmetry conditions are set on the upper and lower boundaries of the computational domain. At the outlet we set boundary conditions that signify the equalization of hydrodynamic and thermal characteristics of the flow.

The no-slip condition are realized at the boundary of the streamlined body, temperature is set constant.

Figure 1 shows the calculation results of the streamlines using triangular mesh and finite volume method at a relative rotational speed of the cylinder surface equal to 0.25.
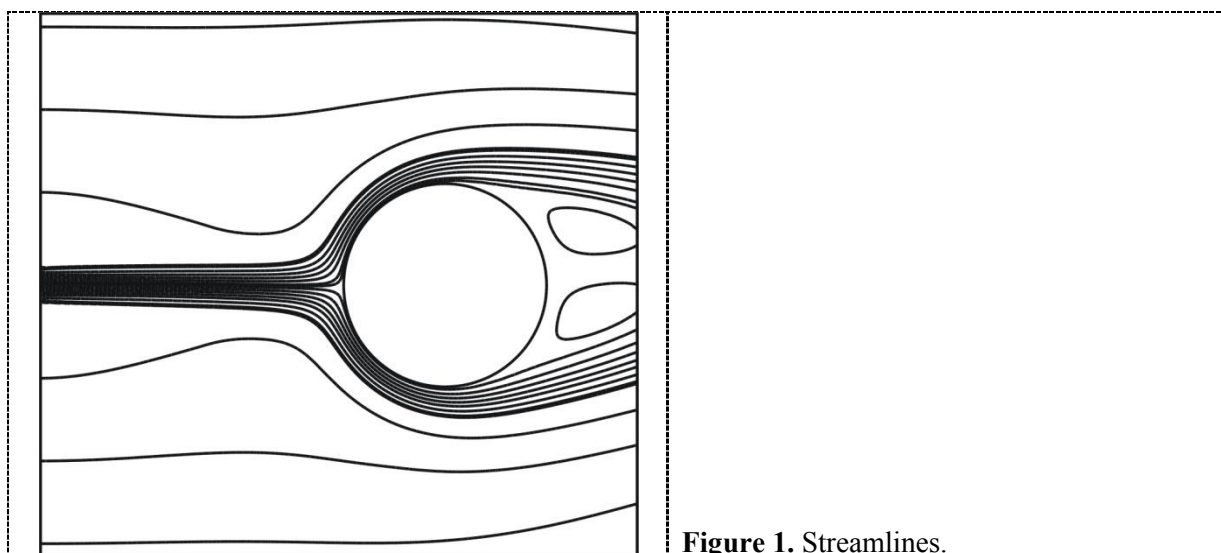

Figure 1. Streamlines.

It can be seen that when the jet flows over the body above and below it air is attracted to the jet, there is an effect of ejection which consists in the fact that at high speeds the pressure is reduced as a result the environment flows into this area. In addition cylinder rotation causes a contraction of the oncoming flow in the upper part of the flow region near the front point of the body and some shift upwards of the vortex region behind the body. It should be noted that unlike the case when rotating cylinder is streamlined by an unlimited flow [4] where Karman Street is formed behind the body, in this case such structures are not observed.

3. Calculation of the thickness of deposited powder layer

In order to obtain engineering evaluations it is additionally assumed that the lateral dimensions of a streamlined circular cylinder are commensurable with the cross section dimensions of flowing over plane jet near its front point. A model of turbulent jet-source is used to describe the jet flow. The fact that when jet flows over an obstacle we can identify the region of a free jet, the zone of flow turning and trickles moving along the surface of the streamlined body [5] is taken into account. Taking into consideration the above and the fact that thickness of boundary layers on the front part of the body surface is small, the movement of air in them has no substantial effect on the dynamics of powder

particles deposition in the zone of flow turning we identify the phantom cross section S_0 after which the carrying medium flowing over the body is considered an ideal incompressible fluid. It is necessary to understand that when gas suspension cross flows a circular cylinder including the rotating one the particles are deposited mainly on the front surface of the body [4], close to which the effect of fluid viscosity on the flow is insignificant.

When considering the motion of the powder particles the following assumptions are made: particles have a spherical shape, identical dimensions, the particle radius is $r_p = 8 \cdot 10^{-5}$ m, the density of powder material ρ_p =900 kg/m^3, particles do not rotate around its own axis, their velocity at the nozzle outlet is the same $u_{pc} = 0.8$ m/s, powder mass flow rate through the slotted nozzle of the spraying gun with the size 0.016x0.016 m $G_p = 0.003$ kg/s, the distance between the particles is about $5 \cdot 10^{-4}$ m, volume concentration $1.5 \cdot 10^{-2}$, mass concentration – 0.92. Because of small particle size, volume concentration it is assumed that when moving in the air they do not break up and do not stick together in the jet from the nozzle section to the cross section S_0 particles velocity is close to the velocity of flow particles, gas suspension is a homogeneous medium. Rectangular Cartesian coordinate system xOy is introduced its beginning is at the center of a circular cylinder and axis Ox is directed along the symmetry axis of the jet along the flow. Based on solutions for the main portion of a submerged turbulent jet [5] cross flow of a circular cylinder by an ideal fluid [6] taking a number of assumptions in cross-section S_0 that is located at a distance $|x_s|$ from the center of the rotating cylinder we obtain for the longitudinal particle velocity u_{ps} a dependence

$$u_{ps} = 3.8 u_{pc} \left(\frac{\overline{l}_0}{\overline{x}_{s\Pi}} \right)^{1/2} \left(1 - 9.7 \left| \frac{\overline{y}_{ps}}{\overline{x}_{s\Pi}} \right|^{3/2} \right)^2 \tag{1}$$

Here $\overline{l}_0$, $\overline{x}_{s\Pi}$ – dimensionless divided by/ attributed to cylinder radius half the width of the nozzle section, remoteness of cross section S_0 from the pole of the jet source, $a = 0.05$ m, $\overline{l}_0$ =0.16, $\overline{x}_{s\Pi}$ =5.0, $\overline{x}_s$ =2.2. The ordinate of the source from which the particles that hit the control point on the cylinder surface K with dimensionless coordinates $\overline{x}_{pK}$, $\overline{y}_{pK}$ are emitted will be:

$$\overline{y}_{ps} = \overline{y}_{pK} \left[1 - 0.5 \frac{v_0 \overline{x}_{pK}}{a} \left(\frac{1}{R_\mu} - \tilde{\tau}_k \right) \right] + \frac{\omega \overline{x}_{pK}}{R_\mu}, \tag{2}$$

where $v_0 = 4.55 u_{pc} \overline{l}_0 / \overline{x}_{s\Pi}$ – velocity of the oncoming flow of an ideal fluid; $R_\mu = k_c r_p \mu / m_p$ – parameter characterizing the effect of the aerodynamic drag force on the particles, k_c =19÷25 – coefficient of proportionality, μ – gas viscosity, m_p – particle mass, $\tilde{\tau}_k = (|x_s| - 0.5a)/v_0$.

In the case of a fixed cylinder $(\omega = 0)$ separating on its surface closely located control points K_i and K_{i+1} using (2) we find the distance $\Delta_{pi} = \overline{y}_{ps(i+1)} - \overline{y}_{psi}$ in cross section S_0 and using (1) – the velocities $\overline{u}_{psi}$, $\overline{u}_{ps(i+1)}$, mean velocity $u_i = 0.5 \left(\overline{u}_{psi} + \overline{u}_{ps(i+1)} \right)$ on the interval Δ_{pi}.

Having these data for evaluating the thickness of the powder layer sprayed over a period of time τ_H on the portion of a cylinder surface with a width l_i between these control points we obtain a dependency:

$$h_i = k_\Pi \varepsilon_{pi} u_i \tau_H \left(\rho_p \Delta_{pi} / (\rho_i l_i) \right), \tag{3}$$

where $k_{\varPi}$ – correction coefficient by which you can take into account the movement of the powder particles along the body surface, their blowing away; ρ_i – medium density of powder layer depending on the rate of fall of particles onto the processed surface, their size, degree of fritting and other factors; ε_{pi} – mean volume concentration of particles of gas suspension flowing through the portion Δ_{pi} of the cross section S_0.

If the cylinder rotates $\left(\omega \neq 0\right)$ then at inversion of motion the "spot" of deposited particles will move across the cylinder surface in the clockwise direction at a velocity $v_{\varPi} = a\omega$. In this case we can identify three characteristic stages of spraying: initial stage starting from the beginning of particles deposition $\tau = 0$ to $\tau_{\varPi} = l_{\varPi}/v_{\varPi}$ when the spot will cover a distance equal to its width $l_{\varPi}$; regular stage during which the thickness of the sprayed powder layer remains constant and final stage over a period of time τ_k before the end of the spraying.

Assuming in (3) $\Delta_{pi}/l_i \square 2\delta_{ps}/l_{\varPi} = k_{s\varPi}$ (δ_{ps}– half of the width of particles layer in the cross section S_0, which are deposited on the cylinder surface), $\rho_i = \rho_H$, to evaluate the thickness of layer of deposited particles at the initial stage we obtain the relation:

$$h_0 = h_0\left(l\right) = \frac{k}{v_{\varPi}} \int_0^l \varepsilon_p\left(\eta\right) u_p\left(\eta\right) d\eta \quad \left(0 \leq l \leq l_{\varPi}\right). \tag{4}$$

Here $k = k_{\varPi} \cdot k_{s\varPi} \rho_p/\rho_H$, ρ_H – mean material density of the sprayed powder layer, l – length of the circular arc, $\eta = l - \tau v_{\varPi}$ – longitudinal coordinate moving with the sprayed "spot".

When you move to the regular stage ($\tau = \tau_{\varPi}$, $l = l_{\varPi}$) thickness of powder layer h_p is equal to $h_0\left(l_{\varPi}\right)$. In particular if in cross section S_0 the concentration of powder particles, their longitudinal velocity varies insignificantly then

$$h_p \square k\varepsilon_p u_p l_{\varPi}/\left(a\omega\right), \tag{5}$$

where ε_p, u_p – mean at a section $2\delta_{ps}$ volume concentration and longitudinal velocity of particles.

In contrast to (4) at the final stage of spraying with increasing l the thickness of deposited powder layer h_k decreases according to formula

$$h_k = h_k\left(l\right) = Lh_p - \frac{k}{v_{\varPi}} \int_0^l \varepsilon_p\left(\eta\right) u_p\left(\eta\right) d\eta. \tag{6}$$

Here L – number of complete revolutions of the "spot" along the cylinder surface with overlapping the initial section. When thickness of the sprayed layers is small the time $T_{\varPi}$, during which such a revolution is performed will be $T_{\varPi} = \tau_{\varPi} + 2\pi/\omega$. If τ_H – total spraying time ($\tau_H > LT_{\varPi}$), then over a period of time $\tau_k = \tau_H - LT_{\varPi}$ the "spot" moves relatively to the cylinder surface on a distance $l_k = v_{\varPi} \cdot \tau_k$. Accordingly, in (6) parameter l will change from 0 to l_k.

4. Conclusions
In conclusion we note that the obtained relationships to calculate the layer thickness of the sprayed polymer powder as in the case of fixed circular cylinder and in the case of rotating circular cylinder contain all main technological parameters of the considered process and allow evaluating their influence and choose rational regimes of spraying.

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