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Heat transfer of gas suspension jet flow on the product surface when applying polymer powder coatings

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Abstract. Thermal processes occurring at jet spraying of polymer powder materials on the surface of a rotating cylinder are considered. The initial problem is solved numerically using the finite volume method and under certain assumptions analytically. Relationships to calculate the temperature, its rate of change and other indices in the sprayed layer and processed body are presented.

1. Introduction

Research of heat exchange processes at interaction of laminar and turbulent jet flows with streamlined bodies represents both theoretical and practical interest. Turbulent jets are widely used in metallurgy when drying various materials, products, in heating and ventilation systems, at heat treatment, materials cutting and thermal drilling. At the same time, cold gas jets are used for cooling the heated elements of constructions, machines, apparatuses, instruments and in many other cases [1, 2].

When spraying powder on the surface of parts, products, constructions as well as at their preheating, further thermal treatment of sprayed powder layer along with the processes of aerodynamics the heat exchange of working media with the powder layer and base material is of great interest [3-5]. It is necessary that the material of polymer powder layer deposited on the body surface was heated to a temperature that provides its spreading over the surface, reduces the porosity to a minimum and the acceptable adhesion. On the other hand, excessive heating of the powder material may lead to blowing off of the coating by the gas jet, its run-off under action of gravity, the degradation. It should be noted that for most of the used polymer powder materials allowable range of temperature change is very small.

The main factors affecting the dynamics of material heating of the sprayed powder layer are thermal and physical characteristics of the carrier gaseous medium: density ρ, viscosity μ, coefficient of thermal conductivity λ, specific heat at constant pressure c, temperature at the nozzle outlet T_0, volume flow rate G_0, respectively, mean longitudinal velocity u_0. An important role is also played by thermal and physical parameters of powder material its density ρ_p, coefficient of thermal conductivity λ_p, specific heat at constant pressure c_p, mean temperature at the nozzle outlet T_{pc}, velocity u_{pc}, volume concentration ε_{pc}, characteristics size of powder particles d_p, thickness of powder layer on the body surface h_H, mean thermal and physical characteristics of the medium of this layer: density ρ_H, coefficient of thermal conductivity λ_H, specific heat c_H.

Of course, sizes and shape of a processed body, its movement relative to the nozzle or vice versa, movement of the nozzle relative to the body, their relative position and thermal and physical properties of the material of processed body have a noticeable effect on the heat exchange: density ρ_m, coefficient of thermal conductivity λ_m, specific heat c_m, initial temperature T_{m0}, characterizing the heating of material before spraying, including the initial temperature of the treated body surface T_{w0}.

In all these cases, heat transfer at the contact surface of gas suspension and streamlined body is forced convection its intensity is characterized by the Nusselt number including the complex heat exchange: convection in conjunction with thermal radiation when effective coefficient of convective heat exchange is used for an engineering evaluation of heat transfer [6]. For jet spraying of polymer powders the jets are mainly flat or axisymmetric, processed bodies are of various shapes and sizes and the situation when lateral dimensions of the body and width of the jet flow are close is possible.

Taking into account the above mentioned we consider the heat exchange of fixed or rotating circular cylinder at jet spraying of polymer powder.

2. Governing equations

We assume that the nozzle of a spraying device is slotted and the jet of gas suspension is flat. Considering that for jet spraying of polymer powder the most intense heat transfer is observed in the vicinity of the front point of a cross flowed cylinder we confine ourselves to considering of heat exchange processes at this section. Let's introduce the local fixed coordinate system $\xi O \eta$ its center O is located at the position of the cylinder front point, axis $O\xi$ is directed along the contour of the cylinder surface, axis $O\eta$ – along the outer normal to the surface along the jet symmetry axis.

Thickness of the sprayed powder layer $h_H = h_H(\tau, \xi)$ depends on time τ ($0 \le \tau \le \tau_H$, τ_H – spraying time) and longitudinal coordinate ξ. Value h_m is assumed constant. It can be wall thickness of a tube or if the processed cylinder is massive thickness of the heated layer. Further in the named coordinate system we write the heat transfer equations in both layers in the absence of the source terms taking into account the convective components caused by the rotation of a cylinder together with a sprayed layer.

At the initial time τ=0 it is assumed that on the surface of the considered body section there is a very thin powder layer of constant thickness h_{H0} with mean values ρ_{H0}, λ_{H0}, c_{H0} and temperature T_{H0}. Initial material temperature of the processed body layer $T_{m0} = T_{m0}(\eta)$ varies only along its thickness according to a given law.

On the outer surface of the sprayed layer blown by the jet of gas suspension also being under the influence of infrared radiation we write the Newton's condition:

$$\eta = h_H : \; -\lambda_H \frac{\partial T_H}{\partial \eta} = \alpha\left(T_{H2} - T_g\right). \tag{1}$$

Here $\alpha = \alpha_k + \alpha_r$, $\alpha_k = \alpha_k(\xi)$ – local coefficient of convective heat exchange of carrier gaseous medium with the layer surface [2,7-9], T_g – mass average temperature of this medium at a distance from the surface of a front section of a streamlined body, $\alpha_r = \alpha_r(\xi)$ – component of the effective heat exchange coefficient characterizing the influence of an infrared radiation on a surface, T_{H2} – mean temperature on the outer surface of a layer.

Let's assume that at the boundary between the sprayed layer and the body we have an ideal thermal contact, respectively,

$$\eta = 0:\ T_{H1} = T_{w1},\ \lambda_H \frac{\partial T_H}{\partial \eta} = \lambda_m \frac{\partial T_m}{\partial \eta}, \tag{2}$$

where T_{H1} – material temperature of the sprayed layer, T_{w1} – material temperature of the body on its surface.

On the back side of the body ($\eta = -h_m$) we assume that

$$T_m = T_{m0} = const. \tag{3}$$

The named boundary conditions should be supplemented by the conditions either on the edges of the selected layers or by periodicity conditions in the circumferential direction.

Specificity of this problem consists of the fact that:

– thermal processes are non-stationary occurring in two thermally coupled layers with different thermal and physical characteristics;

– with time the thickness of sprayed layer changes both because of powder particles coming into the layer and melting of these particles, spreading along the body surface: the first mechanism leads to an increase of h_H, conversely the second leads to a decrease of the thickness because of the decrease of material porosity of the layer;

– at the same time, when porosity of the sprayed layer changes the thermal and physical parameters of its material also change: $\rho_H = \rho_H(\tau)$, $\lambda_H = \lambda_H(\tau)$, $c_H = c_H(\tau)$.

This implies that solution of this problem in a rigorous formulation is very difficult it is reasonable to use numerical methods.

3. Numerical simulation

As an example of the application of numerical methods figure 1 shows the temperature dynamics of polymer powder particles as they fly from the nozzle ($\eta = -0.2$ m) to the surface of rotating counter-clockwise with a relative velocity 0.92 circular cylinder. For the mathematical description of the turbulent air flow the averaged Reynolds equations and closing $k-\varepsilon$ turbulence model are used. Flight simulation of powder particles is carried out using Lagrangian continual approach.

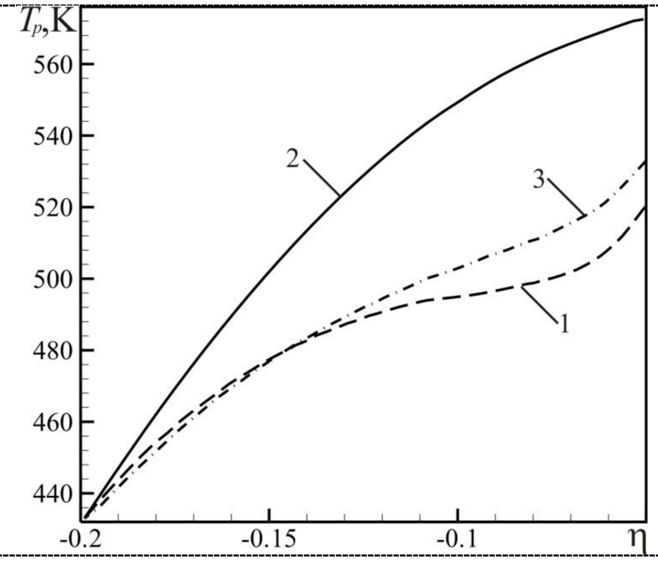

Figure 1. Change of the particle temperature versus its position on the axis η (1 – particle is on the upper boundary of the jet, 2 – in the center of the jet, 3 – particle is on the lower boundary of the jet).

From the results shown in figure 1 it follows that because of the heat exchange with a high temperature gaseous medium of the jet on approaching to the body surface the mean material temperature of powder particles increases notably more intensively increases the particles temperature on the jet axis. The difference in the particles temperature on the upper and lower boundaries of the jet is due to the flow displacement relative to the jet axis at cylinder rotation. Another interesting fact is that behavior of particles temperature on the jet axis and periphery near the cylinder surface differs considerably.

4. Analytical solution

We take additional assumptions to obtain engineering calculating formulas.

1. Assume that the temperature gradient T_H , T_m in the longitudinal direction is small ($\partial T_H / \partial \xi \approx 0$, $\partial T_m / \partial \xi \approx 0$) because thermal effect of the heated gas jet occurs on a large surface, concentration of this heat source is very small.

2. Assume also that $\partial^2 T_H / \partial \xi^2 \approx 0$, $\partial^2 T_m / \partial \xi^2 \approx 0$ heat flows in the longitudinal direction change only slightly.

3. Considered nonstationary thermal processes in the sprayed layer, body are, substantially, additional since materials of polymer powder, substrate are preheated. Moreover from the technological point of view these processes represent the greatest interest closer to the end of spraying, i.e. after a certain time. Consequently, analysis can be limited only to the regular heating mode of the system assuming that the heating rate of powder layer and body are constant:

$$w_H = \left(\frac{1}{\rho_H c_H} \right) \left(\frac{\partial \left(\rho_H c_H T_H \right)}{\partial \tau} \right) = w_{H0} = const \, ; \tag{4}$$

$$w_m = \partial T_m / \partial \tau = w_{m0} = const \, . \tag{5}$$

As a result the initial equations of heat transfer are considerably simplified and take the form:

$$\partial^2 T_H / \partial \eta^2 = \overline{w}_{H0} \left(\tau \right), \; \partial^2 T_m / \partial \eta^2 = \overline{w}_{m0} \, . \tag{6}$$

Here $\overline{w}_{H0} = w_{H0} / a_H$, $\overline{w}_{m0} = w_{m0} / a_m$, $a_H = \lambda_H / \left(\rho_H c_H \right)$, $a_m = \lambda_m / \left(\rho_m c_m \right)$.

Integrating these equations taking into account the boundary conditions (1) and (3) we find:

$$T_H = T_{H1} + \left[\alpha / \lambda_H \left(T_g - T_{H2} \right) - \overline{w}_{H0} h_H \right] \eta + 0.5 \overline{w}_{H0} \eta^2 \, , \tag{7}$$

$$T_m = T_{w1} + \left[\left(T_{w1} - T_{m0} \right) + 0.5 \overline{w}_{m0} h_m^2 \right] \eta / h_m + 0.5 \overline{w}_{m0} \eta^2 \, , \tag{8}$$

wherein in accordance with (2),

$$T_{H1} = T_{w1} , \; \alpha \left(T_g - T_{H2} \right) - \lambda_H \overline{w}_{H0} h_H = \left(\lambda_m / h_m \right) \left(T_{w1} - T_{m0} + 0.5 \overline{w}_{m0} \eta^2 \right) . \tag{9}$$

Unfortunately, the relations (9) are not sufficient in order to find parameters T_{H1}, T_{H2}, $\overline{w}_{H0}$, $\overline{w}_{m0}$. Therefore, in a refinement of the problem (1) – (6) we suppose that the material temperature on the outer surface of the powder layer T_{H2} during spraying is close to the mean temperature of powder particles falling on this surface and temperature of gaseous inclusions of carrier medium. The latter can be measured. In any case over a period of time $0 \le \tau \le \tau_H$ the temperature T_{H2} will change only slightly. Secondly as it is customary at regular heating mode we assume that velocity $w_{H0} \cong w_{m0}$, i.e. the heating rate in the sprayed layer and body are close to each other. Thirdly we take into account that the mean heating rate of powder layer

$$w_H = (q_2 - q_1)/(\rho_H c_H h_H),$$

substrate –

$$w_m = (q_1 - q_0)/(\rho_m c_m h_m),$$

where q_0 – heat flux at the back side of the substrate; q_1, q_2 – heat fluxes on the inner and outer surfaces of the sprayed layer, respectively.

Moreover, assuming that the back side of the processed body is insulated (q_0=0) using (8) from the last relation we determine the velocity w_{m0} and from (9) – the temperature T_{H1}:

$$w_{m0} = \left(\frac{\alpha\left(T_g - T_{H2}\right)}{\rho_m c_m h_m}\right)\Big/\left(1 + k_H\right), \tag{10}$$

$$T_{H1} = T_{m0} + \left[\alpha\left(T_g - T_{H2}\right) - \lambda_H \overline{w}_{H0} h_H\right] h_m/\lambda_m - 0.5\overline{w}_{m0} h_m^2. \tag{11}$$

Here $w_{m0} = \overline{w}_{m0} = \overline{w}_{H0}$, $k_H = (\rho_H c_H h_H)/(\rho_m c_m h_m)$. For small k_H we get:

$$w_{m0} \approx a_m Nu_m \left(T_g - T_{H2}\right)/h_m^2, \tag{12}$$

$$T_{H1} \approx T_{m0} + Nu_m\left(T_g - T_{H2}\right) - 0.5 w_{m0} h_m^2/a_m, \tag{13}$$

where $Nu_m = \alpha h_m/\lambda_m$.

We make sure that the temperature on the contact surface of the sprayed layer and the substrate is determined by the temperature T_{m0}, heat input into the layer from the gas suspension , the heating rate of material: the higher is the heating rate the lower is the temperature T_{H1}.

In order to establish an explicit dependence of the thermal indices of the considered system on time τ for the strip of width $\Delta\xi = 1$ we write the heat balance equation:

$$q_2 d\tau = d\left(\rho_H c_H h_H \overline{T}_H + \rho_m c_m h_m \overline{T}_m\right).$$

Here $\overline{T}_H, \overline{T}_m$ – mean material temperature in the sprayed layer and the substrate, respectively, $q_2 = \alpha\left(T_g - T_{H2}\right)$. According to (7), (8)

$$\overline{T}_H = T_{H1} + 0.5 Nu_H\left(T_g - T_{H2}\right) - 0.33\overline{w}_{H0} h_H^2, \quad \overline{T}_m = 1.5 T_{H1} - 0.5 T_{m0} + 0.67\overline{w}_{m0} h_m^2,$$

where $Nu_H = \alpha h_H/\lambda_H$.

Assuming that in $\overline{T}_H\left(T_{H1}, h_H\right)$, $\overline{T}_m\left(T_{H1}\right)$ variable parameter is the temperature T_{H1} (layer thickness h_H assumed to be known) under the condition that at the initial time ($\tau \approx 0$) $T_{H1} = T_{H0}$ we define:

$$T_{H1} = T_{H0} + \chi_H\left(T_g - T_{H2}\right)\tau, \tag{14}$$

where $\chi_H = 0.67\alpha / \left(\rho_m c_m h_m + 0.67\rho_H c_H h_H\right)$.

Further, considering the equations (13) – (14) as a system, we find the approximate dependencies for $T_{H1}(\tau)$ and $T_{H2}(\tau)$:

$$T_{H1} \approx T_{m0} + \left(T_{H0} - T_{m0}\right)/\left(1 - \tau\chi_H/Nu_m\right), \tag{15}$$

$$T_{H2} \approx T_g - \left(T_{H0} - T_{m0}\right)/\left(Nu_m - \tau\chi_H\right). \tag{16}$$

Taking into account (16) from (10) it follows:

$$w_{m0} = a_m \left(T_{H0} - T_{m0}\right) \Big/ \left(h_m^2 \left(1 + k_H\right)\right) \approx a_m \left(T_{H0} - T_{m0}\right) \Big/ h_m^2 \ .$$

It can be seen that for small k_H thermal and physical parameters of a thin sprayed powder layer has little effect on the heating rate, substrate characteristics, its thickness and temperature diffusivity coefficient of the material are dominating.

Temperature gradient in the sprayed layer is also of interest. Its mean value

$$T_{H\eta} = \left(T_g - T_{m0}\right) \Big/ h_H - \left(T_{H0} - T_{m0}\right)\left(1 + Nu_m\right) \Big/ \left(h_H \left(Nu_m - \tau\chi_H\right)\right) . \tag{17}$$

In particular, for small $\tau\chi_H / Nu_m$

$$T_{H\eta} \approx \left(T_g - T_{m0}\right) \Big/ h_H - \left(T_{H0} - T_{m0}\right)\left(1 + 1/\,Nu_m\right) \Big/ h_H \ .$$

5. Conclusions

Despite the relative simplicity of the obtained calculation relationships they fully reflect the influence on the basic parameters of thermal processes occurring at jet spraying of polymer powder materials of all of the above mentioned parameters including the most important mode parameters, such as, gas and powder flow rate, their temperature, nozzle width of a spraying gun, the distance from it to the surface of the processed body, rotation velocity. However, for the most part indirectly through the heat exchange coefficient α and thickness h_H of the powder layer sprayed on the cylinder surface.

References

[1] Abramovich G N, Girshovich T A, Krasheninnikov S Yu, Sekundov AN and Smirnova I P 1984 *Theory of turbulent jets* (Moskow: Nauka) 717

[2] Yudaev B N 1988 *Engineering thermodynamics. Heat transfer* (Moskow: Vysshaya Shkola) 479

[3] Galimov E R, Zverev E V, Tukbaev E E, Galimova N Ya, Kuryntsev S V and Mukhin A M 2012 *Polymer powder coatings for special purposes* (Kazan: Ofset Servis)

[4] Galimov E R, Galimova N Ya and Tukbaev E E 2010 *Problemy energetiki* **4**

[5] Borisov Yu S, Kharlamov Yu A et al. 1983 *Gas-thermal coatings from powder materials* (Kiev: Naukova dumka) 568

[6] Bennett K O and Mayers D E 1966 *Hydrodynamics, heat and mass transfer* (Moskow: Nedra) 727

[7] Kutateladze S S 1990 *Heat transfer and hydrodynamic resistance* (Moskow: Energoatomizdat) 367

[8] Fedyaev V L, Morenko I V, Siraev A R, Galimov E R, Gimranov I R, Fazlyev L R and Takhaviyev M S 2015 *IOP Conf. Series: Materials Science and Engineering* **86** 1–5

[9] Morenko I V and Fedyaev V L 2014 *Journal of Engineering Physics and Thermophysics* **87**(3) 566–572