BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LVIII No. 3/2006	49 - 56	Seria Tehnică

The Modelation of the Dynamic Processes at the High-Speed Flame Thermal Spraying

Doina Petrescu, Niculae Napoleon Antonescu, Marian Neacşu

Universitatea Petrol-Gaze din Ploieşti, Bd. Bucureşti 39, Ploieşti
e-mail: dpetrescu@upg-ploiesti.ro

Abstract

In the present paper the authors realised a mathematical model simulating the dynamics of the deposit process on the basis of some studies made by different authors that treated separately the phenomena from the areas of burning and fluid expansion from the thermal spraying pistol.
The model presented takes into account the burning processes, the particles and fluid dynamics from inside and outside the thermal spraying pistol and also the heat and mass transfer process that take place during the thermal spraying process (application on the Cr_3C_2-NiCr powder particles).

Key words: *modelation, thermal spraying, powder particles.*

Introduction

A complex study was made by the authors by using certain independent models that take into account the combustion process, the particles dynamic, the fluid dynamic and also the particle fluid transfer processes where it takes place the high-speed flame thermal spraying. In order to realize this study, it has been started with the actual stat-of-the-art of the researches concerning the processes that take place in the combustion chamber. In the present paper we have studied: the fluid parameters, the determination of the speed and fluid temperatures values (the mixture formed from the particles and the combustible fluid fuel) at the characteristic points that exist on the particle route; the particle-fluid moment transfer; the heat transfer; the mass transfer during the thermal spraying.

For the proposed study, the following hypothesis were made:

1. for the combustion process it is supposed an one-dimensional model that may be used for the equilibrium composition (the powder chemical composition is the same) and also for situations that have as consequence other behavioral states of the composition;
2. the processes that take place in the expansion zone of the spraying pistol proceed after a adiabatic law and the characteristic technological parameters have average values;
3. the fluid expansion takes place after an isothermal law;
4. the pressure at the entrence in the combustion chamber is approximately equal to the atmospheric one and at the outlet from the expansion zone; the pressure is about 10^5 Pa [4];
5. the calculus relations are specific to the two components fluid and particle because at the high-speed flame deposit procedure, the massic fracture η has a very little value (η << 1);

6. the equation system for the particle fluid may be separated in two parts, one for the fluid and the other for the powder particles;
7. the factor that takes into account the particle fluid interaction is introduced in the kinetic equation of the movement quantity transfer for the particle;
8. the dynamic processes take place with mass transfer.

Fluid Parameters

For the study of the particle mechanical and technical behavior it is necessary to know the fluid speed and temperature. The solution of an equation system for the mixture fluid – particle [8] was is found in order to determine this behavior. Because of the fact that the volumetric fraction η in the high-speed flame deposit system is the smallest ($\eta \ll 1$), the equation system for fluid – particle may be separated in two parts: one for the fluid and the other for the powder particles. Also, the factor that takes into consideration the fluid-particle interaction is introduced in the kinetic equation of the movement quantity transfer for the particle [8,9].

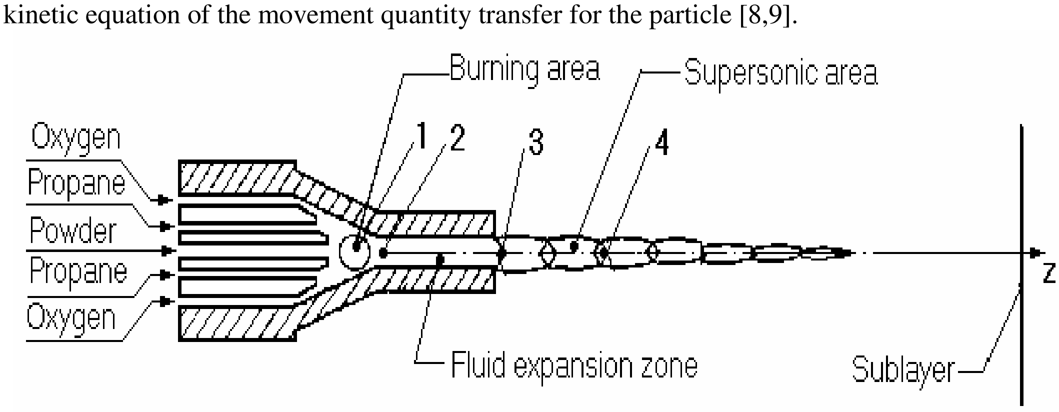

Figure 1. Scheme of the high – speed flame thermal spraying: 1, 2, 3, 4 - study regions for the fluid speeds and temperatures.

Taking into account the above, the fluid speeds and temperatures must be determined in the combustion chamber and at bigger projection distances (figure 1), in the points 1, 2, 3, 4.

The Combustion Chamber

The high – speed flame combustion process may be considered similar to the one that take place at the rackets driving mechanism. The same one-dimensional model for the high – speed thermal spraying process may be also used. This model may be used also for the equilibrium compositions and for situations that have as consequences the components states because the reaction products are rapidly eliminated, the composition remaining the same [10].

The combustion products are far from an equilibrium composition, thus it may be considered the most realistic situation, that in which the powder composition remains the same [10]. Without doubt, in order to obtain the more precise results, there will be necessary to include in the model the kinetic combustion products and the fluid dynamic phenomena from the combustion chamber.

The general equation system that describes the turbulent discharge and the mass transfer during the combustion process is extremely complicated for the one-dimensional case. On the other hand, the parameters as viscosity, diffusion coefficients, combustion speed constants etc. that are at high temperatures, are very little known. That is why it is necessary to introduce semi-empirical corrections in order to obtain more precise results.

The temperature T_{f1} and the fluid speed v_{f1}, in the combustion chamber, may be calculated with an approximate [12] that uses correction experimentaly factors, obtained in order to adjust fluid temperature and speed (from the combustion chamber), when it is known the density of the material that has to be thermally sprayed:

$$T_{f1} = T_{f0} + b_1[2500 \cdot \varphi - 700(\varphi - 1)],\ \varphi > 1\ , \tag{1}$$

$$v_{f1} = \frac{0{,}78}{\left(\frac{10^4}{T_{f2}} + \frac{900}{T_{f0}}\right)^{4{,}938}} P_{f1}^{-0{,}09876}\ , \tag{2}$$

$$v_{f2} = b_2 \cdot v_{f1}, \tag{3}$$

in which: b_1, b_2 are correction factors; φ - powder's density, $kg\cdot m^{-3}$; T_{f0} – fluid initial temperature, ^oC; T_{f1} – fluid temperature in the region 1 of the combustion chamber, ^oC; T_{f2} – fluid temperature in the region 2, ^oC; P_{f1} – fluid pressure in the combustion chamber, Pa; v_{f1} – fluid speed in the combustion chamber, $m\cdot s^{-1}$.

Pistol Fluid Dynamic Processes

In order to simplify the mathematical problem and to classify the process physics it must be considered that the pistol fluid discharge is adiabatic and that there are not combustion reactions. For the calculus average values will be used for the following thermodynamic parameters: specific heat (c_p), the function of the specific heats (γ), the gas universal constant (R), the fluid molecular mass (m) and implicitly for the rapport R/m, wrote with r. Taking into account the relation between the pistol length L and the Mach number M, inside the pistol and at a distance z from the entry in the point $M_3 = 1$[13], it results the formula of drop pressure coefficient χ,

$$\frac{\chi}{D}(L - z) = \frac{1 - M^2}{\gamma M} + \frac{\gamma + 1}{2\gamma}\ln\left[\frac{(\gamma+1)M^2}{2 + (\gamma - 1)M^2}\right]. \tag{4}$$

The fluid temperature in the region 3 is

$$T_{f3} = \frac{2 + (\gamma - 1)M_2^2}{2 + (\gamma - 1)M^2} T_{f2}, \tag{5}$$

and the pressures in the point 2 and 3 (see figure 1) are:

$$P_{f2} = r \cdot \rho_{f2} \cdot T_{f2}, \tag{6}$$

$$P_{f3} = P_{f2} \cdot M_2 \frac{K_2}{K_3}\sqrt{\frac{T_{f3}}{T_{f2}}}\ , \tag{6'}$$

in which: γ - specific heats function; $T_{f2,3}$ – fluid temperature in the points 2, 3; $P_{f2,3}$ - fluid pressure in the points 2, 3, Pa; $r = \frac{R}{m}$, the relation between the gas universal constant and fluid molecular mass, $J\cdot kg^{-1}\cdot K^{-1}$; ρ_{f2} – fluid density in the point 2, $kg\cdot m^{-3}$; M_2 - Mach number in the point 2 ; K_1, K_2, K_3 - correction factors that take into account the sonic speed, having dissipative effects inside the pistol.

Fluid pressure is deduced from the following expression:

$$\rho_f = \rho_{f2} \frac{K_2 \cdot M_2}{K \cdot M} \sqrt{\frac{T_{f2}}{T_f}} ,$$

$$P_f = r \cdot \rho \cdot T_f . \tag{7}$$

The drop pressure coefficient has the following expression [15],

$$\frac{1}{\sqrt{\chi}} = -2\lg\left(\frac{2{,}51}{\mathrm{Re}\sqrt{\chi}} + \frac{\varpi}{3{,}17D}\right), \tag{8}$$

in which: χ - the drop pressure coefficient; Re- Reynolds' number; D – pistol diameter; ϖ - pistol wall roughness, m.

If there are take into consideration the fluid-particle interactions, this coefficient will modify [16] and has the value χ_*:

$$\chi_* = \chi(1 + B \cdot \varsigma), \tag{9}$$

$$B = 1{,}2 - 0{,}1 \cdot \ln(\mathrm{St}), \tag{10}$$

$$\mathrm{St} = \frac{\rho_p \cdot d_p^2 \cdot K \cdot M \sqrt{\gamma r \cdot T_f}}{18\mu_f \cdot L} , \tag{11}$$

in which: ς - the relation between particle mass discharge and fluid; B - experimentaly constant; St – Stokes criterion; ρ_p – particular density, kg·m^{-3}; d_p - particle diameter, m; K – correction coefficient; M – Mach number; γ - specific heats function; μ_f – fluid dynamic viscosity, kg·m^{-1}·s^{-1}; L – pistol length, m.

Fluid Expansion at the Pistol Out Going

Because right before the pistol out going the fluid pressure overtakes the atmospheric one an expansion of the fluid is produced at the same time with the incremental increase of the Mach number and the formation of the shock waves [2,13].

The diameter from the superior region gradually decreases as a result of the energy dissipated at the limited surface that leads to the disappearance of this region [2].

Considering the isentropic expansion and taking into account that the pressure at the pistol exterior P_4, is one bar, there may be known the fluid temperature, density and speed and the Mach number in the point 4 and also the fluid speed in the point 3 [13, 14].

Also, the supersonic beam length L_c is deduced from the equations [14,15]:

$$L_c = D(3{,}917 M_4 + 1{,}963) ,1 \le M_4 \le 1{,}6, \tag{12}$$

$$L_c = D(14{,}712 M_4 + 15{,}31) ,1{,}6 \le M_4 \le 2{,}4 , \tag{13}$$

in which: D – pistol diameter, m; M_4 – Mach number in point 4.

The beam expansion is relatively smaller than the sonic speed. In these conditions the behavior of the fluid jet makes the deposited fluid layers incompressible [17]. As a result of the high-speeds that are used in the high-speed flame projection there are taken into consideration only the longitudinal components of the fluid and particle speed [2, 4]. Outside the pistol, there are considered the fluid speeds v_{f3} and v_{f4}, the fluid temperatures T_{f3} şi T_{f4}, from the points 3 and 4 and also the experimental values v_{f5} and T_{f5} at the sub-layer surface [3, 5].

Moment Transfer

Taking into account the fluid-particle interactions and those of the fluid acceleration/deceleration, the movement equation for the spherical particles is the following [3, 9, 18, 19]:

$$\frac{dv_p}{dt} = \frac{3}{4}\frac{C_D}{d_p}\frac{\rho_f}{\rho_p}\left(v_f - v_p\right)\left|v_f - v_p\right| + \frac{18\mu_f \cdot \eta}{d_p^2 \cdot \rho_f}\left(1 + 0{,}15\,\mathrm{Re}^{0,687}\right)\left(v_f - v_p\right) - \frac{3b_3}{4}\frac{d\left(v_f - v_p\right)}{dt} \quad (14)$$

in which: v_p-particle speed, $\mathrm{m \cdot s^{-1}}$; v_f – fluid speed, $\mathrm{m \cdot s^{-1}}$; C_D – particle transport coefficient, $\mathrm{m \cdot s^{-1}}$; d_p – particle diameter, m; ρ_p – particle density, $\mathrm{kg \cdot m^{-3}}$; ρ_f – fluid density $\mathrm{kg \cdot m^{-3}}$; μ_f – fluid dynamic viscosity, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$; η - particles volumetric fraction; Re - Reynolds criterion; b_2 – correction coefficient.

The second term from the right side of the equality describes the fluid-particle interactions [9, 16] and the thermal contribution introducing the effect of the fluid discharge acceleration/deceleration [18]. The transport coefficient C_D is deduced from the following equation [19]:

$$C_D = \frac{23{,}707}{\mathrm{Re}}\left(1 + 0{,}165\,\mathrm{Re}^{\frac{2}{3}} - 0{,}5\,\mathrm{Re}^{-0,1}\right)$$

$$0{,}15 \le \mathrm{Re} \le 500,$$

$$\mathrm{Re} = d_p\, v_p\text{-}\, v_f\, \rho_f\, \mu_f^{-1}, \quad (15)$$

The initial condition for the equation (14) is

$$v_p(0) = \mathrm{v}_{p0}\,, \quad (16)$$

and the position results from the relation

$$z(t) = \int_0^t v_p(t)\,dt \quad (17)$$

in which t is the time, in s.

Heat Transfer

The thermal behavior of the spherical particles results from the heat conductivity equation [3,20]:

$$\rho_p \cdot c_p \cdot \psi(T_P)\frac{\partial T_p}{\partial t} = \frac{1}{x^2}\frac{\partial}{\partial x}\left(x^2 \cdot \lambda_p \frac{\partial T_p}{\partial x}\right), \quad 0 \le \mathrm{x} \le R_{p,t} > 0 \quad (18)$$

$$\psi(T_p) = 1 + q \cdot c_p^{-1}(1-k)^{-1}(T_K - T_L)^{-1}\left(\frac{T_K - T_L}{T_p - T_L}\right)^{\frac{2-k}{1-k}},$$

$$T_S \le T_p \le T_L;$$

$$\Psi(T_p) = 1, \quad T_p > T_L, \; T_p < T_S, \tag{19}$$

in which: c_p – particle specific heat, J·kg^{-1}·K^{-1}; ρ_p – particle density, kg·m^{-3}; Ψ - efficiency parameter; T_p – particle temperature, ^{o}C; λ_p – particle thermal conductivity, W·m^{-1}·K^{-1}; q – fusion heat, J·kg^{-1}.

The powder particle temperature T_p depends on the time t and on the radial coordinate x. In order to solve the equation (18) two limit conditions are necessary. In the particle center is introduced the symmetric condition for the temperature (19) while for the particle surface is introduced the equation of heat interchange between the particle and the fluid:

$$\frac{\partial T_p}{\partial x}(0,t) = 0. \tag{20}$$

In the initial moment, the particle temperature in any point is constant and equal to T_{p0}. The heat transfer coefficient α is obtained from the semi-empiric Ranz-Marshall equation [18]:

$$\mathrm{Nu} = \frac{\alpha d_p}{\lambda_f} = 2 + 0{,}6\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}},$$

$$\mathrm{Pr} = \frac{c_f \mu_f}{\lambda_f}, \tag{21}$$

For the calculus of the criteria Re, Nu, Pr there are introduced the average values of ρ_f , μ_f , c_f , λ_f in the interval $T_{ps} \le T \le T_f$.

The equation that defines the moment transfer and also the heat transfer do not take into account the Knudsen effect [3].

The Mass Transfer During the Thermal Spraying

The mass transfer during the thermal spraying takes place as a result of the dissolution of a carbide part and thus it increases the C and Cr proportion in the metal phase.

The experimental results show that the biggest part of the chrome carbide, Cr_3C_2, is found after spraying while the little particles suffer a partial or total dissolution during the thermal spraying.

The M_7C_3 carbides suffer a similar process increasing the carbide content and also that of Cr, of the regions enclosed in the melted state [7].

The cooling that powder particles suffer when the sub-layer forms is of 10^6...10^7 K/s, for which the structure resulted in the regions that suffer partial or total fusion is amorphous and/or mono-crystalline. For the evolution of the thermodynamic properties of the particles material it has to be taken into account the particles oxidation during the spraying and also the chrome oxide formation especially of Cr_2O_3.

is taken into consideration The carbides global volumetric fraction is taken into consideration. This fraction may be written thus [18]:

$$\varepsilon = \varepsilon_0 (1 - A \cdot t)^{\frac{3}{2}},$$
$$\beta = 1 - \varepsilon, \tag{22}$$

where: β is the metal phase volumetric fraction;
ε – chrome carbide volumetric fraction;
ε_0 – chrome carbide initial volumetric fraction;
t – time, in s;
$A = t_*^{-1}\left[1 - \left(\varepsilon_* \cdot \varepsilon_0^{-1}\right)^{\frac{3}{2}}\right]$ is a coefficient;
t_* – the initiation time of the metal phase diffusion, s.

Similarly the chrome oxide volumetric fraction, δ, is:

$$\delta = \delta_0 (1 + G \cdot t)^{\frac{3}{2}}, \tag{23}$$

where: δ - is the chrome oxide volumetric fraction;
δ_0 - chrome oxide initial volumetric fraction;
t – is time, in s;
$G = t_*^{-1}\left[\left(\delta_* \cdot \delta_0^{-1}\right)^{\frac{3}{2}} - 1\right]$ is a coefficient.

In the expression (23) it is introduced a very small value of powder oxidation δ_0, from technical reasons. The parameters ε and δ are used for obtaining the material thermal properties, material that is used for forming the powder particles according to the melting laws.

Conclusions

- On the grounds of the study processes that take place in the combustion chamber at the high – speed flame projection, there was developed a theoretical model of the dynamic deposit processes by high-speed flame thermal spraying, that allows to calculate the speed, the temperature and the pressure in different points (distances) according to figure 1.
- In order to simplify the mathematical problem and to classify the process physics it has to be considered that the fluid debit in the pistol varies adiabatic and that there are no other combustion reactions.
- The particle fluid moment transfer takes into account the fluid particle interactions and also the fluid acceleration/deceleration.
- The powder particle temperature T_p depends on the time *t* and the radial coordinate *x*.
- The mass transfer during the thermal spraying takes place as a result of the dissolution of a chrome carbide part and thus it increases the C and Cr proportion in the metal phase.
- The dynamic model proposed in this paper takes into account the combustion process, the particles dynamic, the fluid dynamic inside and outside the pistol for thermal spraying and the heat transfer processes.

References

1. Parkery D.W., Kutner G.L., *Advise Mater. Proces*, 1994, 7, 31-35,.
2. Petrescu D., *Cercetări teoretico-experimentale privind depunerile superficiale prin metalizare*, Lucrare de dizertație, 2002.

3. Petrescu D., *Aplicaţii ale pulverizării termice (metalizării) în domeniul realizării şi recondiţionării pieselor*, Referat de Doctorat, 2003.
4. Sobolev V.V., Guilemanz J.M. a.a., University of Barcelona, Barcelona, Comunicacion Privada, *Surf. Coat. Technology*, 1996.
5. Introduction to the CDS Technology, *Plasma Technique AG*, Wohlen, 1990, p. 12.
6. Guilemany J.M., Calero J.A., University of Barcelona, Barcelona, *Communication Privada*, 1995.
7. Han K.S., Chung M.K., Sung H.J., Transfer ASME, *Journal Fluid Engineering*, vol. 113 , 1991, p. 130-136.
8. Sobolev V.V., Guilemanz J.M., Calero J.A., University of Barcelona, Barcelona, *Therm. Spray Technology*, 4(3) , 1995, p. 276-287.
9. Gordon S., McBride B., NASA, *Lewis Research Center*, 1976, p. 273.
10. Swank W.D., Fincke J.R. s.a., *Thermal Spray Industrial Application*, ASM Imternational, Materials Park, Ohio, 1994, p. 313-318.
11. Horlock J.H., Winterbone D.E., *The Thermodynamics Combustion Engines*, Ed. Clarendon Press, Oxford , 1986, p. 824-848.
12. Duziaux R., Perrier J., *Mecanique des Fluides Appliquée*, vol.2, Dunod, Paris, pg. 11-78.
13. Garmier J.C., *Plasma Technique* S.A. France, Villefontaine, Communications Privées, 1990.
14. Duziaux R., Perrier J., *Mecanique des Fluides Appliquée*, vol.11, Dumond, Paris, 1972, p. 216-223.
15. Dodge F.T., Green S.T. s.a., Trans. ASME, *Journal Fluid Engeniering*, vol. 113, 1991, p. 469-474.
16. Szekely J., Themelis N.J., *Rate Phenomena in process Metalurgy*, Wiley-Interscience, New-York , 1971, p. 718-724.
17. Temkin S., Menta H.K., *Journal Fluid Engeniering*, vol. 116, 1982, p.297-313.
18. Sobolev V.V., Trefilov P.M., *Thermophysics of Metal Solidification During Continuos Casting Metallurgy*, Moscow, 1998, p. 271-294.
19. Guilemany J.M., Nutting J., Lorca-Isern N., *Powder Metallurgy*, vol. 37(4), , 1994, p. 6-16.
20. Yoshida T., Akashi K., *Journal Fluid Engeniering*, vol. 48(6), 1977, p. 2252-2260.

Modelarea proceselor dinamice de pulverizare termică cu flacără de mare viteză

Rezumat

În această lucrare autorii au realizat un model matematic, simulând dinamica procesului de depunere, pe baza unor studii efectuate de diverşi autori, dar care tratau separat fenomenele din zonele de ardere şi de expansiune a fluidului din pistoletul de pulverizare termică.
Modelul prezentat ţine cont de procesele de ardere, de dinamica particulelor şi a fluidului din interiorul şi din afara pistoletului de pulverizare termică, precum şi de procesele de transfer de căldură şi de masă, care au loc în timpul procesului de pulverizare termică.