Pure & Appl. Chem., Vol. 70, No. 6, pp. 1217-1222, 1998.
Printed in Great Britain.

Eulerian and Lagrangian modelling of dust-laden plasma jets

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Abstract: Plasma jets with admixture of inertia particles have found wide application in a number of modern branches of engineering and technology (plasma spraying; spheroidization, atomisation and production of powder materials; recovering the metals from the ores; synthesis of refractory materials; gasification of low-calorific value coals in thermal plasma; plasma ignition and lighting processes in pulverised-coal burner of boiler units, etc.). The aim of the paper presented is the analysis of some problems concerning the Eulerian and Lagrangian modelling the turbulent mixing in single- and multicomponent plasma jets (both homogeneous and heterogeneous ones) flowing out of dc plasma torches.

1 INTRODUCTION

Plasma processing is one of the promising methods of producing new materials. A wide temperature and gasdynamic range of plasma jets as well as the possibility of using various plasma-forming media, such as neutral, oxidizing and recovering, allow both chemical and phase transformations providing the required modification of the initial powders and obtaining materials characterized by specific structural and other properties to be combined in one and the same technological process. At the same time, plasma processing of powders is a highly science-extensive technology whose potentialities are far from being used fully due to the fact that "plasma torch - gas-disperse flow - final material" system has been imperfectly understood. Progress in this field may be achieved only by realisation of the complex experiment (Ref.1) covering all the stages of the formation of final product with predetermined properties which can be guaranteed both under laboratory and industrial levels.

Effectiveness and productivity of the powder materials plasma processing depend on many factors: (i) flow conditions in jet of a specific plasma torch, (ii) method and stability of powder injection into the plasma flow, (iii) thermal power of the jet, (iv) granulometric composition and physical properties of powder, etc. As a whole, the total effectiveness and productivity of the process, as well as the quality of product, are determined by the peculiarities of motion and heating of individual particles introduced into the plasma flow.

The aim of the paper presented is to discuss some problems concerning the Eulerian and Lagrangian modelling the turbulent heat- and momentum transfer in single-phase and dusted plasma jets outflowing from dc plasma torches. The following problems are under consideration: (i) single-phase (homogeneous) plasma jets (correction of the standard *(k-ε)* - model of turbulence taking into account a high level of gas density gradient), (ii) Eulerian modelling of dusted plasma jets (dense loading conditions; additional equation characterising the stochastic motion of particles; influence of particles on turbulence of the carrier flow), (iii) Lagrangian modelling of dusted plasma jets (two approaches: (1) - Lagrangian Stochastic Deterministic model and (2) - Lagrangian modelling of representative ensemble of particles with account for their inner complecated aggregate state in the plasma flow).

2 SINGLE-PHASE PLASMA JETS

A high-temperature jet outflowing of a plasma torch is a principal main technological region in different powder treatment processes. Therefore, the physico-mathematical description of specific carrier high - temperature flow, along with a chosen dependencies characterising the interphase exchange, define the correctness and accuracy of Eulerian and Lagrangian modelling of dust-laden plasma jet as a whole.

As a rule, the regime of plasma technological flows is turbulent, and the standard *(k-ε)* - model is used (Refs.2-4) usually for their modelling. This model, developed on the basis of experimental data characterising the rather simple turbulent flows, has received wide acceptance at numerical investigation of quasi-isothermal turbulent flows. Generalisation of the model equations system for computation of the flows with space-varying density (supersonic boundary layer, flows with combustion, plasma flows) is commonly based on Favre averaging, that permits to avoid the appearance of additional correlation due to a density pulsation. The physico-mathematical model derived in Ref.2 in the framework of this approach was applied to compute the argon plasma jet exhausting into the air atmosphere. The comparison of the numerical results obtained with experimental data showed a different level of accuracy (from satisfactory up to a significantly different). The attempt to improve the accuracy of the modelling by more accurate calculation of the plasma properties was undertaken in Ref.3. The comparison with extended set of the experimental data presented in Refs.4,5 emerged the common tendency of exceeding the axial gas temperature and argon concentration computed. The authors of Ref.6 have developed the two-fluid model of turbulence as applied to argon plasma jet outflowing into an argon media. This approach permitted to reach a rather good agreement with experiment. However, it is pertinent to note that generalisation of this model for studying the multicomponent plasma jets presents the significant difficulties. In this connection, it is evident the problem of further developing the simple models providing the prediction of temperature, velocity and concentration fields in the turbulent plasma jets with sufficient accuracy.

When formulating these models based on Favre averaging, one have to account that plasma jets are characterized by essential density gradients. As it is followed from the comparison of computed and experimental data, the standard *(k-ε)* - model of turbulence underrates significantly the value of transfer coefficients. We proposed the approach of greatest practical utility in Ref.7, which lies in the increasing the turbulent viscosity coefficient $\mu_{ft} = c_\mu k_f^2 / \varepsilon_f$ by correction of the constant c_μ according to expression $c_\mu = c_{\mu 0}\left[1 + a\left|\nabla\rho_f\right| k_f^{3/2} / (\rho_f \varepsilon_f)\right]$. Here the characteristic local linear scales of the turbulent eddies and density non-homogeneity are $k_f^{3/2} / \varepsilon_f$ and $\rho_f / \left|\nabla\rho_f\right|$, respectively; a is an additional constant of the model, $c_{\mu 0}$ =0.09 is a standard constant. Here and below, index *'f'* corresponds to parameters of the gas flow. As may be seen, the local value of the dimensionless parameter $L = \left|\nabla\rho_f\right| k_f^{3/2} / (\rho_f\, \varepsilon_f)$ is small in the case of smooth temperature field. In opposite limiting case, there is an essential temperature drop inside the large-scale turbulent eddies. The radial distributions of the parameter L in the vicinity of the plasma torch nozzle are presented in Fig.1. The computation has been fulfilled by application of the standard *(k-ε)* - model for the argon plasma jet (nozzle diameter of 10 mm) outflowing into the cold air atmosphere.

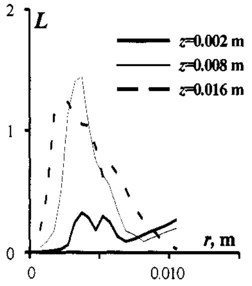

Fig.1. Distribution of parameter L in cross-sections of the argon plasma jet.

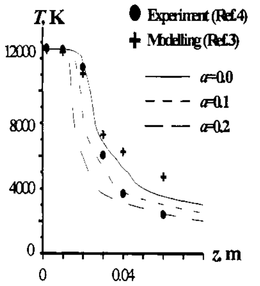

Fig.2. Comparison of results obtained with the help of standard model and corrected one for different value of ***a***.

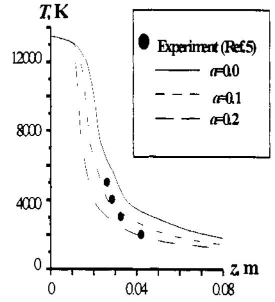

Fig.3. The results of additional comparison with the experimental data of Ref.5 (u_o=657 m/s, T_o=13721 K).

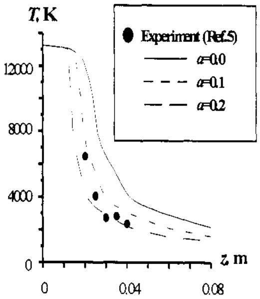

Fig.4. The results of additional comparison with the experimental data of Ref.5 (u_o=336 m/s, T_o=13506 K).

The profiles have peaks on the boundary of high-temperature core, which shift to the axis of jet when the distance from the nozzle increases and temperature core is smoothed. The radial distributions of parameter L show that significant temperature gradients take place inside the large-scale turbulent eddies generated at the boundary of the high - temperature core. With the help of the turbulent viscosity correction proposed there was fulfilled the modelling the same experiments which were used by authors of Ref.3. In our calculations, there were used the following set of the model constants: $c_{\mu 0}$=0.09, $c_{\varepsilon 1}$=1.44, $c_{\varepsilon 2}$=1.65, Sc_k=1.0, Sc_ε=1.3, Pr_t=0.75, Sc_t=0.75. The results of comparison, presented in Fig.2, characterize the axial temperature distribution. As indicated by Fig.2, the value of the parameter a=0.1 provides a rather good correlation with the experimental data. The similar results of comparison with the experimental data of Ref.5, corresponding two regimes of jet outflow, are presented in Figs.3,4. All presented illustrates the validity of the approach to correction of the standard *(k-ε)* - model as applied to turbulent plasma jet. But this question requires a further study, especially, as applied to plasma jets of complex gas composition. In closing, it must be emphasised that most known publications, devoted to modelling plasma jets, use the Favre averaging which for variable-density flow are defined as $\tilde{a} = \overline{\rho a} / \bar{\rho}$, where the line over means a time averaging the corresponding parameters. Whereas the procedure of Reynolds averaging is defined as $< \rho a > = \bar{a}\bar{\rho} + \overline{\rho'' a''}$. Here and below two primes mean the time pulsation of the parameters. Hence, we have the relation between these two types of gasdynamic parameters averaging $\tilde{a} = \bar{a} + \overline{\rho'' a''} / \bar{\rho}$, from which it is followed that only at $\bar{a} << \overline{\rho'' a''} / \bar{\rho}$, i.e. at rather low level of density pulsation's, we have $\tilde{a} \approx \bar{a}$. Otherwise as a result of modelling with the use of Favre averaging, there can be obtained irregular fields of mean velocity, temperature, etc. In this connection, it is necessary to fulfil the comprehensive comparative physical and computational experiments to studying the possibilities of models based on two above-mentioned methods of averaging. Among other things, the results of this study are of interest for correct prediction of the disperse phase behavior in plasma jets.

3 DUSTED PLASMA JETS

A considerable number of papers (Refs.8-21, etc.) are devoted to simulation of interphase momentum, heat and mass transfer in plasma flows with additive of the disperse particles. Depending on method of the disperse phase description, all available models can be divided into two types: Eulerian and Lagrangian ones.

Eulerian modelling

The Eulerian models (Refs.11-14, 20, etc.) are based on the representation of an ensemble of particles moving in the flow as a continuum, and heterogeneous flow is considered generally as two interpenetrating and interacting continua. The possibility of the Eulerian description of disperse phase is related to the fulfilment of two conditions: 1) the size of individual particles should be much less than the specific linear flow scale; 2) their concentration should be sufficiently high to assign to each point of the space occupied by the particles a certain density, velocity, temperature etc. upon averaging with respect to a small control volume which is defined by specific size of the system. The advantage of the models using the Eulerian approach to the description of gas and disperse phases is the relative simple account of turbulent additive transport. They enable natural generalisation for the case of polydisperse particle composition; and moreover interparticle collisions can be readily taken into account. The Eulerian approach allows us to take into account relatively easily both direct and inverse interactions between the carrying flow and particles of the additive in averaged and fluctuating motions.

Noting that dust-laden plasma jets used in the processes of spraying, spheroidization, etc. have, as a rule, a low volume concentration s_p of suspended particles and their size D_p in practically important cases does not exceed 100-150 μm, we base our studies on the averaged equations of motion and energy of turbulent polyphase flows in Frankl-Dyunin's form (see Refs.22-24). These equations, which are derived by the method of the sequential spatial and temporal averaging of the initial balance integral relationships, are the most reliable for description of multicomponent systems. The change over to continuous media by means of this method is possible for any type of motion of mixture components, both with and without account of phase transformations. The effectiveness of this approach in application to modelling of turbulent two-phase jets has been confirmed by us in Refs.12, 14, 20, 25, 26, etc. According to Refs.22-24, the sequential spatial and temporal averaging for the space-time cylinder V_Ax$2\Delta t$, can be carried out as:

$$\left\langle F_p \right\rangle = \frac{1}{2\Delta t}\int_{2\Delta t}\left[\frac{1}{V_A s'_{pA}}\int_{V_A} F'_p dV\right] s'_{pA} dt = \frac{1}{2\Delta t}\int_{2\Delta t} F'_{pA} s'_{pA} dt = \frac{1}{2\Delta t}\int_{2\Delta t} (F_p + F''_p)(s_p + s''_p) dt = F_p s_p + \left\langle F''_p s''_p \right\rangle,$$

where F_p is scalar function characterising a certain property of particles, V_A is a constant volume and $2\Delta t$ is a constant time interval of averaging. The sign 'two primes' denotes the time pulsation of instantaneous volume-averaged quantities, while $s'_{pA} = V'_{pA} / V_A$ is the instantaneous concentration of disperse particles, where V'_{pA} is the instantaneous volume occupied by particles in volume V_A. Averaging of s'_{pA} in the time interval $2\Delta t$ gives the mean-volume concentration of the admixture: $s_p = (\int_{2\Delta t} s'_{pA} dt) / (2\Delta t)$.

The available models of high-temperature dust-laden flows, based on the Eulerian description of the disperse phase require mutual comparison and development with due account of the peculiarities of plasma processing (different flow regimes in a jet including turbulence level and its scale; a wide spectrum of materials and their granulometric compositon; powder and plasma flow rates ratio; polydispersity; multicomponent structure; turbulent additive diffusion; effect of the stochasticity of the particle injection process on cross migration in a jet; condensed phase effect on the structure of turbulence of the carrying flow as well as possible evaporation of particle material on the dynamic and thermal non-equilibrium state of phases, etc.). Some of the above problems are discussed by us in Refs.11,12,14 and 20. In particular, in Refs.14 and 20 the Eulerian model of a high-temperature axially symmetric jet with an addition of high-inertia particles was proposed, which allows to take into account the stochasticity of the process of powder material injection into the flow. This model is based on the standard *(k-ε)* - model supplemented by the equations of gas and particle heat balance as well as the kinetic energy k_p of stochastic motion of the particles and corrected with due account for the interphase momentum and heat exchange in both averaged and pulsational motions of the phases. For brevity of further description, let us introduce the differential operator

$$\left\langle \frac{d}{dt} g \right\rangle_l \equiv \frac{\partial g}{\partial t} + \frac{\partial}{\partial z}\left\{ g w_{zl} + \left\langle g'' w''_{zl} \right\rangle \right\} + \frac{1}{r} \cdot \frac{\partial}{\partial r} r \left\{ g w_{rl} + \left\langle g'' w''_{rl} \right\rangle \right\},$$

where *t* is time, *g* is arbitrary scalar function, index *l=f, p* corresponds to gas and disperse phase respectively. The model, for steady-state axially symmetric heterogeneous jet with monodisperse particles, includes two subsystems written boundary layer approximation:

- equations, characterising the carrier turbulent gas flow,

$$\left\langle \frac{d}{dt} \rho_f \right\rangle_f = 0; \left\langle \frac{d}{dt} \rho_f w_{zf} \right\rangle_f - \frac{1}{r} \cdot \frac{\partial}{\partial r} r \mu_{ft} \frac{\partial w_{zf}}{\partial r} = -\rho_p F_p^{(z)}; \left\langle \frac{d}{dt} \rho_f h_f \right\rangle_f - \frac{1}{r} \cdot \frac{\partial}{\partial r} r \frac{\lambda_f}{c_{pf}} \cdot \frac{\partial h_f}{\partial r} = -\rho_p Q_p;$$

$$\left\langle \frac{d}{dt} \rho_f k_f \right\rangle_f = \mu_{ft} \left(\frac{\partial w_{zf}}{\partial r} \right)^2 - \rho_f \varepsilon_f - \rho_p \Delta S_{kp}; \left\langle \frac{d}{dt} \rho_f \varepsilon_f \right\rangle_f = c_{\varepsilon 1} \mu_{ft} \left(\frac{\partial w_{zf}}{\partial r} \right)^2 \frac{\varepsilon_f}{k_f} - c_{\varepsilon 2} \rho_f \frac{\varepsilon_f^2}{k_f} - \rho_p \Delta S_{\varepsilon p}$$

- equations, characterising the disperse phase,

$$\left\langle \frac{d}{dt} s_p \right\rangle_p = 0, \left\langle \frac{d}{dt} s_p w_{zp} \right\rangle_p = F_p^{(z)}, \left\langle \frac{d}{dt} s_p h_p \right\rangle_p = Q_p, \left\langle \frac{d}{dt} s_p k_p \right\rangle_p = \Delta S_{kp}.$$

The closing relations used in the model are presented in Refs.20 and 27, in which it has been fulfilled the testing of model as applied to the isothermal two-phase jet. The results of additional testing the model of turbulent diffusion of particles are presented in Fig.5. Some of the results of testing the developed Eulerian model for the case of a dusted plasma jet are illustrated by Figs.6,7 (solid curves are computed data, w_{fo} and T_{fo} are the maximum of gas velocity and temperature in the exit cross-section of plasma torch nozzle). The experimental data of Ref.32 were used for this purpose. In this paper, the interphase heat and momentum exchange between Al_2O_3 - particles (D_p=18 µm) and Ar-H_2 plasma jet (30% H_2, P=29 kW) have been studied. It can be seen that all aforesaid results of comparison are quite satisfactory.

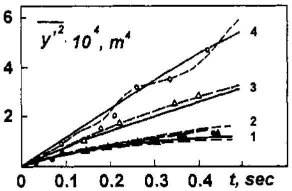

Fig.5. Comparison of experimental (dots, see Ref.31) and calculated (curves) data for turbulent migration of inertia particles: 1-copper, D_p=46.5 µm; 2-hollow glass balls, D_p=87 µm; 3-maize pollen, D_p=87 µm; 4-hollow glass ball, D_p=46.5 µm; solid curves - Eulerian model; dotted curves - Lagrangian model.

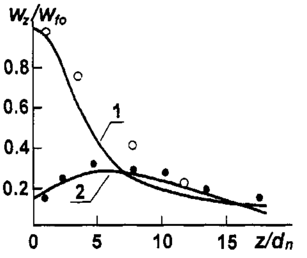

Fig.6. Distribution of longitudinal component of averaged velocity of gas (1) and particles (2).

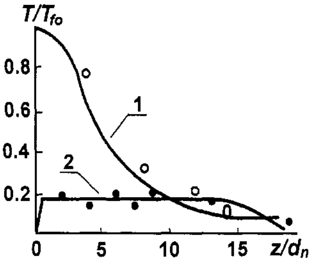

Fig.7. Distribution of temperature of gas (1) and particles (2).

Lagrangian modelling

The Lagrangian approach (or the "trajectory" method) combines in itself the Eulerian description for the carrier gas flow and the Lagrangian one for the disperse phase. The solution of motion and heat - mass transfer equations for a single particle in gas flow with precomputed (commonly with the help of two-parameter (*k-ε*) - model) or experimentally measured velocity and temperature fields is of more physical nature. It is readily realised in the case of rather inertial particles, when their turbulent diffusion can be neglected. The situation is more complicated when it is necessary to take into account the turbulent interphase momentum and heat exchange as the stochastic nature of equations incorporating the actual values of phase velocities and temperatures causes statistical modelling of the process with subsequent averaging of velocities, temperature and aggregate state for the particle ensemble. In this case to increase the accuracy of computational experiment, one should increase the number of test particles. But, taking into account their inverse effect on the carrying flow, one should correct the velocity and temperature fields of carrier flow with the help of iterations in each temporal layer using the obtained parameters of disperse phase. Lagrangian approach was used for modelling the particles bihavior in rf plasma (Ref.10) and dc plasma plume (Refs.8,9,11,15-21, etc.). In all these papers the gradientless model of particle heating was applied for description of the disperse component. Though a small particles size justifies application of this model, the estimations show, that the error can be significant for the case of widely used ceramics, such as Al_2O_3, ZrO_2, etc. The accurate prediction of the particles heating is the main purpose of the modelling, especially for technologies, which require the guarantee provision of the specific inner aggregate (or phase) particles state. In this connection, it was necessary to compare these results with ones obtained by the application of more exact method, taking into account the temperature gradient inside the particles (Ref.27). In the first step of this study, the temperature gradient within the particle was not taken into account when a thermal state of the disperse phase was modelled, i.e. the particle's surface temperature was assumed to be equal to its mean-volume value. In accordance with aforesaid, the losses due to particle radiation were taken into account in a heat balance of the disperse phase. Possible collisions of the particles in the heterogeneous flow were neglected. In the second stage, the obtained gasdynamic field of the carrier gas flow, taking into account the inverse influence of the disperse phase on gas averaged and turbulent characteristics, was used thereupon as known under numerical modelling of the particle ensemble with consideration for the temperature gradient inside them. In this study the results, obtained in Ref.28, were chosen for realisation of the comparison. The mathematical model included the *(k-ε)* - model for closing the equations characterising the carrier flow. Lagrangian Stochastic Deterministic model (Ref.29) describing the particles motion in a high temperature turbulent flow and Particle Source in Cell (PSI-cell) method (Ref.30) for computing the particle-plasma interaction were used. The model, presented in Refs.14 and 20, was used to take into consideration the suppression of the turbulence energy by the disperse phase. This model does not require any new empirical constants, so the standard values of constants were used: $c_\mu=0.09$, $c_{\varepsilon 1}=1.43$, $c_{\varepsilon 2}=1.92$, $Sc_k=1.0$, $Sc_\varepsilon=1.3$, $Pr_t=0.9$. The geometry of flow under consideration is shown in Fig.7. The dusted plasma flow was calculated in two steps. At first, the flow within the plasma torch channel was calculated. The distributions of velocity, temperature and energy of the turbulence at the initial section were uniform in the flow region behind the area of axial symmetrical ("diffusive") arc attachment. At the outlet of the channel all variables had boundary conditions of the boundary layer type. The particles were introduced into the plasma flow normally to the z-axis at the distance of $0.5 \cdot d_n$ behind the initial section (d_n is diameter of the channel). The distribution of initial particles coordinates along the injector slit were assumed to be uniformly random, while their initial velocities had the Gaussian distribution with mean value $w_{rpo}=1.64$ m/s.

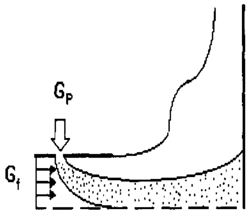

Fig.7. The diagram of flow (G_f and G_p are the mass flow rates of plasma-forming gas (air) and alumina powder of 25-75 μm.

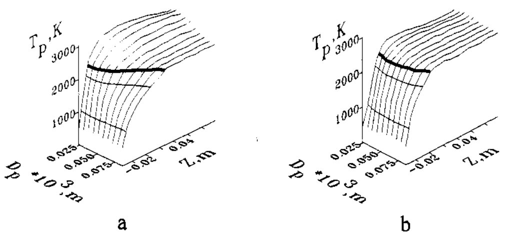

Fig.8. Variation of particles temperature along their trajectories. a - **k=1**, b - **k=2**.

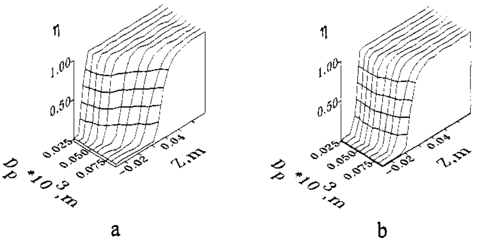

Fig.9. Variation of particles melting degree along their trajectories. a - **k=1**, b - **k=2**.

The variation of particles temperature along their trajectories, corresponding to ten groups of particles considered, is shown in Fig.8. Here $k=G_p/G_f$. It is seen that bigger particles penetrate deeper into the high temperature core. (Initial part of trajectories does not resolved in used scale). The sharp temperature fall due to intensive mixing at the nozzle exit is more pronaunced for smaller particle flow rate. The temperature level is smaller for greater particle flow rate (k=2) due to intensive gas flow cooling by particles. The dark isotherms correspond to melting temperature of particle material. It is necessary to note that for the smaller loadung ratio the big particles heating is slower due to the higher velocities of the carrier flow. The behavior of the particles melting degree η along their trajectories is shown in Fig.9. These plots are in accordance with Fig.8 and also show the more rapid melting of the big particles for greater loading ratio. The range of particles temperature prior to their collision with substrate is of $2300 \div 2700$ K for low loading ratio and of $2380 \div 2440$ K - for higher one. The temperature differences between these results and corresponding results obtained by gradientless model are higher for k=1 and are of 15%.

4 CONCLUSIONS

Correction of the standard *(k-ε)* - model of turbulence taking into account a high level of gas density gradient in the plasma jet was proposed which provides the better agreement with experimental data. Eulerian model of high-temperature dusted jet has been suggested which allows to take into consideration the stochasticity of particles velocity under powder injection. The model is based on a standard *(k-ε)* - model complemented by equations of gas and particle heat balance as well as kinetic energy of stochastic motion of the particles, and corrected with due account of interphase momentum and heat transfer both in averaged and pulsation motions of the phases. For more realistic Lagrangian modelling the turbulent plasma jets with an admixture of inertia particles, it is desirable to combine simultaneously two approaches: (i) - Lagrangian Stochastic Deterministic model and (ii) - Lagrangian modelling of representative ensemble of single particles with account for their complex aggregate state in-flight.

It is necessary to carry out the experimental examination of a number of modelling plasma jets with the addition of inertia particles to obtain a representative set of the experimental data, characterising the distribution of the parameters of the gas and particles in cross-sections of flow. This would enable the mutual comparison of various physico-mathematical models. Taking into account the extremely high labour content of formulating physical experiments for 3d - flows, this problem should be solved initially for the case of axially symmetric heterogeneous plasma jet.

Acknowledgement

This work was supported by the Russian Foundation for Basic Research, Grant No.96-02-19051 and by European Commission, Grant INTAS-94-1766.

References

1. O.P.Solonenko. *Pure & Appl. Chem.*,**62, 9,** 1783-1800 (1990).
2. Dilawari, J.Szekely and R.Westhof. *Plasma Chemistry and Plasma Processing*, **10, 4,** 501-514 (1990).
3. J.D.Ramshaw and C.H.Chang. *Plasma Chemistry and Plasma Processing*, **13, 2,** 189-209 (1993).
4. J.R.Fincke, W.D.Swank and D.C.Haggard. *Unpublished* (Analized in Ref.2).
5. M.Brossa and E.Pfender. *Plasma Chemistry and Plasma Processing*, **8, 1,** 75 (1988).
6. P.C.Huang, J.Heberlein, E.Pfender, *Plasma Chemistry and Plasma Processing,* **15, 1,** 25-46 (1995).
7. O.P.Solonenko and A.L.Sorokin, *Ann. Program of 3rd International Workshop "Thermal Plasma Torches and Technologies",* p.51. 25-29 Aug. 1997, ITAM, Novosibirsk, Russia.
8. J.McKelliget, J.Szekely, M.Vardelle and P.Fauchais. *Plasma Chemistry and Plasma Processing*, **2, 3,** 317-332 (1982).
9. N.El-Kaddah, J.McKelliget and J.Szekely. *Metallurgical Transactions B*, **15B, March,** 59-70 (1984).
10. P.Proulx, J.Mostaghimi and M.Boulos. *Int. J. Heat Mass Transfer*, **28, 7,** 1327-1336 (1985).
11. D.Milojevic, O.P.Solonenko and G.M.Krylov. *Transfer Processes in Single- and Two-Phase Media.* pp.70-80. ITF SO RAN SSSR, Novosibirsk (1986) (in Russian).
12. G.M.Krylov and O.P.Solonenko. In *Proc. of 8th Intern. Symp. on Plasma Chem.*, Tokyo, Japan, **1,** 75-80 (1987).
13. O.Simonin, P.L.Viollet and N.Mechitoua.. In *Plasma Jets in the Development of New Materials Technology* (O.P.Solonenko and A.I.Fedorchenko, eds.), pp.3-16. VSP, Utrecht (1990).
14. M.F.Zhukov and O.P.Solonenko. *High-Temperature Dusted Jets in the Powder Materials Processing,* ITF SO RAN SSSR, Novosibirsk (1991) (in Russia).
15. J.Szekely and R.C.Westhoff. In *Thermal Plasma Applications in Materials and Metallurgical Processing*, pp.55-73. TMS, Pennsylvania (1992).
16. P.Lj.Stefanovic, P.B.Pavlovic, Z.G.Kostic and S.N.Oka. *J. of High Temperature Chemical Processes*, **Supplement au Vol.1, 3,** 359-366 (1992).
17. P.B.Pavlovic, G.S.Zivkovic, P.Lj.Stefanovic and A.V.Saljnikov. *J. of High Temperature Chemical Processes*, **Supplement au Vol.1, 3,** 381-388 (1992).
18. S.-W.Nam, M.Okubo, H.Nishiyama and Shin-ichi Kamiyama. *Heat Transfer - Japanese Research*, **22, 5,** 493-505 (1993).
19. P.Stefanovic, P.Pavlovic, Z.Kostic and S.Oka. In *Heat and Mass Transfer Under Plasma Conditions*, (P.Fauchais, ed.), pp. 169-176. Begell House, Inc., New York (1995).
20. O.P.Solonenko. *Thermal Plasma and New Materials Technology. Vol.2: Investigation and Design of Thermal Plasma Technologies* (O.P.Solonenko and M.F.Zhukov eds.), pp.7-97. Cambridge Intersience Publishing, Cambridge, England (1995).
21. H.Nishiyama, T.Saito ans Shin-ichi Kamiyama. *Plasma Chemistry and Plasma Processing*, **16, 1,** 265-286 (1996).
22. F.I.Frankl. *Dokl. AN SSSR*, **92, 247** (1953) (in Russian).
23. A.K.Dyunin. *Mechanics of Snow-storms*, SO RAN USSR, Novosibirsk (1963) (in Russian).
24. A.K.Dyunin, Yu.T.Borshchevsky and P.Yu.Yakovlev. *Fundamentals of Mechanics of Multicomponent Flows.* Nauka Publishing, Siberian Division, Novosibirsk (1963) (in Russian).
25. O.N.Lebedev and O.P.Solonenko. *Izv. SO RAN USSR, Ser. tekh. nauk.* 1980, **13, iss.3,** 117-125 (1980) (in Russian).
26. O.N.Lebedev and O.P.Solonenko. *Fluid Mech. Sov. Res.* **9, 5,** 55-66 (1980).
27. O.P.Solonenko. In *Werkstofftechnologie auf dem Weg in das 21. Jahrhundert: Vortrage und Veroffentlichungen des gleichnamigen 15. Dortmunder Hochschulkolloquiums am 17 und 18 Oktober 1996 in Dortmund*, pp.33-46. Lehrstuhl fur Werkstofftechnologie, Universitat Dortmund.-Aachen: Mainz (1996).
28. O.P.Solonenko and A.L.Sorokin. In *VDI-Gesellschaft Werkstofftechnik:3rd Europ. Congr. on Thermal Plasma Processes,* pp.129-136. VDI-Verl., Dusseldorf (1995).
29. D.Milojevic. In *Proc. of 2nd Workshop on Two-Phase Flow Prediction,* pp.31-33, Erlangen, Germany (1985).
30. C.T.Crowe, M.P.Sharma and D.E.Stock. *Trans. of ASME, J. Fluids Engineering,* **June,** 325-332 (1977).

31 W.H.Snyder and J.L.Lumley. *J.Fluid Mechanics*, **48,** 41-71 (1971).

32. M.Vardelle, A.Vardelle and P.Fauchais. In *Proc. of 10th Intern. Thermal Spray Conf.*, Essen, Germany, 89-92 (1983).