SWIRLING TWO-PHASE TURBULENT JET IN SYSTEMS OF COMBUSTION

(INTEGRAL METHOD FOR NUMERICAL INVESTIGATION)

Nguyễn Thanh Nam
Trường Đại Học Kỹ Thuật
Hoàng Đức Liên
Khoa Cơ Điện - Trường Đại Học Nông Nghiệp Hà Nội
(Bài nhận ngày 06/10/1998)

ABSTRACT : The solution of a swirling two-phase turbulent jet is done on the basic equations of quantity, moment of quantity, particle content and turbulent energy. A so called "two-fluid" scheme of the stream is used, where the second phase (liquid or solid) is treated as a continuous environment with no tensor of inner stresses attributed. That's how a mathematical model at most close to the physical nature of the flow is made and its' numerical results become applicable in designing system of combustion, engineering practices, etc.

SYMBOLS

$u_{i\,(i=p,g,o,m)}$ - Axial components of Velocity $p_{i\,(i=\infty,o,min)}$ - Pressures

$w_{i\,(i=p,g,o,m)}$ - Tangential components of Velocity I_o, M_o- Quantity&Moment of quantity of motion

G_o - Initial specific weight $R_{i\,(i=u,p)}$- Boumdary layer (dynamic & diffusion)

$\chi_{i(o,m)}$ - Concentrates x, r, θ- Coordinates of Cylindrical Coor. System.

$l_{i\,(i=u,p)}$ - Mixing length (dynamic & diffusion) D_p - Massiveness of fraction

Re, Sc - Reynold & Schmidth numbers S_o - Initial swirling degree

$_{p,\ g,\ o,\ max}$ - symbols of admixture; gas; in the initial section; max. values

INTRODUCTION

The swirling two-phase turbulent jets find application in the modern technologies and technological devices as dust-suction, agricultural technique, in the food processing industry and chemical industry machinery in fire-extinguishing, etc. Particularly in combustible technique the swirling two-phase turbulent jet is widely used as control facility for the size of a flame, its' form, effective and clean combustion because it allows to reduce length of a flame (respectively size of combustible chambers) at expense of increasing speed injection air from environment and increasing intensity of the process mixing; to increase stability of a flame thanking to the good prepared products for combustion; to increase the life of equipment, to reduce the fuel consumption and environmental pollution as the stabilisation comes true.

In systems of combustion the ejecting devices are requested to ensure the main requirements of combustion as high efficiency; easily ignition; steady work; low issue of pollution substance; small consumption of fuel; acceptable size of the chamber of combustion..., and the fuels (especially liquids) have to be very good fractionalised and mixed with the air in the suitable ration of burning. The above mentioned requirements of the combustible system should be satisfied by ejection a swirling two-phase (fuel-air) turbulent jet.

Regarding methods applied for designing systems of combustion, beside a long and very expensive experimental models, the mathematical & numerical models are recognised and become standard method for investigation. The computer programmes are successfully applied in engineering practice because they need minimum preliminary input information.

In conformity with [1], such streams arise both in the case of out-flowing of an advance prepared two-phase mixture and also when spraying a liquid jet in a gas environment. In this work an integral method for investigation is suggested, basing on the basic integral equations, which characterise the distribution of a swirling two-phase turbulent jet. When working out the mathematical model a two-fluid scheme of a stream is used [2]. the second, the transported phase (solid fractions or liquid drops) is treated as a continuum by analogy with the transporting gas. Anagogic equations for motion, respectively integral conditions are valid for it. In actual fact this means that it's possible to write for the second phase the integral conditions for the quantity and moment of quantity of motion, for the turbulent energy, etc.

A characteristic feature of the swirling turbulent jets is the presence of a condition for holding the moment of quantity of motion too. It reveals the nature of the process of swirling - a product of the mass flow in a fixed point *(ρurdr)* multiplied by the swirling (tangential) velocity *w* and the radius *r*.

SYSTEM INTEGRAL EQUATIONS

When working out the integral conditions of a swirling two-phase turbulent jet, the authors, by contrast with [3], [4], proceeded from the circumstance that the stream of the two phases is united, and has a total quantity of motion and a moment of quantity of motion for the two phases. The so adopted model is suitable for solving whole spectrum of problems for liquid spraying in gas environment until out flowing of the advanced prepared two phase mixture. In that case later on the initial moment and quantity of motion redistribute between the two phase along the stream and part of them is gone for ejecting, accelerating and swirling of the gas fraction transported in motion.

The forces of in phase interaction nullify (one another) when uniting the moment and quantity of motion but this does not lead to reduction of the solution correctness, because they are given in the equations of turbulent gas energy and particles. The differential equation of cross pressure distribution is added to the integral conditions, and it gives the relation *p* on *w*, and the relation between quantity and the moment of quantity of motion is carried out by *p*.

The system of integral equations, describing a swirling two-phase turbulent jet is:

$$\int_0^{\infty}(\rho_g u_g^2 r + p r)\, dr + \int_0^{\infty}\rho_p u_p r\, dr = I_o \qquad (1)$$

$$\int_0^{\infty}\rho_g u_g w_g r^2\, dr + \int_0^{\infty}\rho_p u_p w_p r^2\, dr = M_o \qquad (2)$$

$$\int_0^{\infty}(\rho_g \chi u_p r)\, dr = G_o \qquad (3)$$

$$\frac{\partial}{\partial x}\int_0^{\infty}(\rho_g u_g^3 r)\, dr + \int_0^{\infty} 2 u_g \frac{\partial p}{\partial x} r\, dr = -\int_0^{\infty} 2\rho_g r \nu_{tg} \left(\frac{\partial u_g}{\partial r}\right)^2 dr - \int_0^{\infty} 2 u_g F_x r\, dr \qquad (4)$$

$$\frac{\partial}{\partial x}\int_0^{\infty}(\rho_p u_p^3 r)\, dr = -\int_0^{\infty} 2\rho_p r \nu_{tp} \left(\frac{\partial u_p}{\partial r}\right)^2 dr + \int_0^{\infty} 2 u_p F_x r\, dr \qquad (5)$$

$$\frac{\partial}{\partial x}\int_0^{\infty}(u_p \chi^2 r)\, dr = -\int_0^{\infty} 2\rho_g r \frac{\nu_{tp}}{S_c} \left(\frac{\partial \chi}{\partial r}\right)^2 dr \qquad (6)$$

$$\frac{\partial p}{\partial r} = \rho_g r\left[\frac{w_g^2}{r}\right] \qquad (7)$$

Equations (1) and (2) describe holding the quantity and moment of quantity of motion and equation (3) the particle content in the stream. The turbulent energy of the gas environment and particles (the drops) are expressed in equation (4) and (5). Equation (6) is an integral condition of a higher rank without a clearly stated physical interpretation. The relation between p and w is given in the differential equation (7).

Boundary Conditions:

- In the axis of the flow ($r = 0$):

$$\frac{\partial u_g}{\partial r} = \frac{\partial u_p}{\partial r} = 0\,; \quad \frac{\partial \chi}{\partial r} = 0\,; \qquad (8)$$

$w_p = w_g = 0$;

- On the boundary layer ($u_i = 0$):

$$w_g = w_p = 0\ ;\quad u_p = u_g = 0\ ;\ p = 0 \qquad (9)$$

Initial Values:

$u_{io} = u_o;\ \chi_o = \rho_p/\rho_g;\ w_o = S_o u_o;$ (10)

Where S_o is initial swirling factor: $S_o = M_o/(I_o r_o)$

The values of initial integral parameters are given in table 1.

Table 1

Parameter	*common case*	*fluid running in gas*	*gas running in fluid*
M_o	$\rho_g(1+\chi_o)u_o w_o r_o^3 \beta_1$	$\rho_g \chi_o u_o w_o r_o^3 \beta_1$	$\rho_g u_o w_o r_o^3 \beta_1$
I_o	$\rho_g(1+\chi_o)u_o^2 r_o^2 \beta_2$	$\rho_g \chi_o u_o^2 r_o^2 \beta_2$	$\rho_g u_o w_o r_o^2 \beta_2$
G_o	$\rho_g \chi_o r_o^2 \beta_3$	$\rho_g \chi_o r_o^2 \beta_3$	

β_1, β_2, β_3 - are analogical to the Businex coefficient giving correspondingly the initial irregularity of velocity and particle distribution. The concentration is written as a local ratio $\chi=\rho_p/\rho_g$; respectively initial $\chi_o=\rho_{po}/\rho_{go}$ Schmidth's turbulent number as per [1] is:

$$S_c = S_{cg}(1 + \sqrt{1+\zeta_o}))$$

ζ_o is an adjusted initial particle concentration which is expressed by the following ratio:

$$\zeta_o = \chi_o / (1 + \chi_o)$$

It is considered that $S_{cg} = 0{,}75$ in the investigation [1].

The turbulent energy equations (4) ÷ (6) require using a suitable turbulence model for completing the system of equations.

In our previous equations an analogue to Shetz's model is suggested [6] and after it:

$$\nu_{tg} = k\, R_u\, u_{gmax}$$

$$\nu_{tp} = k\, R_u\, u_{pmax}$$

The coefficient k, by contrast with [2] is not constant. It is admitted, that the influence of the second phase of turbulent stresses is analogous to the influence over the coefficient of resistance of the moving particle [5]:

$$k = B(1 + b_1 R_{ep}^{0.5} + b_2 R_{ep})$$

Where $B = 0.01 \div 0.03;\ R_{ep} = u_{po}D_p/\nu;\ b_1 = 0.179;\ b_2 = 0.013.$

The following prerequisites are necessary when solving the integrals in equations (1÷7):

It is assumed that the cross dimensionless distribution of the velocity of the two phase is described by an universal relation and in the functions of $\eta = r/x$ as follows:

- For the axial velocity components u_p and u_g:

$$u_i/u_{imax} = exp(-k_u \eta^2); \qquad (11)$$

- For the swirling (tangential) velocity components w_p and w_g :

$$w_i/w_{imax} = C\eta + D\eta^2 + E\eta^3; \qquad (12)$$

- For the pressure:

$(p - p_\infty)/(p_{min} - p_\infty) = exp(-k_u\eta^2);$ (13)

- For the concentration of particles:

$\chi/\chi_{max} = exp(-k_\chi\eta^2);$ (14)

The relations, describing the dimensionless cross distribution are after [7] and their constants are given in table 2:

Table 2

k_u	k_p	k_χ	S_o			0.066<	0.066÷0.134	0.134÷0.234	>0.234
$\frac{92.0}{1+6S_o}$	$\frac{150.0}{1+8S_o}$	$S_c k_u$	$\frac{M_o}{I_o R_o}$			7.7 71.5 -542.0	10.7 20.0 -326.0	18.1 -98.8 138.0	15.1 67.2 75.4

Since $S' = w_{gmax}/u_{gmax} = \overline{S_o}'/\overline{R_u} = w_{go}/(u_{go}R_u)$ the following relation between dirnentionless values of u_{gmax} and w_{gmax} is written:

$\overline{w}_{gmax} = \overline{R}_u \overline{u}_{gmax}$ (15)

As we know the dynamic and diffusion boundary layers are not identical i.e . $\overline{R}_u \neq \overline{R}_p$ Their ratio is determined on the base of Schmidth's turbulent number S_c. It is assumed, that the ratio of the dynamic l_u, and diffusion l_p mixing-length of the boundary layer, remains constant :

$l_u/R_u = l_p/R_p = idem$ or

$R_u/R_p = l_u/l_p = S_c$ and therefore :

$R_u = S_c R_p$ (16)

SYSTEM ALGEBRICAL EQUATIONS & NUMWRICAL RESULTS

Having solved the integrals and done the revision and dimentionlessness we come to the following system of equations that describes swirling diffusion outflowing jet in the system of equations:

$A_1\overline{u}^2_{gmax}\overline{x}^2 - B_1\overline{P}_{min}\overline{x}^2 + A_3\overline{u}^2_{pmax}\overline{\chi}_{max}\overline{x}^2 = I_1$ (17)

$A_2\overline{u}_{gmax}\overline{w}_{gmax}\overline{x}^3 + A_4\overline{u}_{pmax}\overline{\chi}_{max}\overline{w}_{pmax}\overline{x}^2 = M_1$ (18)

$A_3\overline{u}_{pmax}\overline{\chi}_{max}\overline{x}^2 = G_1$ (19)

$\overline{p}_{min} = A_{66}\overline{w}^2_{gmax} + B_{66}\overline{\chi}_{max}\overline{w}^2_{pmax}$ (20)

$\partial(A_7\overline{u}_{pmax}\overline{\chi}^2_{max}\overline{x}^2)/\partial\overline{x} = -B_7\overline{u}_{pmax}\overline{\chi}^2_{max}\overline{R}_u$ (21)

$\partial(A_8\overline{u}^3_{gmax}\overline{x}^2)/\partial\overline{x} - B_8\overline{u}_{gmax}\partial(\overline{p}_{min}\overline{x}^2)/\partial\overline{x} = -C_8\overline{u}^3_{gmax}\overline{R}_u - D_8\overline{\chi}_{max}\overline{u}_{gmax}(\overline{u}_{gmax} - \overline{u}_{pmax})^2\overline{x}^2$ (22)

$\partial(A_9\overline{u}^3_{pmax}\overline{x}^2)/\partial\overline{x} = -C_6\overline{u}^3_{pmax}\overline{\chi}_{max}\overline{R}_u + D_8\overline{\chi}_{max}\overline{u}_{pmax}(\overline{u}_{gmax} - \overline{u}_{pmax})^2\overline{x}^2$ (23)

$\overline{u}_{gmax} = \overline{R}_u\overline{w}_{gmax}$ (24)

$R_p = R_u/S_o$ (25)

The coefficients in the system of equation (11-19) are given in table 3-a and 3-b. Dimentionlessness is done like this:

$\overline{x} = x/r_o$; $\overline{R}_u = R_u/r_o$; $\overline{R}_p = R_p/r_o$; $\overline{u}_{gmax} = u_{gmax}/u_o$; $\overline{u}_{pmax} = u_{pmax}/u_o$;

$w_{pmax} = w_{pmax}/w_o$; $w_{gmax} = w_{gmax}/w_o$; $p_{min} = (p_{min} - p_\infty)/ p_{omin} - p_\infty)$

The system equations can be solved numerically using a computer programme. On the basis of the numerical investigation we get information for the change in the basic parameters of a swirling two phase turbulent jet. The input data are the initial swirling degree S_o , initial particle concentration χ_o, massiveness of the fractions (drops) D_p, initial stream velocities u_o, w_o. The coefficient B may vary in the limits, mentioned above. As we notice, the so described mathematical model of stream and its numerical realisation require very little input information which makes it applicable in engineering calculations.

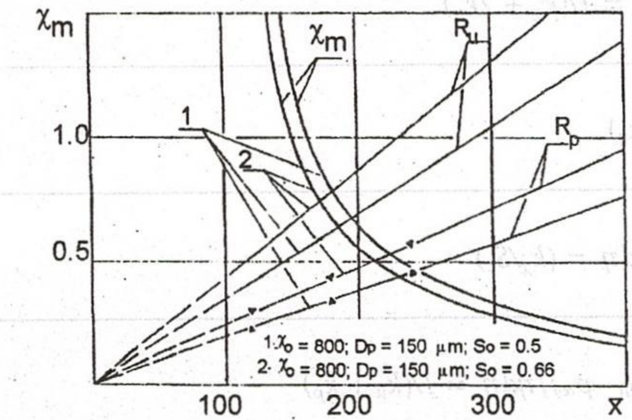
Table 3-a

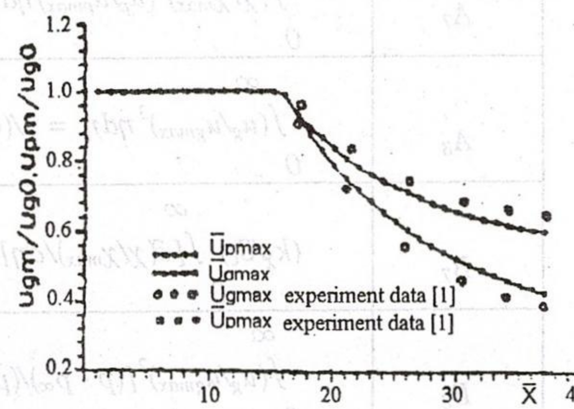
Coefficient	Values
A_1	$\int_0^\infty (u_g/u_{gmax})^2 \eta d\eta = 1/(4k_u)$
B_1	$\int_0^\infty [(p - p_\infty)/(p_{min} - p_\infty)]^2 \eta d\eta = 1/(k_p)$
A_3	$\int_0^\infty (\chi/\chi_{max})(u_p/u_{pmax}) \eta d\eta = 1/(k_\chi + 2k_u)$
A_2	$\int_0^\infty (u_g/u_{gmax})(w_g/w_{gmax}) \eta^2 d\eta = C/(k_u)^2 + 1.33\, D / (k_u)^{2.5} + 2\, E / (k_u)^3$

Table 3-b

Coefficient	Values
A_4	$\int_0^\infty (\chi/\chi_{max})(u_p/u_{pmax})(w_p/w_{pmax})\eta^2 d\eta = C/(k_\chi + k_u)^2 + 1.33D/(k_\chi + k_u)^{2.5} + 2E/(k_\chi + k_u)^3$
A_5	$\int_0^\infty (\chi/\chi_{max})(u_p/u_{pmax})\eta d\eta = 1/(k_\chi + k_u)$
D_3	$\int_0^\infty k_x(\chi/\chi_{max})(u_p/u_{pmax})\eta d\eta = k_\chi/(k_\chi + 2k_u)$
A_7	$\int_0^\infty (\chi/\chi_{max})^2(u_p/u_{pmax})\eta d\eta = 1/(k_\chi + 2k_u)$
A_8	$\int_0^\infty (u_g/u_{gmax})^3 \eta d\eta = 1/(6k_u)$
B_7	$(k_\chi/S_c) \int_0^\infty [\partial(\chi/\chi_{max})/\partial\eta]\eta d\eta = (k_\chi/S_c)$
B_8	$\int_0^\infty (u_g/u_{gmax})^2[(p - p_\infty)/(p_{min} - p_\infty)]\eta d\eta = 1/(k_u + k_p)$
C_6	$\int_0^\infty [\partial(u_g/u_{gmax})/\partial\eta]^2 \eta d\eta = k_\chi$
D_8	$k_\chi \int_0^\infty (\chi/\chi_{max})(u_g/u_{gmax})^2 \eta d\eta = k_\chi/(k_\chi + 3k_u)$
A_9	$\int_0^\infty (\chi/\chi_{max})(u_p/u_{pmax})^3 \eta d\eta = 1/(k_\chi + 3k_u)$
C_9	$\int_0^\infty [\partial(u_p/u_{pmax})/\partial\eta]^2(\chi/\chi_{max})\eta d\eta = (4k_\chi k_u^2)/(k_\chi + 2k_u)^2$
A_{66}	$2(w_o/u_o)^2 \int_0^\infty (w_g/w_{gmax})^2[(p_\infty - p)/(p_\infty - p_{min})]d\eta/\eta$
A_{66}	$2(w_o/u_o)^2 \int_0^\infty (w_g/w_{gmax})^2[(p_\infty - p)/(p_\infty - p_{min})] (\chi/\chi_{max})d\eta/\eta$

For the purpose of demonstration applicability of swirling two phase turbulent jet, a comparison with own experimental results is done after [8],[9]. Unfortunately, because of the undoubted difficulty when measuring and lack of the necessary Laser-Doppler device a comparison is possible only in the parameter of the diffusion boundary layer growing i.e. an expansion in the particles jet R_p. On figure 1 there is a parallel between R_p and experimental data for two values of swirling $S_o = 0.5$ and $S_o = 0.66$, water spraying in air environment using swirling mechanism for axial and tangential liquid out-flowing jet. The mean massiveness of the drops is about $150\mu m$. A good conformity between the numerical results and the experimental data presents on the figure. For the rest parameters there are not any own data to make the parallel. The comparison of numerical result for u_{pmax}, u_{pmax} ($\chi_o=1.0$; $D_p=45\mu m$; $u_{go}=u_{po}=35m/s$; $\rho_{go}=1.16kg/m3$; $\rho_{po}=3950kg/m^3$) with experimental data [1] is made for S_o=0 on fig. 2. The good conformity between the values proves practical application of the numerical results.





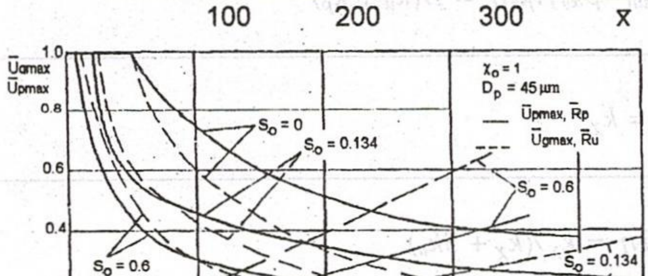


Fig. 3

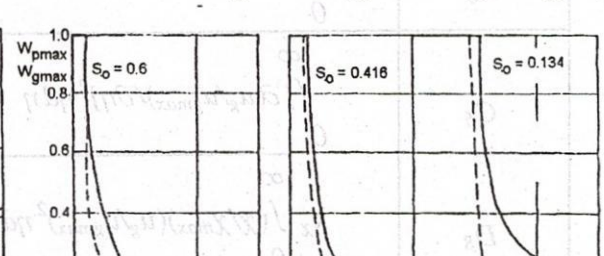


Fig 4

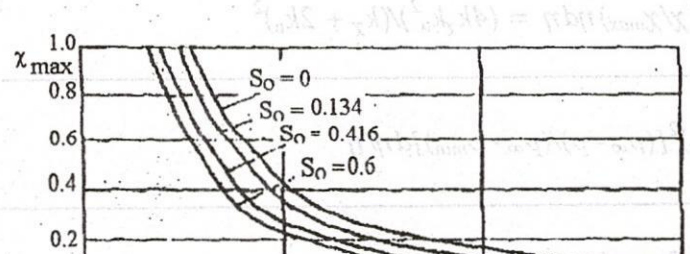


Fig. 5

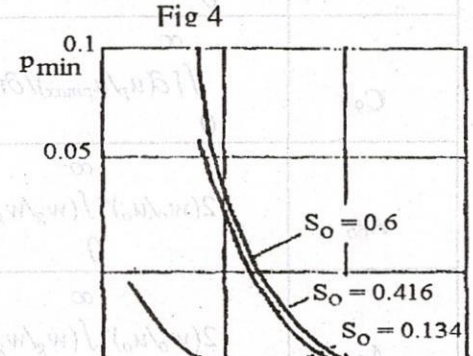


Fig. 6

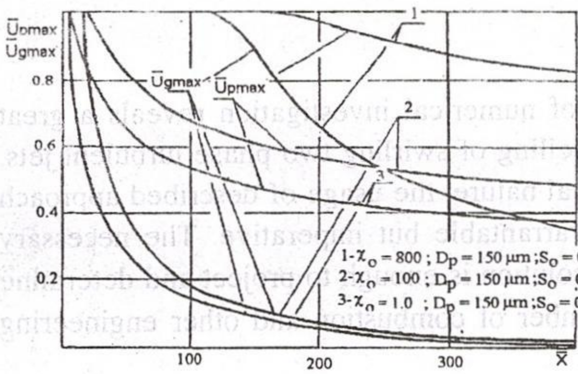


Fig. 7

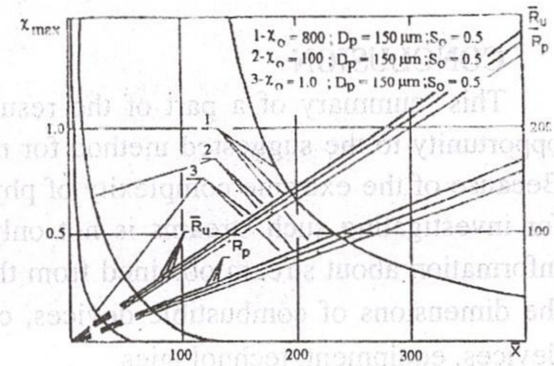


Fig. 8

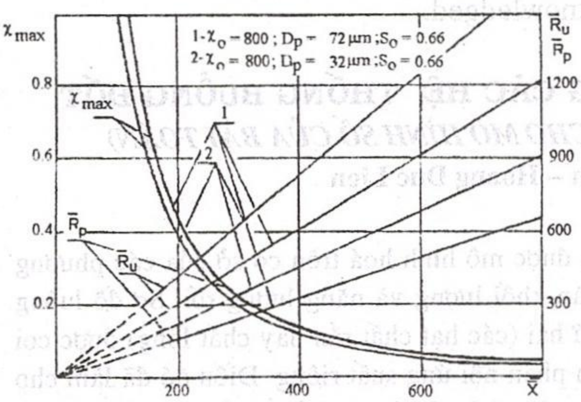


Fig.9

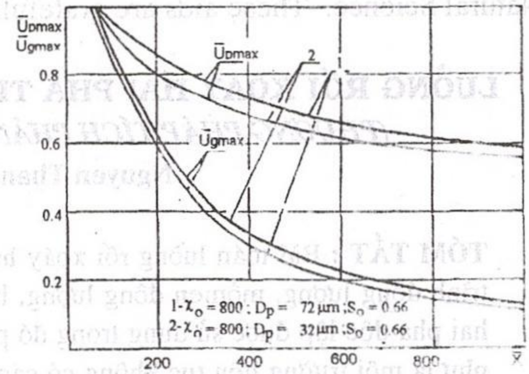


Fig. 10

ANALYSIS

Results of the numerical investigation of a two phase stream with low initial concentration of the particles $\chi_o = 1$ and massiveness of the fractions D_p are shown on figures 3÷6. The change in the swirling degree in the limits of $S_o = 0$ till $S_o = 0.6$ shows the following : while increasing S_o the velocity components for the two phases and the concentration of particles decay faster and the jet boundary layers expand intensively (in the combustible chamber it means decreasing lengths of a flame at expense of increasing speed injection air from environment and increasing intensity of the process mixing). An important feature of the swirling turbulent jets becomes visible on these figures - the opportunity to control the jet front (the extent of its vertical section) and the decaying of velocity components. The velocities of gas phase decay faster in comparison with the ones of particles $u_g < u_p$, respectively w_g to w_p. This means a presence of skid velocity between particles and gas. The decay of min pressure p_{min} in function of S_o and x is shown on figure 6.

The influence of initial concentration is illustrated on fig. 7 and 8 where we see that decrease of χ_o leads to a faster decaying of max values of velocity components for the two phases and concentration and to a faster expansion of the boundary layer of gas phase and to a narrow diffusion layer.

Increase on fraction massiveness (fig. 9, 10) leads to a slower decaying of particle velocity, accelerates decaying of gas velocity. While increasing D_p the diffusion boundary layer contracts, and the one of gas phase extends.

CONCLUSION

This summary of a part of the results of numerical investigation reveals a great opportunity to the suggested method for modelling of swirling two phase turbulent jets. Because of the extreme complexity of physical nature, the usage of described approach for investigating such streams is not only warrantable but imperative. The necessary information about stream obtained from the solution is enough to project and determine the dimensions of combustible devices, chamber of combustion and other engineering devices, equipment, technologies.

The work was supported by Vietnam National Foundation, for Basis Research on Natural Science. These aids are gratefully acknowledged.

LUỒNG RỐI XOÁY HAI PHA TRONG CÁC HỆ THỐNG BUỒNG ĐỐT

(PHƯƠNG PHÁP TÍCH PHÂN SỐ CHO MÔ HÌNH SỐ CỦA BÀI TOÁN)

Nguyen Thanh Nam – Hoang Duc Lien

TÓM TẮT : Bài toán luồng rối xoáy hai pha được mô hình hoá trên cơ sở của các phương trình động lượng, mômen động lượng, bảo toàn khối lượng và năng lượng rối. Sơ đồ luồng hai pha độc lập được sử dụng trong đó pha thứ hai (các hạt chất rắn hay chất lỏng) được coi như là môi trường liên tục không có các thành phần nội ứng suất riêng. Điều đó đã làm cho mô hình toán học của luồng có thể phản ánh một cách chính xác bản chất vật lý của dòng chảy, đồng thời tạo cho mô hình số một giá trị thực tế trong thiết kế các hệ thống buồng đốt cũng như trong thực tế của các thiết bị công nghệ khác sử dụng kiểu luồng rối xoáy hai pha

TÀI LIỆU THAM KHẢO

[1] Abramovich, I.P., T.A. Grishovich, S.Y. Krashninakov, A.N. Sekulidov, I.P. Sinimova *Theory of the turbulent jets,* Moscow, Nauka, 1984, in Rusian.

[2] Schetz J.A., Injection and mixing in turbulent flow. *Process in Astronauts and Aeronautics,* Vol. 68, New York, 1980.

[3] Antonov, I.S., N.T. Nam Two-fluid integral method for numerical investigation of a two-phase turbulent swirling jet. *News for "Lenin" VMEI,* 1990. in Bulgarian.

[4] Nam N.T., I.S. Antonov, About an approximate model of a two-phase turbulent swirling jet. *News for "Lenin", VMEI,* 1990, in Bulgarian.

[5] Antonov I.S., N.T. Nam, Numerical methods of a two-phase turbulent swirling *jet, Int. Symp. on Hydro- and Aerodynamics in Marine Engineering, HADMAR'91,* Vama, Bulgaria, 28 Oct.-1st Nov., 1991, Proceedings, Vol.1.

[6] Schreiber, A.A., L.B. Gavin, V'.N. Naumov, V.P. Latsenko, *Turbulent flows in gas-particle mixtures,* Kiev, Naukova dumka, 1987, in Russian.

[7] Gupta, A.K., D.S. Lilley, N. Syred, *Sivirl Flows,* Abacus Press. 1984.

[8] Antonov I.S., I.P. Donchev, N.T. Nam. Integral investigation of a swilling two-phase (water-air) turbulent jet. *Mechanical Engineering,* 1986, issue 7, in Bulgarian.

[9] Donchev I.P., Model investigations and creating a regulated centrifugal-jet fire extinguishing device, *Autoesay on a dissertation,* 1985, in Bulgarian.