Vietnam Journal of Mechanics, NCST of Vietnam Vol. **23**, 2001, No 2 (87 – 94)

CALCULATION OF TURBULENT DIFFUSION JETS UNDER EFFECTS OF GRAVITY AND MOVING SURROUNDING AIR

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ABSTRACT. The basis theory for the turbulent diffusion of jet and flame has been presented previously [1, 2]. But that one applies only in quiet surrounding air with the effects of buoyancy neglected. In the present paper the theory is developed further by establishing an integral model for a jet in more general conditions with variable inclined angles, under effects of gravity and surrounding air velocity in any direction compared to the jet axis. The system of equations is closed by turbulence k-ε model and is solved by 4^{th} order Runge-Kutta method. In the first stage, the model is applied to predict the velocity field, the concentration field and width development of a 0.3 m diameter jet.

1. Introduction

As compared to a premixed combustion process, the diffusion flame combustion of a nonpremixed mixture is process mainly controlled by the mass transfer of fuel and air comming from two separate sources. Considerations so far have provided little or no insight into the mechanism of the mass transfer but the most important point is how to determine the fuel distribution in diffusion jet. Then, basing on the distribution we can calculate both the combustion velocity and the formation of pollutants. Moreover, although turbulent diffusion flame are in common use, due to the lack of mathematical solution, many scientists have relied upon practical methods for determining the mechanism of mass transfer in order to improve the diffusion process and limit pollution emission.

Experimental measurement in the turbulent diffusion combustion process is considered to be very difficult and even impossible in some cases. So, mathematical modeling of the diffusion combustion process bears a great practical significance. This allows us to predict the phenomena occurring in turbulent diffusion flames then control them in the same way as we do with the premixed flames.

For the purpose of modeling the turbulent diffusion flame, a model of a turbulent jet has to be established. One-dimensional Integral models were established and analysed for calculation of vertical turbulence diffusion jet in still air by many authors [1]. On the base of these researches, a model of vertical turbulent diffusion flames in still air was established to calculate the pollutants exhausted from industrial chimneys as well as from the smoke of pool fires [2, 3]. Additionally, it was possible to calculate the turbulent process and formation of soot in Diesel engine [4] and NO_2 in a separate combustion chamber but neglecting swirl effects [5].

The assumption of stationary air surrounding turbulent jet plus the omission of gravitational for the purpose of simplifying the calculation sometimes causes trouble in the case of the swirl combustion chambers since the turbulent jet is strongly influenced by these factors. So, establishing a mathematical model to calculate the structure of a general diffusion jet with different inclined angles in moving air will enhance practical application of the model. In this paper we will firstly consider the general diffusion jet in order to calculate the concentration field in a turbulent diffusion jet. We believe this better simulates the fire working condition in an engine thus making the combustion process more precise.

2. Establishing Equations

Equations describing the general laminar jet (Fig. 1) are

$$\frac{d\dot{m}}{ds} = \frac{\dot{W}_g/\hat{U} + 2\pi R\rho_\infty\beta|\hat{U} - U_\infty\cos\theta|}{2 - U_\infty\cos\theta/\hat{U}}, \tag{2.1}$$

$$\frac{dW}{ds} = \dot{W}_g + U_\infty\cos\theta\frac{d\dot{m}}{ds}, \tag{2.2}$$

$$\dot{m}\hat{U}\cdot\frac{d\theta}{ds} = \pi R^2(\rho_\infty - \langle\rho\rangle)g\cos\theta - U_\infty\sin\theta\cdot\frac{d\dot{m}}{ds}, \tag{2.3}$$

where

$$W = 2\pi\int_0^\infty \overline{\rho}U^2 r\cdot dr, \tag{2.4}$$

$$\dot{m} = 2\pi\int_0^\infty \overline{\rho}Ur\cdot dr, \tag{2.5}$$

$$\hat{U} = W/\dot{m}, \tag{2.6}$$

$$R = \dot{m}/\sqrt{\pi\rho_\infty W}, \tag{2.7}$$

$$\beta = 0.23\sqrt{\rho_{st}/\rho_\infty}, \tag{2.8}$$

$$\dot{W}_g = \pi R^2\cdot g\cdot\sin\theta(\rho_\infty - \langle\rho\rangle) \tag{2.9}$$

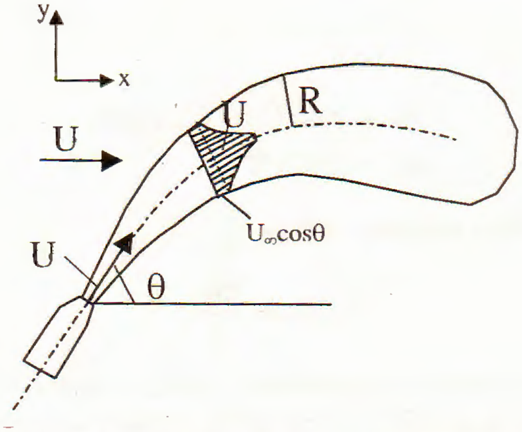

Fig. 1. Scheme of the general diffusion jet

In case of diffusion flux, there is a presence of dynamic turbulent viscosity μ_τ in the mass conservation equation (2.1). By neglecting the influence of acceleration due to gravity and movement of the air, equation (2.1), as described by Tamanini [6], can be written as follows:

$$\frac{d\dot{m}}{ds} = c_k \pi (\mu + \mu_\tau) \tag{2.10}$$

After being derived and re-arranged, equation (2.1) becomes:

$$\frac{d\dot{m}}{ds} = \frac{\dot{W}_g/(2\hat{U}) + \rho_\infty R\hat{U}\beta\pi|1 - U_\infty \cos\theta/\hat{U}|}{1 - U_\infty \cos\theta/(2\hat{U})} . \tag{2.11}$$

On neglecting the influence of acceleration due to gravity ($W_g = 0$), in still air ($U_\infty = 0$) and vertical jet ($\cos\theta = 0$), knowing that $\mu_\tau \sim \rho RU$, we see that the two equations (2.10) and (2.11) are coincided. That allows us to re-write the general mass conservation equation (2.1) as follows:

$$\frac{d\dot{m}}{ds} = \frac{\dot{W}_g/(2\hat{U}) + c_k\pi(\mu + \mu_t)|1 - U_\infty \cos\theta/\hat{U}|}{1 - U_\infty \cos\theta/(2\hat{U})} . \tag{2.12}$$

Equation of momentum conservation (2.2) and equation governing the direction of jet (2.3) are unchanged.

In equation (2.12) dynamic turbulent viscosity μ_τ is allowed for by the use of mass weighted kinetic energy of turbulence k and its dissipation ε:

$$\mu_\tau = c_\mu \cdot \langle\rho\rangle \cdot \frac{k^2}{\varepsilon} \tag{2.13}$$

k and ε can be calculated by the following equations:

$$\frac{d(k\dot{m})}{ds} = P_k - D_k, \tag{2.14}$$

$$\frac{d(\varepsilon\dot{m})}{ds} = \frac{\varepsilon}{k}(c_{\varepsilon_1} P_k - c_{\varepsilon_2} D_k), \tag{2.15}$$

where

$$P_k = \pi\mu_\tau(U_0 - U_\infty \cos\theta)^2, \tag{2.16}$$

$$D_k = \langle\rho\rangle\varepsilon\pi R^2, \tag{2.17}$$

U_c is the maximum axial velocity of flux

$$U_c = \frac{2W}{\dot{m}}. \tag{2.18}$$

In summary, the system of equations, which control the general diffusion jet with different inclined angles in moving air includes 5 equations: (2.2), (2.3), (2.12), (2.14), (2.15). The system of equations is performed by using the 4^{th} order Runge-Kutta method. For all presented results, the nozzle diameters is 0.3 m taken as representative of industrial chimneys.

3. Numerical Results

Figure 2 illustrates the influence of effective exit velocity in case of constant air velocity and gas density is $\rho = 2$ kg/m^3. With a small exit velocity, substances in turbulent jet (their density being more than that of air) will fall down more closely to the source than in the case of strong exit velocity. When changing air velocity we have the same result (Fig. 3). That allows us predict the area that is under influence of pollutants exhausted from industrial chimneys for the purpose of designing chimneys and planning residential areas.

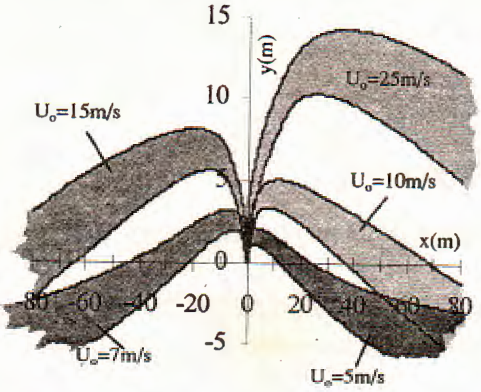

Fig. 2. Influence of exit velocity to jet profile ($U_\infty = 5\,\mathrm{m/s}$; $\rho = 2\,\mathrm{kg/m^3}$; $D = 0.3\,\mathrm{m}$; $\theta = 90°$)

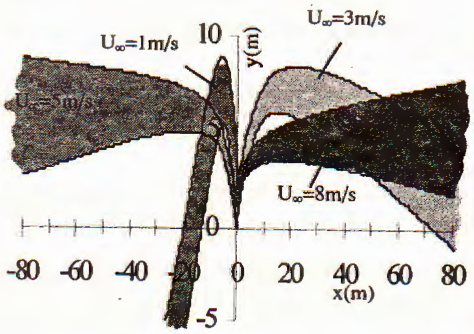

Fig. 3. Influence of air velocity to jet profile ($U_c = 10\,\mathrm{m/s}$; $\rho = 1.5\,\mathrm{kg/m^3}$; $D = 0.3\,\mathrm{m}$; $\theta = 90°$)

The specific density of substance strongly effects the jet profile. In the similar condition, the higher specific density of gas, the polluted area is closer to the nozzle source air due to gravitational acceleration. When the specific density of polluted is smaller than that of air, pollutants will diffuse in the ambient because of gravity acceleration. Fig. 4 illustrates jet profiles for the case of pollutants with different specific densities based on the assumption that the initial concentration of pollutant is unity ($c = 1$). In the practice of industrial chimneys, the initial concentration of pollutants is very small and reduces rapidly because of the air entrainment.

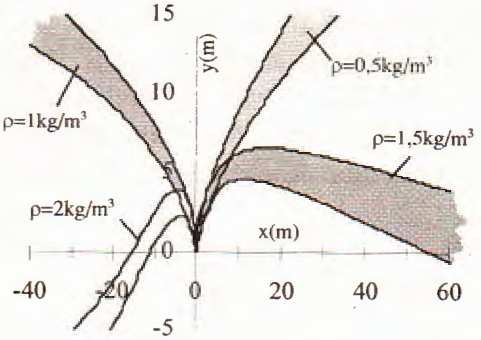

Fig. 4. Influence of specific density of pollutants to jet profile ($U_c = 10\,\text{m/s}$; $\rho = 1.5\,\text{kg/m}^3$; $D = 0.3\,\text{m}$; $\theta = 90°$)

Fig. 5 illustrates the velocity profiles of pollutants inside a diffusion jet for different surround air velocities. The influence of initial exit velocity tends toward reducing along the jet axes farther from jet source where there is only the influence of the surrounding air wind.

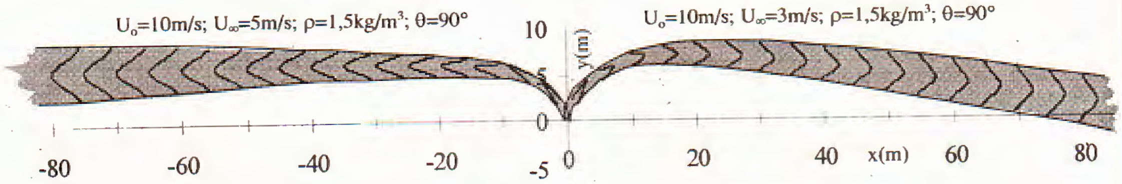

Fig. 5. Influence of set of different factors to jet profile

The pollutant distribution inside a diffusion jet (when its initial concentration $c = 1$) is illustrated in Fig. 6 and Fig. 7. The initial concentration of pollutants rapidly reduces in the direction away from the jet source because of air entrainment.

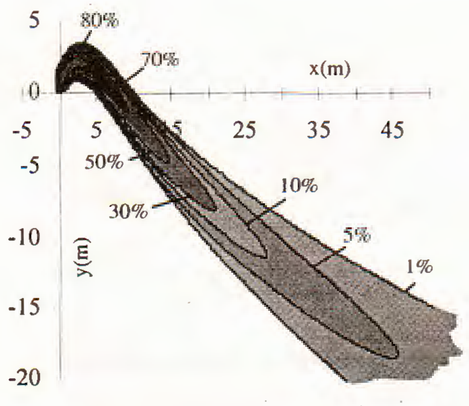

Fig. 6. Concentration distribution in jet ($U_\infty = 1\text{m/s}$; $U_c = 5\text{m/s}$; $\rho = 1.5\text{kg/m}^3$; $D = 0.3\text{m}$; $\theta = 90°$)

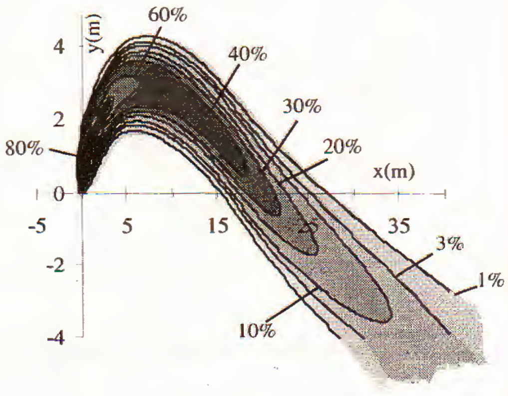

Fig. 7. Concentration distribution in jet ($U_\infty = 3\text{m/s}$; $U_c = 10\text{m/s}$; $\rho = 2\text{kg/m}^3$; $D = 0.3\text{m}$; $\theta = 90°$)

4. Comparison with experimental data

The performance of the model has been evaluated by making comparison with experimental data that were obtained from the smoke-jets with different source diameters, different inclined angles and different air velocities. Comparisons between experimental data on radial velocity and predictions of the model in case of changing inclined angle of jet are shown in Fig. 8. The experimental radial velocities have been measured with 8 nodes over the half-width of the jet and a maximum radial step size corresponding to 5% of the current radius of the flow. Fig. 9, Fig. 10 and Fig. 11 illustrate the comparisons that are performed by changing source diameter, exit

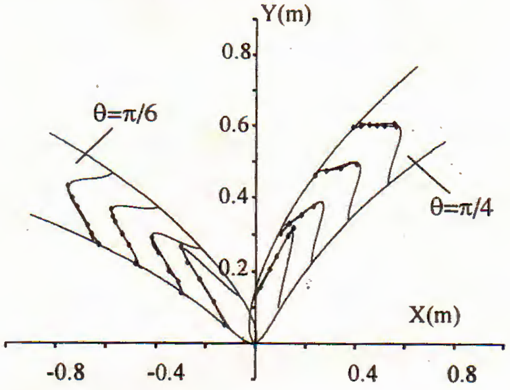

Fig. 8. Comparison of radial profiles of axial velocity measured experimentally and calculated. Exit velocity: 40m/s; Air velocity: 2.2m/s; Jet diameter: 0.01m

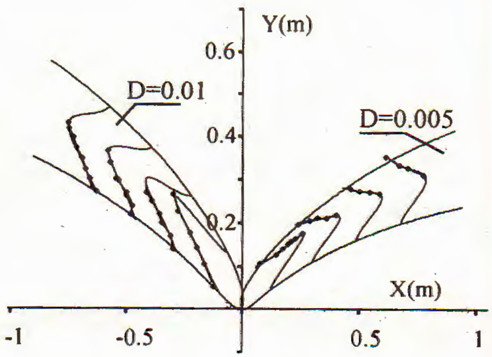

Fig. 9. Comparison of radial profiles of axial velocity measured experimentally and calculated. Exit velocity: 40m/s; Air velocity: 2.2m/s; Inclined angle: $\theta = \pi/3$

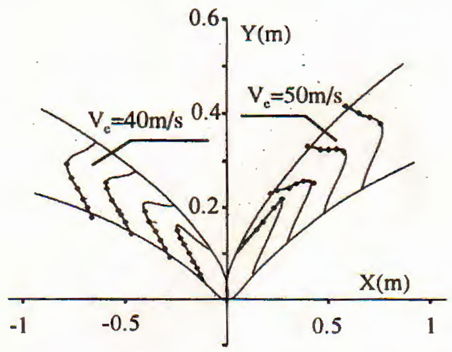

Fig. 10. Comparison of radial profiles of axial velocity measured experimentally and calculated. Jet parameters: Jet diameter: 0.01m; Air velocity: 2.2m/s; Inclined angle: $\theta = \pi/3$

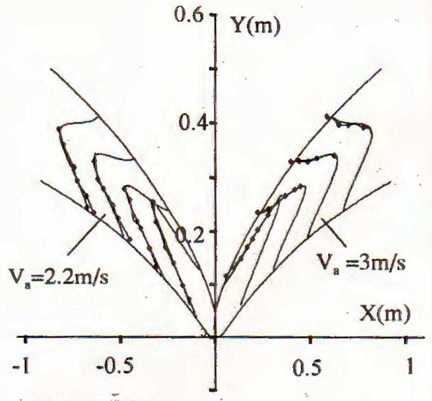

Fig. 11. Comparison of radial profiles of axial velocity measured experimentally and calculated. Jet parameter: Exit velocity: 40m/s; Jet diameter: 0.01m Inclined angle: $\theta = \pi/3$

velocity and velocity of air. The numerical results obtained with the model and experimental data also shown in the figures exhibit good agreement over the whole of the jets with almost predictions giving reasonable representations of the experimental data. especially, the model closely predicts the centerline velocities of the jets.

4. Comparison with experimental data

The performance of the model has been evaluated by making comparison with experimental data that were obtained from the smoke-jets with different source diameters, different inclined angles and different air velocities [9].

5. Conclusion

The general diffusion jet model allows us to calculate profile, velocity distribution, and concentration distribution inside the diffusion jet. On the basis of these research, it is also possible to develop for calculation the turbulent diffusion flame in Diesel engine, including swirl effects and calculate the concentrations distribution of gas inside engine combustion chamber.

Nomenclature

s : axial coordinate [m]
r : radial coordinate [m]
x : horizontal coordinate [m]
y : vertical coordinate [m]
R : radius of section [m]
$\hat{U}$: average axial velocity [m/s]
U_∞ : average horizontal velocity of surrounding air [m/s]
U_c : axial velocity at centre of section [m/s]
W : momentum [N]
$\dot{m}$: mass flow [kg/s]
g : gravity acceleration [m/s^2]
k : turbulence kinetic [m^2/s^2]
c_k, c_μ : constant
$c_{\varepsilon_1}, c_{\varepsilon_2}$: constant
β : constant
$\langle\rho\rangle$: average specific mass [kg/m^3]
ρ_∞ : specific mass of surrounding air [kg/m^3]
θ : direction angle [°]
μ : dynamic viscosity [kg.s/m]
μ_τ : turbulence dynamic viscosity [kg.s/m]
ε : rate of dissipation of turbulence kinetic [m^2/s^3]

This research is financed by the Fundamental Research Program "Modeling of Pollutants Formation in Combustion" of the Council for Natural Science of Vietnam.

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Received January 4, 2001

TÍNH TOÁN TIA PHUN KHUYẾCH TÁN RỐI

Kết quả nghiên cứu tia phun và ngọn lửa khuyếch tán rối trong môi trường không khí yên tĩnh, bỏ qua lực trọng trường đã được giới thiệu trong các công trình trước đây [1, 2]. Bài báo này phát triển những kết quả đạt được bằng việc thiết lập một mô hình tích phân ứng với tia phun tổng quát hơn có góc nghiêng bất kỳ, dưới tác dụng của lực trọng trường trong môi trường không khí chuyển động theo hướng bất kỳ so với trục tia. Hệ phương trình được khép kín bởi mô hình rối k-ε và được giải bằng phương pháp Runge-Kutta bậc 4. Bước đầu mô hình được áp dụng để xác định trường tốc độ, trường nồng độ và biến dạng của tia phun có đường kính 0,3 m.