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CHARACTERISTICS OF TWIN AXISYMMETRIC FREE JETS

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ABSTRACT

Axisymmetric single free jet and twin identical free jets with three nozzle spacing have been investigated numerically. Flow characteristics of single jet, twin jets and two superimposed individual jets are compared, and effect of nozzle spacing on twin jet flows is studied. Turbulence closure in those jet flows was achieved by one equation model. The governing equations were solved by using Implicit θ-Scheme and Tridiagonal Matrix Algorithm. Mean motion augmentation and turbulence attenuation occur on the axis of symmetry of twin jets compare to single jet and two superimposed individual jets. Both converging and combining points of twin jets are found to move downstream with the increase in nozzle spacing. It also appears that increase in nozzle spacing is associated with mean motion attenuation and turbulence augmentation at any axial location of the flows between the nozzle centerlines.

Keywords: Axisymmetric Twin Jets, Numerical Study, Vortex Breakdown.

1. INTRODUCTION

Most of the published data on axisymmetric turbulent free jets describe the developed region. There are few experimental data on the developing region of these jets [1-3]. The flow structure in developing region of the jet is important in many engineering applications, for instance, impinging jets are used for augmentation of convective heat or mass transfer process.

Compared to single jet, there is little information available in literature on the flow characteristics of interacting twin jets [4]. Interaction and mixing of twin jets are fundamental problems of turbulent shear flows that occur in a wide variety of engineering applications such as burners and thrust augmenting ejectors for V/STOL aircrafts, premixers for gas turbine combustors, chemical reactors, chemical lasers, propulsion systems, pollutant disposal devices, air conditioners and fluidics.

Twin jets are classified in literature as ventilated if they are issued from two free-standing nozzles or unventilated if the space between the two nozzles is blocked by a wall. The flow of twin axisymmetric turbulent jets is schematically shown in figure 1. In general, twin interacting jets develops through three successively distinct regions: converging region, merging region and combining region. In the converging region, the inner layers of the individual jets merge towards the centerline between the nozzles. Converging region terminates at the initiation of merging point and the two individual jets continue to merge until the combined point appears where the mean axial velocity becomes maximum on the axis of symmetry. Far downstream from the combined point, the twin jet flow resembles a single jet. Mutual entrainment of the surrounding fluid creates a subatmospheric region between the unventilated jets that causes their convergence and reversal of considerable fraction of the total flow at the axis of symmetry against a strong downstream force of turbulent shear. The same mechanism of mutual entrainment of the surrounding fluid is also operative in ventilated twin jets that converge into an atmospheric region prohibiting the formation of vortices upstream of the merging region [5-6]. Flow characteristics in the merging region of twin axisymmetric jets are three-dimensional, highly anisotropic and non-self-preserving, and these characteristics in the combining region are similar to a single jet.

Detail knowledge of flow characteristics of twin jets in the converging and merging regions is essential to the understanding of many observed complex phenomena in the aforesaid applications. For this reason, initial region of twin jets draw interest of the researchers. The lengths of converging and combining regions depend on the configuration of twin jets, i.e. plane jets converge and combine faster than axisymmetric jets, unventilated jets converge and combine faster than ventilated jets, and small spacing jets converge and combine faster than large spacing jets. Literature shows substantial discrepancies in the published data for converging and combining lengths of twin jets with small nozzle spacing [7].

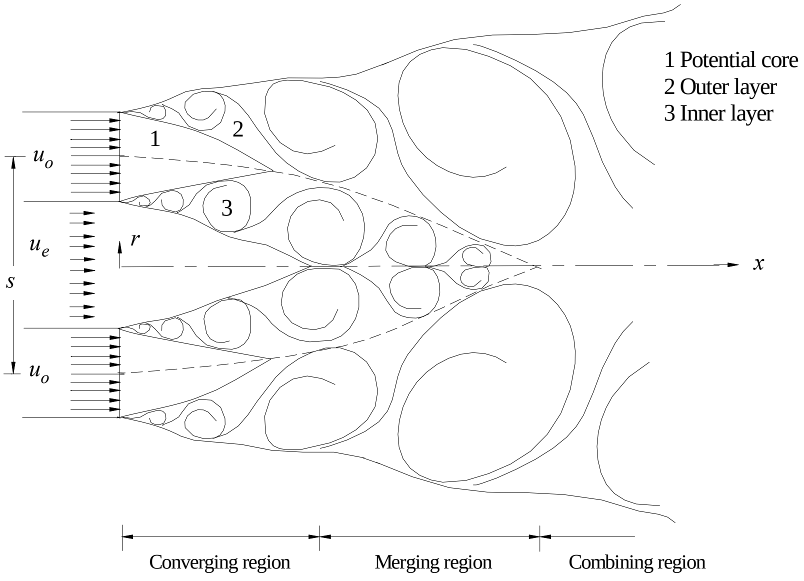

Figure 1. Schematic of twin axisymmetric free jets.

Studies show that nozzle spacing affects the flow structure, development and degree of mixing of twin jets quantitatively. On the other hand, Reynolds number (R_e) does not affect the flow structure of twin jets [7], moreover, the structure of high speed twin jets is identical to that of low speed twin jets [8]. One of the objectives of the present study is to compare the structure and development of the flows for single jet and twin jets in the merging region. Another objective is also to investigate the effect of nozzle spacing on the flow characteristics in the same region.

2. GOVERNING EQUATIONS

The merging region of the interacting twin axisymmetric jets is three-dimensional. However, flow in the vicinity of the symmetry plane connecting the nozzle centerlines is fairly two-dimensional. Hence the mean governing equations for such single phase, steady state and constant property fluid flow $\left(\bar{v}, 0, \bar{u}\right)$ in cylindrical co-ordinates $(r,\ \theta,\ x)$ by thin shear layer approximation under uniform pressure are

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\bar{v}\right)+\frac{\partial \bar{u}}{\partial x}=0 \tag{1}$$

$$\bar{v}\frac{\partial \bar{u}}{\partial r}+\bar{u}\frac{\partial \bar{u}}{\partial x}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\nu\frac{\partial \bar{u}}{\partial r}-\overline{u'v'}\right)\right]. \tag{2}$$

The closure between Eqs. (1)-(2) is achieved through one equation turbulence model by expressing Reynolds shear stress $\overline{u'v'}$ as

$$-\overline{u'v'}=0.38k \tag{3}$$

and solving k from the kinetic energy equation [9]

$$\bar{v}\frac{\partial k}{\partial r}+\bar{u}\frac{\partial k}{\partial x}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\nu+\nu_t/\sigma_k\right)\frac{\partial k}{\partial r}\right]+ \nu_t\left(\frac{\partial \bar{u}}{\partial r}\right)^2-C_D\ell_m^{-1}\,k^{3/2}. \tag{4}$$

There ν_t Boussinesq's eddy viscosity is expressed by

$$-\overline{u'v'}=\nu_t\frac{\partial \bar{u}}{\partial r}, \tag{5}$$

ℓ_m Prandtl's mixing length is expressed by

$$\nu_t=\ell_m^2\frac{\partial \bar{u}}{\partial r}, \tag{6}$$

and k, ν, σ_k and C_D are the turbulence kinetic energy, fluid viscosity, turbulence Prandtl number and constant of proportionality.

3. NUMERICAL PROCEDURE

The closed set of Eqs. (1), (2) and (4) is solved by using Implicit θ-Scheme, which is the Crank-Nicolson Scheme for $\theta=0.5$ [10] where θ is the weighting factor, and by using Tridiagonal Matrix Algorithm [11]. The flow domain due to two identical axisymmetric jets, with nozzle spacing s, is symmetric about x-axis allowing computation in half of the flow domain. The boundary conditions are $\partial\bar{u}/\partial r\left(0,x\right)=\partial k/\partial r\left(0,x\right)=\bar{v}\left(0,x\right)=\overline{u'v'}\left(0,x\right)=0$ and the initial conditions are $\bar{u}\left(r\le r_o,0\right)=u_o$, $\bar{u}\left(r>r_o,0\right)=u_e$ and $k\left(r,0\right)=\bar{v}\left(r,0\right)=\overline{u'v'}\left(r,0\right)=0$ where r_o is the jet radius, and u_o and u_e are the uniform jet exit velocity and uniform external velocity, respectively. Grid spacings are uniform in x- direction with $\Delta x=1.6\Delta r_1$ and variable in r- direction such that $\Delta r_{j+1}=K\Delta r_j$ where

$$\Delta r_1 = r_o\left(K-1\right)\Big/\left(K^{nj-1}-1\right) \qquad (7)$$

and number of grid points $nj = 31$ for single jet over $r_o = 20\ mm$ with $K = 1.01$.

4. RESULTS AND DISCUSSION

The set of Eqs. (1), (2) and (4) is solved numerically for the initial and boundary conditions appear in the free shear flow of single jet and twin jets, and for $\sigma_k = 1.0$ and $C_D = 0.18$. All the presently investigated air jets are identical with respect to the flowing fluid, jet diameter and its velocity, i.e., the jets are of the same Reynolds number. Implicit θ-Scheme is found to work well with $\theta = 0.3$ for the axisymmetric jets in the present study. The obtained results from computation are presented in this section for single free jet and twin free jets in the moving ambient of $u_e = 0.1u_o$.

4.1 Comparison of Single Jet and Twin Jets

Twin jets are characterized by converging, merging and combining regions. Combining region initiates when merging of two jets is complete and flow in this region resemble a single jet. In the initial region of single free jet, the vortices are separated by the potential core and rotate outwardly whereas vortices in the inner layers of twin free jets rotate inwardly (figure 1). This makes the flow physics of single jet different from that of twin jets in the initial region.

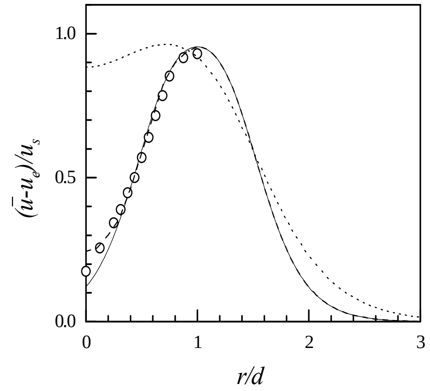

Figure 2. Mean axial velocity distributions at *x/d=6* for different jets. ——— Single free jet, - - - - - - Superposition of two jets with *s=2d*, ········· Twin jets with *s=2d*, ○ Single free jet data [1].

Mean axial velocity $\bar{u}$, Reynolds shear stress $\overline{u'v'}$ and turbulent kinetic energy k are plotted against the radial distance *r/d* in figures 2-4 at axial location *x/d=6*. In figure 2, $\left(\bar{u}-u_e\right)/u_s$ against *r/d* is presented for single free jet and twin free jets with *2d* nozzle spacing between the nozzle centerlines where *d* is jet diameter and $u_s = u_o - u_e$. The mean velocity profile of the twin jets with depression on the axis of symmetry indicates that the profile is located in the merging region. This velocity profile compare to that of single jet shows mean motion augmentation in twin jets. Mean velocity profiles of two individual jets with *2d* nozzle spacing are superimposed which show that the flow of the twin jets between the nozzle centerlines is not a simple superposition. Sami et al data [1] for circular jet ($Re=22x10^4$ at jet exit) in quiescent ambient are found to decay a bit higher and as a consequence spread a bit higher than the single free jet ($Re=1.6x10^4$) in the present study. Otherwise, the data show good agreement with the present results for mean axial velocity indicating the effectiveness of the numerical scheme used for solving the governing equations.

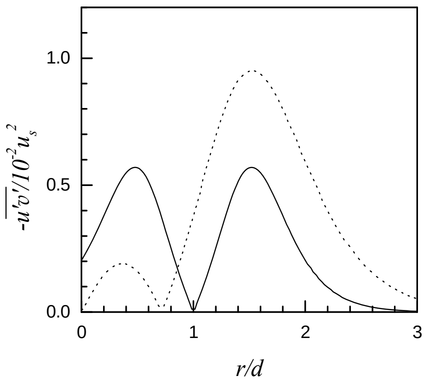

Figure 3. Reynolds shear stress distributions at *x/d=6* for different jets. See figure 2 for legends.

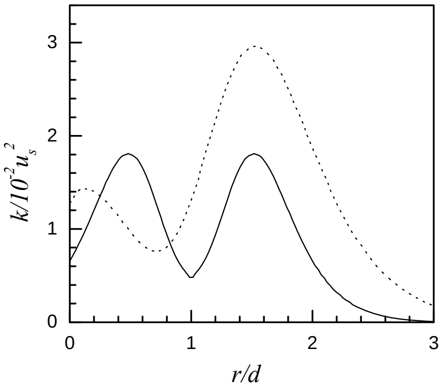

Figure 4. Turbulent kinetic energy distributions at *x/d=6* for different jets. See figure 2 for legends.

Figures 3-4 show that $\overline{u'v'}/u_s^2$ and k/u_s^2 are weakened in the merging region of twin jets compare to single jet. This is due to intense vortex breakdown by the inwardly counter rotating vortices and also by the squeezing of inner layers resulting from reduction in volume flux due to momentum flux constancy.

4.2 Structure and Development of Twin Jets

The profiles of $\left(\bar{u}-u_e\right)/u_s$, $\overline{u'v'}/u_s^2$ and k/u_s^2 are plotted in figures 5-7 against *r/d* for twin jets with *2d* nozzle spacing. The profiles of mean velocity in figure 5 show that inner layers converge on the axis of symmetry for *x/d<1* and combine into a single jet at *x/d=13*. Beyond the combine point this twin jet flows as a single free jet. Figures 6-7 show that the profiles of $\overline{u'v'}/u_s^2$ and k/u_s^2 decay in the downstream and resemble a single jet at *x/d=13*.

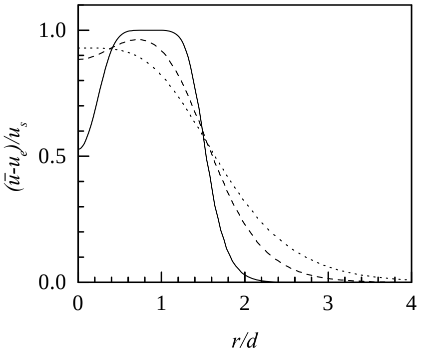

Figure 5. Mean axial velocity distributions for twin jets with *s=2d*. ——— *x/d=1,* - - - - - - *x/d=6,* ·········· *x/d=13.*

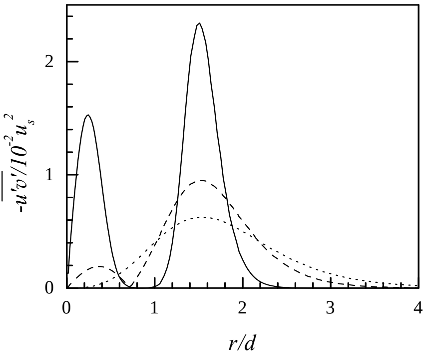

Figure 6. Reynolds shear stress distributions for twin jets with *s=2d*. See figure 5 for legends.

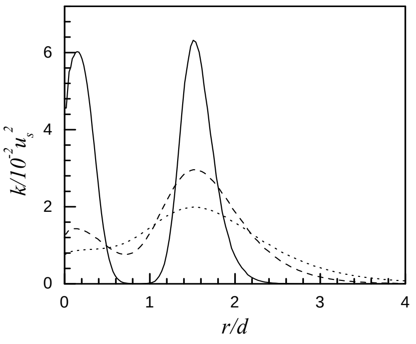

Figure 7. Turbulent kinetic energy distributions for twin jets with *s=2d*. See figure 5 for legends.

4.3 Effect of Nozzle Spacing on Twin Jet Flow

Twin jets with three nozzle spacing *1.5d*, *2d* and *2.5d* are investigated numerically to discern the effect of nozzle spacing on their flows. The profiles of $\left(\bar{u}-u_e\right)/u_s$ at the converging and combining points of twin jets for three nozzle spacing are plotted against *r/d* in figure 8. The converging and combining points of the jets are found to appear in the figure as: converge at *x/d = 0.04, 0.12* and *0.32*, and combine at *x/d = 10, 13* and *17*, respectively, for *1.5d*, *2d* and *2.5d* nozzle spacing. This implies that both converging and combining points of twin jets move downstream with increasing nozzle spacing. The figure also indicates that peak of the mean velocity profile at combined point reduces with increasing nozzle spacing. Ko and Lau [12] made measurements on unventilated twin plane jets with small nozzle spacing of *2.5d* where *d* is jet width and

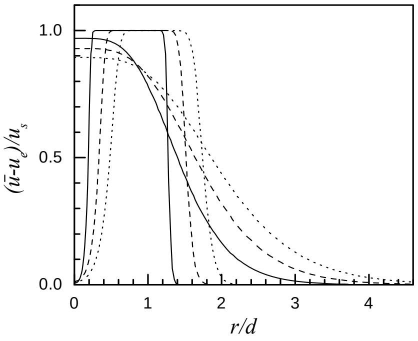

Figure 8. Mean axial velocity distributions at converging and combining points for twin jets. ——— *s=1.5d, x/d=0.04, 10*; - - - - - - *s=2d, x/d=0.12, 13;* ·········· *s=2.5d, x/d=0.32, 17.*

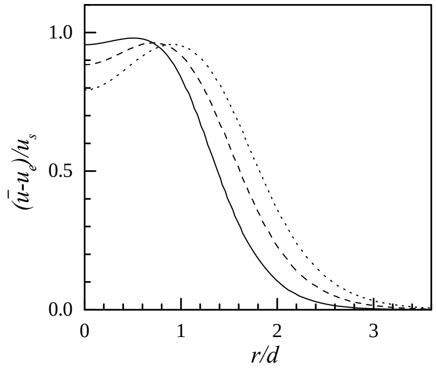

Figure 9. Mean axial velocity distributions for twin jets at *x/d=6.* ——— *s=1.5d,* - - - - - - *s=2d,* ·········· *s=2.5d.*

obtained combining point at *10.5d* but did not mention the distance of converging point. This discrepancy in the data of combining length may be attributed to the difference in jet's configuration.

Figures 9-11 describe the profiles of $\left(\bar{u}-u_e\right)/u_s$, $\overline{u'v'}/u_s^2$ and k/u_s^2 against the radial distance *r/d* at *x/d=6* for three different nozzle spacing. It appears from these figures that increase in nozzle spacing attenuates mean motion and augments turbulence at any axial location of the flows in the merging region. The figures also show that the peaks of mean velocity, shear stress and kinetic energy are offset radially outward with increasing nozzle spacing.

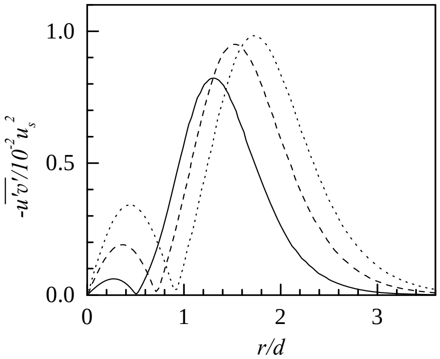

Figure 10. Reynolds shear stress distributions for twin jets at *x/d=6*. See figure 9 for legends.

5. CONCLUSIONS

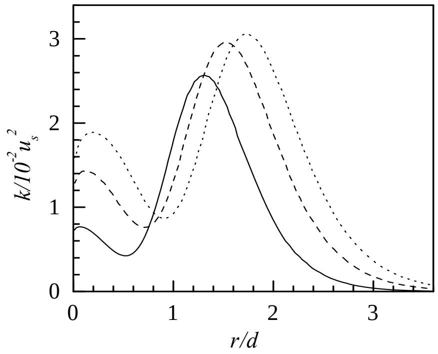

Figure 11. Turbulent kinetic energy distributions for twin jets at *x/d=6*. See figure 9 for legends.

Comparison of single and twin axisymmetric jet flows reveals that inner layers of twin jets converge much earlier than if the flow of two individual jets were superimposed. Turbulence quantities in the flow between the nozzle centerlines of twin jets reduce due to intense vortex breakdown by the counter rotating vortices and squeezing of the inner layers by the reduction in volume flux as a result of momentum flux constancy. Thus in the merging region of twin jets mean motion becomes stronger and turbulence becomes weaker than those of a single jet. This stronger mean motion can cause thrust augmentation and weaker turbulence can cause sound attenuation in aircrafts.

With increased nozzle spacing, both converging and combining points of twin jets move downstream. Increase in nozzle spacing reduces the degree of mixing in the merging region due to reduction in vortex breakdown leading to an increase in segregation of the jet fluid.

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