PD EA 0905

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G.RAMESH and S. B. VERMA
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AR&DB Project DARO/07/1011316/M/I

Project Document EA 0905
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National Aerospace Laboratories
Bangalore 560 017, India

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EAD Project No E-1-231 (AR&DB)

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2. Name &Address of Institution	National Aerospace Laboratories Bangalore –560017
3. Title of the project	Investigation of a near filed flow of an elliptic jet in the presence of co flowing outer stream using 2D PIV. (AR & DB Project No. E-1-231)
4.Sanction letter references	DARO/08/1031336/M/I Dtd.: 20/12/2005
5. Period for which sanctioned	24 Months
6. Date of Commencement of work	01-08-2005
7. Total amount sanctioned	: **Rs. 9.994 L (8.674 L + 1.32 L)**
	Rs 6.136 for 1st year **Rs 2.538 + 1.32** for 2nd year

STATEMENT – 3

UTILIZATION CERTIFICATE

Certified that out of the sum of Rs 9.994 Lakhs of Grant-in-Aid released during year 2005 in favor of National Aerospace Laboratories, Bangalore for carrying out R&D work on ``Investigation of a near filed flow of an elliptical jet in the presence of co flowing outer stream using 2D PIV '' under Govt. of India, Ministry of Defence, Directorate of Aeronautics (R&D), Aeronautics R&D Board sanction letters mentioned below:

Letter No.	Date	Amount (Lakhs)
DARO/08/1031316/2005-07/M/I	**20/12/2005**	**8.674**
DARO/08/1031316/2005-07/M/I	**30/11/2007**	**1.320**

1. A sum of Rs. 9.994 Lakhs (8.674+1.32) has been utilized for the purpose for which it was sanctioned.
2. It is further certified that I have satisfied myself that the conditions on which Grant-in-Aid was sanctioned have been duly fulfilled and I have exercised necessary check to see that the money was actually utilized for the purpose for which it was sanctioned.

Signature
Principal
Investigator
Place : Bangalore
Date : 15th April 2009

Signature
Executive Authority /
Head of the Institution
Place : Bangalore
Date : 15th April 2009

Counter-signed correct

Signature
Audit Authority of the Institution
Place : Bangalore
Date : 15th April 2009

STATEMENT –2
STATEMENT OF EXPENDITURE

Heads under which grant released	Amount sanctioned and released (2005-06)	Expenditure incurred	Balance returned
	(Rs in lakhs)	(Rs in lakhs)	(Rs in lakhs)
Capital Equipment	2.70	2.54	0.16
Research staff	1.08	1.12	-0.04
TA/DA	0.25	0.212	0.038
Consumables	4.92	5.12	-0.20
Contingencies	0.306	0.336	-0.030
.Overheads	0.738	0.738	0.00
Total	**9.994**	**10.066**	**-0.072***

*Excess spending of Rs.7200 is absorbed in the lab funds.

Signature of the Executive Authority/ Head of the Institution

Signature of the Principal Investigator

Signature of the accounts Officer

Signature of Audit Authority

(a) Aim of the Project:

- To develop a co flow Jet Facility and to investigate the near flow field of a small aspect ratio elliptic nozzle jet in the presence of co-flow using 2D PIV.
- The measurements are to be carried out for two velocity ratios λ (The ratio between central to outer jet)) ie. 0.3 and 1.5.
- To study time averaged turbulence quantities as well as the spatial velocity and vortical structures in elliptic jet in the presence of co flow and study the axis switching phenomenon in elliptic jets.

(b) Keywords: co flow, elliptic jet, PIV, axis switching, jet growth

(c) Classification of the Project: Applied research

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AR – Jet Aspect Ratio (AR = a/b)

.2a – major axis diameter

.2b - minor axis diamter

De - Normalized Diameter of the jet

H   -Jet half width

Uo – Jet exit velocity outer jet

Ui   - Jet exit velocity central jet

.x,y,z,- Co-ordinates

Abstract:

Co-flowing jets (co-axial jets) are present in many engineering systems such as combustions, thrust vectoring, chemical reactions, high bypass ratio engines etc. The near field study of these jets is relevant in the context of increasing the mass entrainment and mixing apart from the jet noise reduction at high speeds. The near field flow structure of a co-flowing jet is considerably complex and understanding the broad features of this flow would greatly help to improve our data base for modeling and design of engineering system. To study the near field of a small aspect ratio elliptic jet in the presence of annular flow at subsonic speed a coaxial jet facility is developed in the Experimental Aerodynamics Division of NAL. The Jets are driven by compressed air from the central compressor. A high speed blower is also connected to the settling chambers as the backup source for both the jets. The two jet velocities are independently controlled using pressure regulating valves to set the required pressure in settling chambers. A virtual Instrumentation based controls and data acquisition system was developed for the pressure and velocity measurements. The initial calibration tests showed the existence of top hat profiles in mean velocity. The low exit turbulence (< 0.05%) in both the jets is indicative of the high care taken in the design of the facility.

The study of the near field of a central elliptic jet in the presence of external co flow using Particle Image Velocimetry (PIV) is carried out for two chosen velocity ratio. PIV being a unique tool that provides both time averaged flow statistics as well as the instantaneous flow field has brought out the various flow features of the near field elliptic jet flow in the presence of external co flow. The various important features observed from the PIV measurements are discussed in this report.

1. Introduction

1.1. Co- flow Jet studies and its importance.

The flow-fields associated with jets issuing from two coaxial nozzles provide a simple case of wide ranging engineering problem that involve the mixing between turbulent shear flows. Eg. Combustion, premixed flame burners, cooling systems, jet pumps. The near field structure of a coaxial jet configuration is considerably complex and understanding of the broad features of this flow would greatly help to improve our data base, for modeling and design of engineering systems. Fig. 1 shows a schematic of the flow field from a co-axial jet. The mixing in a co-axial jet is primarily dominated by the vortex structures that are present in the inner and outer shear layers. The interaction of these structures governs the growth, entrainment, and mixing of the jet. There are a number of experimental and theoretical studies in this broad area that includes some variants such as homogeneous co-flow, heated jets, flows with density gradients, reacting flows and also with various active forcing schemes.

Ko and Kwan [1] using hot-wire measurements showed the existence of two types of vortices due to primary and secondary mixing regions and the dominance of either type depends largely on the velocity ratio (λ = Ui / Uo). Williams's et.al. [3] with their experimental studies in subsonic coaxial jet (λ = 0.05, 0.5, 0.7, 1.03) observed that there was an initial attenuation in noise with increasing co flowing velocity. The work on the flow structures of the coaxial jet was reported by Chiegier and Beer [2], Tang and Ko [8]. Daham et.al. [6] gave a detailed flow visualization of the vortex dynamics in the near field of a co-axial water jet. Kiwata et.al [7] showed the existence of a reticulating region along the axis of the jet and coherent structures in the inner and outer mixing regions of an unexcited coaxial jet.

Bruesti et. al [9] used Laser Doppler Velocimetry (LDV) and obtained mean axial velocity profiles and axial and radial turbulence intensities and shear stresses of a particular coaxial jet configuration with turbulence characteristics of typical industrial application. The coaxial jet upon acoustic excitation was studied by Wicker and Eaton [10] and they found that the excitation of inner jet produces periodic structures in the inner layer but does not have a significant effect on the evolution of the outer layer. Durao and Whitelaw [4] in their experimental study in coaxial jet (λ = 0.23, 0.62) using the hotwire measurements observed that coaxial jet tend to reach a self preserving state much more rapidly than ax symmetric jet. It is clear from the above studies that the co-axial jet results in higher entrainment, and their development is strongly dependent on the velocity ratio ($\lambda = U_i / U_o$).

1.2. Small Aspect Ratio Elliptic Jet and co flow configuration

The interest in non-axisymmetric jets has arisen due to their potential as a passive mixing enhancement device in the context of combustion, thrust augmentation, reactive flows etc. In this continuing experimental research, such jets are being investigated with the aim of increasing the mixing and spreading and for the understanding of the flow mechanism behind such phenomena. Furthermore, there is considerable interest in non-axisymmetric jets in view of the existence of the axis-switching phenomenon in them, which influence the mixing and entrainment properties. Interest in small aspect ratio elliptic jet flow gained importance since they were found to give high mass entrainment and increased mixing compared to circular jets [15]. The mass entrainment at the end of potential core was shown to be three to eight times in the case of a 2:1 elliptic nozzle compared to circular nozzle of equivalent area. Yuan lin et al [18] studied the dependency of axis switch over location in a 2:1 jet on the excitation frequency in jet column. Hussain et al [19] showed that the axis switching location is also a strong parameter of exit velocities and the exit momentum thickness.

Our earlier studies in elliptic jets using a 2D PIV have shown the difference in the flow development between an orifice jet and a contoured nozzle jet that has some correlation to the axis switching.**[JoV]** In order to further our understanding of the phenomenon of axis switching and increased mixing in the near field of small aspect ratio elliptic jets are studied in a controlled environment that is provided by annular flow. There is no known study of small aspect ratio elliptic jet as inner jet in co flow configuration.

The co flow facility developed has an interchangeable central or inner nozzle and a circular outer nozzle. The area ratio can also be varied by replacing the inner nozzle with different exit diameter. The co flow provides a much controlled environment for the central elliptic jet enabling the characterization of the near field flow of elliptic jet. The other design objectives of this facility included provision for implementation of active flow control schemes and extension to supersonic flow regime.To understand the effects of elliptic inner jet in the presence of circular outer flow, near field flow characteristics of turbulent elliptical jet with velocity ratio of 0.3 and 1.5 was measured using Particle Image Velocimetry. Some of the developmental work carried out in the building of this unique facility is reported in the following section.

2. Experimental Setup

2.1. Co Flow Jet Facility

There are a few methods by which coaxial jets are configured and the approach followed here is on the lines of the facility at Von Karman Institute at Belgium. This scheme provides an advantage to study the jets with active forcing techniques that is our interest for future applications. In addition the facility developed here has an interchangeable inner nozzle and for the presented work the inner jet is formed from a small aspect ratio (2:1) contoured elliptic nozzle while the outer one is a circular nozzle. A schematic of the coaxial jet facility is shown in Fig..2. The central jet or the inner jet is sources air from the settling chamber on the left and the piping of this runs through the other settling chamber that provides the supply for the outer jet or annular jet. The desired velocity ratio can be set by independently controlling the exit velocities of the jets using the pressure regulating valves. The detailed descriptions of the different components follow.

2.1. Air supply System and Control Valves.

The coaxial jet in the present work operates in the low subsonic regime. However all the components including the piping for the air supply are designed to take a 150 psig line pressure in order to extend the flow regime to high sub sonic and supersonic. The facility is operated with in a working pressure of not more than 60 psig. The facility is located in the low speed laboratory and the necessary air supply lines are drawn from a 6” pipe line drawn from the central compressor. An isolating valve is provided at the 6 inch pipe line that controls the supply to both inner and outer jets. From here the supply for the inner jet and the outer jets are taken using a 2” and 4” pipe line respectively. In addition a 10HP blower @ 3000 RPM that provides a velocity of 90 m/sec. at the exit of a 4” pipe is also used as a backup source.. A four way control valve is used to select the air supply source for the jets ie either from the receiver or the blower. Two pressure regulating valves of 4” and 2” sizes are used to control the outer and inner jets respectively. A PC based integrated data acquisition and control system is deployed for operating and marinating the jet velocities and for the acquisition of pressure and velocity signals.

2.2. Wide -Angle Diffuser and Settling Chamber

As seen from Fig.2. the coaxial jet facility has two identical settling chambers for both the jets, the variation being only in the exit pipe size. A wide-angle diffuser decelerates the high speed flow from the supply line to a low speed and recovers some portion of the dynamic pressure. The diffuser is a conical shaped component, which has circular inlet and outlet. The inlet is of cylindrical which is to receive air from the supply. The main purpose of using wide-angle diffuser is to decelerate the high-speed flow from the supply. A total of four diffusers are fabricated, two for each of the settling chambers. The included angle of the diffuser is 45 degree. A perforated cone also adds in spreading the incoming high speed flow uniformly into the settling chamber. This cone contains many holes drilled at uniform intervals that are of the sizes of 20 mm diameter. The cone also reduces the large scale turbulence and provides a symmetrical entry of the flow into the settling chamber. Four such wide angle diffusers have been fabricated that are fixed to either side of the settling chamber.

The inlet diameter and the outlet diameter of the diffuser are 100mm and 500mm respectively. For an included angle of 30° and diameter ratio of 5 the corresponding length of the diffuser is calculated. The actual length of the conical component is 381.5mm and the length of cylindrical entrance and flange is 100mm. Hence the total length of the diffuser amounts to 481.5mm.

The diffuser at the larger end has a provision in the form of a slot to accommodate a perforated cone. This cone is used to reduce large scale turbulence. Flanges are provided on both ends of the diffuser for attachment. The flange at the cylindrical part is connected to the supply and the flange at the other end is attached to the settling chamber. Flanges are provided with projections and depressions as a part of locking mechanisms.

In the settling chamber flow settles to a lower velocity and the turbulence is reduced large extent. It is essentially a cylindrical pressure vessel with provisions for air inlet and nozzle exit, instrumentation, seeding and drain ports. The quality of the flow into the nozzle mainly depends on the uniformity of flow in the settling chamber. Uniformity in the flow can be achieved by having settling chamber of large cross section and adequate length. Three screens are installed near the upstream end of the settling chamber. These screens damp out turbulence. The magnitude of the damping is proportional to the pressure drop between the screens.

Settling chambers use cylinders of diameter 500mm and length of 1000mm. At a distance of 185mm from the top there are two ports of diameter 100mm. Seeding can be done either here or on the top from diffuser end. These ports stretch to a distance of 170 mm and end up with a flange. At a distance of 285mm from the upstream end there are provisions for a screen or mesh at an interval of 50mm /100 mm. These screens enhance damping effect and hence reduce turbulence. An annular grove of requisite width is provided to hold these screens. At a plane right angle to the seeding port is the instrumentation port (50mm diameter) for housing the pitot probe for obtaining the stagnation pressure. Along same plane, in opposite direction and at a distance of 185mm from the downstream end a drain hole is located.

The above-mentioned features are common to both central and co-axial jet setup. As mentioned earlier the central jet has an exit pipe diameter of 100 mm while that of the annular one is 300 mm. Apart from this the central jet has a provision for mounting a diaphragm at 180 deg plane of the exit plane. This port that has 100 mm diameter can be used for mounting actuators for selectively exciting the central jet for any phase controlled studies. Another hole of 100mm diameter with a flange is located on the opposite direction to the diaphragm port on the same plane. This port is connected to an intermediate pipe, which in turn connects to the central pipe that runs through the second settling chamber. The co-axial jet setup has a port of diameter 100mm with a flange near the downstream end of the settling chamber at a distance of 285mm from the same. This part is connected with the intermediate pipe and central jet pipe. Opposite to this port on the same plane another hole of 300mm diameter is located along with a flange. This port is connected to a second intermediate pipe that in turn connects to the outer

2.3 Nozzles

There are two nozzles in the coaxial jet facility, one at the end of the 100 mm diameter pipe originating from the settling chamber at the left and the other connected to the 300 mm diameter pipe. The pipe lines are concentric and the nozzles are so contoured to maintain parallel stream lines in the annular area. The outer and the inner nozzle are concentric and their contours are parallel at beginning and at the end. The outer nozzle is connected to a co-axial jet pipe, which in turn connects with the settling chamber. The outer nozzle is formed from a circular entry to circular exit with respective diameters being 300mm and 100 mm. The nozzle is so contoured that it is tangential both at the entry and the exit and a circular arc contour is provided in such a way there is no steep gradient at any point on the contour (> 7 deg.). The length of the nozzle is fixed to 300 mm. The inner nozzle is connected the central jet pipe, which is connected to the central jet settling chamber with the help of intermediate pipe. The inner nozzle has a diameter of 100mm at the connecting end and has a diameter of 36mm at the free end. There are three supports located between the central jet and co-axial jet. They are located nearer to the nozzle in the same plane and at an angle of 120° b/w each. These parts are in the shape of an aerofoil so that it does not obstruct the flow. The length of the nozzle is decided by the angle between two successive tangents on the contour. This angle is maintained at a maximum of 18°. The tangent locations, which are measured for the angle, are spaced at an interval of 5mm. Schematic of the outer circular nozzle and the inner circular and elliptic nozzles are shown in **fig.4.**

2.4. Fabrication

All the components mentioned above are fabricated using glass fiber. Apart from its light weight and high strength the expertise available in house (Model Shop of the Experimental Aerodynamics Division) weighted our decision produce all the components out of Fiber Reinforced Plastic (FRP). The fabrication procedure using FRP is generally known as Lay-up method. Firstly a wooden master to the required dimension with a fine surface finish is made over which the FRP layers are formed. Cloth pieces of FRP are cut according to the required size based on the component. To start with, a model (or master piece) of the component is made out of wood. A photograph of the wooden masters of the settling chamber is shown in **Fig.5.** The external contour of the wooden masterpiece is made such that it matches to that of the internal contour of the component. The masterpiece is painted to give smooth finishing to the internal parts of the component. For more intricate and extruding parts such as flange for example a separate model or bass piece is made and then joined to the base or the original masterpiece.

First a layer of resin is coated on the master and then pieces of FRP cloth are pasted on it so that it covers the entire surface. This forms the basic layer of FRP. Subsequently alternate layer of FRP and resins are coated. This is lay up procedure continues until the required thickness is obtained. (See *Appendix III* for the relationship between thickness and stress).The number of layers depend on the thickness required which depends on the amount of strength needed to withstand the given pressure or stress. Care is taken where the model presents curves and intricate shapes. After this the model is allowed to dry for stipulated amount of time. It can be subjected to curing in furnace to impart more strength. The FRP component can be separated out from the wooden master after it completely dried.

In the case of settling chamber a wooden cylinder of 500 mm diameter and 1000 mm length is made as master. Necessary wooden blocks were attached to this cylinder that forms the different ports of the facility. FRP layers are formed over the cylinder. In order to use the same master for both the settling chambers it was decided to make cylindrical section of the settling chamber from two half cylinders sectioned in longitudinal direction.

In the case of diffuser it is made as a single piece, lapping the master with the layers of resin and fiber alternatively. Flanges are provided on all external ports. The flanges are matched and connected by means of nut and bolt arrangement. To match diffuser and settling chamber depressions and projections are provided alternatively on both the parts such that it forms a lock and key arrangement. Rubber gaskets are provided between the joints to prevent any leaks. The complete assembly after the installation of the components is shown in **Fig.6.**

3. Instrumentation and Measurement procedure.

3.1. VI based Instrumentation for Pressure and CTA

The controls and data acquisition for the facility is developed using the Virtual Instrumentation concept. The virtual instrumentation based data acquisition card uses a PCI bus based National Instruments Analog and Digital I/O card (PCI 6013). This card has eight channels of analog input with programmable gains, and 32 channels of digital I/O lines. PCI-6013 data acquisition card has a 16 bit resolution and has the maximum sampling rate of 200 KHz. The TTL 8 bit I/O lines are used for reading the logic status like isolating valve status, control valve drive pressure, limit switches and transducer supply. The digital output lines are reserved for emergency shutdown of isolating valve, hooter opening of pneumatic supply for control valve etc. The analog output lines are used for controlling the electro pneumatic valves using PID algorithm. However in the present experiment the pressure regulating valves were operated under open loop control..

The *Furnace controls* make Digital manometer and a *Dantec* make CTA is used to acquire pressure and velocity data from the co-jet experiments.. Furnace control make manometer has a full range of ±200 mm

H_2O and provides full scale output of ±5V. Manometer is calibrated against a Low pressure *Druck* calibrator. Calibration factor for manometer is 39.3 mm H_2O /mV (obtained from the plot).

Hot-wire measurements were also carried out in the co flow jet at several axial locations in the *Y-Z* plane by means of a 99N10 *DANTEC* anemometry system using a *Dantec* 55P11 2-component probe. The probe has platinum plated tungsten wires (1.25mm long and 5μm diameter) and can be used for air applications with turbulent intensities up to 5-10. The probe was calibrated using *Dantec* 9054H01 calibrator with 120mm^2 nozzle in the velocity range between 0-25m/s. The signals from the probe were acquired at a sampling rate of 3 kHz with 10000 samples. The anemometer analog output was acquired by using a differential mode *National Instruments* PCI -6036E having 16-Bit resolution, operating range of ±10V and maximum scan rate of 200Ks/samples. The linearization and processing of the hot wire signal was then carried out digitally.

2.3. Particle Image Velocimetry

Most of the investigations reported here by other researchers uses point wise measurement methods in the coaxial jets. Particle Image Velocimetry (PIV) being unique that this non-invasive technique **[Willert]** provides not only the time mean quantities as well the whole field spatial velocity data. In recent times considerable attention is focused in the application of PIV to various flow fields to study the flow dynamics and interaction of the vortical structures in complex flows. Our earlier studies in a small aspect ratio elliptic turbulent jet using a 2D PIV could successfully document the mean and turbulence quantities **[Ramesh]**. In addition the spatial evolution was studied from the instantaneous vorticity field obtained from the 2D velocity vectors. The axis switching phenomenon observed in these jets is seen to be related to the evolving azimuthal vortical fields. As an extension to the study the present investigation uses the 2D PIV system for the near filed flow studies of elliptic jets in the presence of coflow.

The 2D PIV system uses a 400mJ, dual cavity *Nd: YAG* laser from *Spectra Physics*, capable of pulsing at 15 pairs per second as light source. A light sheet of over 200 mm width, 1 mm thick was generated using a set of spherical and cylindrical lenses. A Kodak ES 1.0 PIV camera of 1008(H) x 1018(V) pixels with a 50 mm *Nicor* lens was used for recording the particle images. Synchronization of the laser pulsing with camera and the grabbing of the images were carried out using *IDT-1000 controller* from *IDT systems* interfaced to a PC via a high speed PCI link. Image acquisition and processing were carried out using *IDT proVISION*® software that operates in Windows NT platform on a Pentium PIV dual core2 duoI PC.

This software for analyzing the images and computing the velocity field has been procured from Integrated Design Tools Inc., who have been pioneers in applying PIV to a variety of flow situations. An image matching approach is used for digital processing of the image pairs to produce the displacement field. A cross correlation algorithm based on Fourier transformation is then used to extract the velocity information from the double exposed images. However, the currently used algorithm differs from the conventional processing speed in its higher spatial resolution and unstructured grid for evaluation. This technique has been proven even in flow with large velocity and / or seeding density gradients. This scheme is very efficient and incorporates a vector validation procedure, making it independent of operator intervention. The time it takes to compute a vector field depends on the computer hardware and it ranges from 750 mesh points/sec to 1400 mesh points per/sec on a 500 MHz Pentium PIII PC.

A pulse interval of 25 microseconds results in a particle image displacement of about 2.5 pixels for the maximum velocity in the jet. The imaging area of 200 mm by 200 mm was set and with 32 pixels interrogation size this provided an effective spatial resolution of 4 mm. With a 50% overlap of interrogation windows the number of vectors in the chosen area turned out to be about 3000.For the estimation of ensemble averaged quantities a total of 1000 frames of data from each set was used.

Seed generator

The flow in the jet is seeded both internally and externally with fine droplets of fog fluid generated from a locally made nebulizer that produces seed particles in the range of 5 to 15μm. A seed generator developed for seeding the particle for PIV experiments and also for the general purpose flow visualization methods is shown in Fig.7. PIV recordings were carried out up to about 6 equivalent diameters spanning a square area of 230 mm by 230 mm.

2.4. Experimental Conditions:

The purpose of this work is to study the near field flow characteristics of small aspect ratio elliptic jet in the presence of external co flow using two dimensional PIV. The major diameter of the elliptic jet was 50.4 mm and that of the minor is 25.2. The equivalent diameter is 36.4 mm. For the data in the present report, the velocity of the inner elliptic jet was held fixed at 60 m/sec. which corresponds to a jet exit Reynolds number of 120,000. The PIV studies were carried out for two velocity ratios (λ) of 0.3 and 1.5 which means that the external jet velocity in these cases was set to 18 m./sec and 90 m/sec. The PIV studies to obtain both the time averaged turbulence quantities as well as the spatial velocity and vortical structures in elliptic jet in the presence of co flow the area of the imaging size was fixed to 200 mm x 200 mm that provided effective stream wise distance of 6 equivalent diameters.

3. Results and Discussion

3.1. Circular Jet in External co flow using CTA

Though the main objective of this work is the PIV studies in the near field flow of small aspect ratio elliptic jet in co flow configuration being a new facility it was important to establish a base line comparison and validation of the co flow jet facility using conventional measurement methods. As there are a number of studies in circular jet in co flow the initial validation was carried out with a central circular jet using CTA. The jet exit Reynolds number for the equivalent are circular jet was 100000.

Fig.4.1 shows transverse mean velocity profiles at three stream wise stations. The exit profiles (at x =0) showed a perfect top hat typical of jet developing from properly contoured nozzle. The azimuthal symmetry is also clearly seen from these profiles. For each axial location the two cross plane measurements were superposed. All the profiles overlap well thus demonstrating the mean azimuthal symmetry of this jet flow. The TI profiles shown in fig. also clearly show the higher levels of energy in the primary shear layer for the velocity ratio of 0.3. The lowest turbulence measured at the jet exit is 0.03% in the potential core. The three meshes and honeycombs used in the settling chamber and the proper contouring of the nozzles are the major reasons for the low turbulence at the jet exit.

3.2 Elliptic Jet Measurement using PIV

3.2.1 Ensemble Averaged Flow

Single jet

Co flow jets

Mean Velocity

Sudden reduction of the mean velocity at the exit for 1.5

Axial Decay

The center line velocity decay is a measure of jet mixing.The length of PC are in agreement with available data with low TI levels.

Shear layer half width

Turbulence intensity

Reynolds Stress

3.2.2 Instantaneous Flow Field

The identification of vortices from instantaneous 2D velocity field obtained from PIV measurements is carried out using the Galilean decomposition suggested in ref. The definition of a vortex as region with rotating (swirling) flow is independent of choice of reference system. There were a few different methods proposed to identify and interpret the vortices from the velocity data obtained from PIV. In 2D flow the spanwise vorticity

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

Is calculated using least operation extrapolation scheme. The spanwise vorticity is shown as representative data because it directly reflects the vortex quantities such as the rotating direction, size and strength.

The fig. shows a snap shot of the instantaneous velocity field and the vorticity obtained using the above relation. From this figure it is not very clear to identify the extent and the center of the vortex.

A Galelian decomposition is applied to the vectors

Uref= 0.65 uj

This reference velocity is subtract ted from the instantaneous velocity and then the vorticity is calculated from the resultant velocity field. It is clear from the above plot the existence of the vortices, their size, strength and the inter vortical spacing etc. Such plot were made for a few frames for both the velocity ratios in the major plane and in the minor plane.

The size of the discrete vortices is of the order of the jet exit diameters; the streamwise distance between two adjacent vortices appear to remain constant at about 1.5D.

Concluding Remarks

A subsonic co axial jet facility is being developed in the premises of the low speed Laboratory. This facility is being developed in such a way that it could also cater to high speed requirements at a later time. Also provisions are made for the active flow control studies providing a diaphragm actuator for the central jet and necessary seed ports for the PIV studies. Necessary pipe lines with manual control valve have been installed. The Pressure regulating valves are being procured. The major components like settling chambers and diffusers have been fabricated using glass fiber technology and are designed to withstand a hoop stress of more than 300 psig. A PC based control and data acquisition system is being developed for the PRV controls and acquisition of pressure transducer and hot wire anemometry signals. The preliminary tests of the automated data acquisition system are implemented in a pilot coaxial jet facility. A 2D PIV system planned to be used has been earlier used in a number of investigations both in low and high speed tunnels. The present arrangement of the facility will have a small aspect ratio elliptic nozzle for the central jet and the experimental studies would focus on the near field flow development of the central jet in particular the phenomenon of axis switching.

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Conclusions giving Achievements with reference to the Main Objectives of the Project

1. A sub sonic co flow jet facility is designed and developed and commissioned that provides good flow quality.

2. PIV studies in the near filed flow of a small aspect ratio elliptic jet in the presence of co flow brought out several interesting features of this complex quasi three dimensional flow.

3. The major objective of gaining a broad understanding the various flow processes associated with the near field flow development in Co flow jets.

Papers Published/ Presented:

(1) NAL internal publication
(2) Students project reportt

High potential to convert them to publication exist

Abstract highlighting the Salient features of the work

A co flow jet facility with high flow quality (top hat exit profiles and low exit turbulence) has been established at Experimental Aerodynamics Division of NAL. The velocity ratio and area ratio at the exit can be easily changed thus meeting the diverse requirements for different applications. The instrumentation developed include a VI based Controls and Data acquisition that controls the operation of the inner and outer jets, acquires pressure data from ESP and velocity from CTA using a 2D automated probe traverse.

The initial studies in a circular jet using one component CTA showed the excellent flow quality achieved in both the jets. The PIV measurements in the near field brought out several interesting features of this highly complex flow.

(i) The axis switching observed in the small aspect ratio elliptic jet flow is absent with the introduction of the external flow.

(ii) The potential core of the central as well as the external jets are dependent on the velocity ratio as well as the absolute value of the exit velocities.

(iii) The shear layer half widths show a marked deviation in the growth of the jet in the major and minor planes.

(iv) The instantaneous flow structures observed in the near field exhibited the

End Use of the work

The Near field flow development charecterises the mixing and growth in coflow jets that are higly relevant in the field of combustion, chemical reaction, high bypass ratio engines cooling etc. The co flow jet facily developed is perhapbs the first in the country with high flow quality that can be used for various basic and applied research in the above mentioned areas. The Hotwire data provides the baseline for any future studies in this facility. A Laskin's nozzle type particle generator is developed for tha application of PIV studies and laser sheet flow visualisation.The near field flow studies using PIV provides the instataneous flow field structures that provides enhanced knowledge of the ellptic jet flow features in the presence of coflow.

Likely End User

GTRE, Combustion Group NAL.

Recognition, awards, patents:

NIL

Number of students trained/likely to be trained in the future:

Presently two groups(eight) of B.Tech (Aero) students have been trained. Possibilities exist to provide training for Maters as well as Doctoral students in the areas of Aeronautical and Applied mechanics in this facility.

Acknowledgements

The authors wish to thank AR&DB for supporting the project. We thank Dr Sajeer Ahmed, Head, and Experimental Aerodynamics Division for his support and encouragement. The technical support of Mr.Ramachandra and his team and Mr.S. Srivatsav, GT during facility design and fabrication is gratefully acknowledged. Mr. Sridhar, NTAF provided us with many useful suggestions in the development of air supply system which is kindly acknowledged. . Mr.Nitin Pawar and Mr.Kumaraswamy developed the required instrumentation for this facility and they are thanked for their role. Mr.Sudhakar and Mr. Suryanarayn have provided all the support to carryout CTA and PIV measurement and they are acknowledged for their efforts

FIGURES

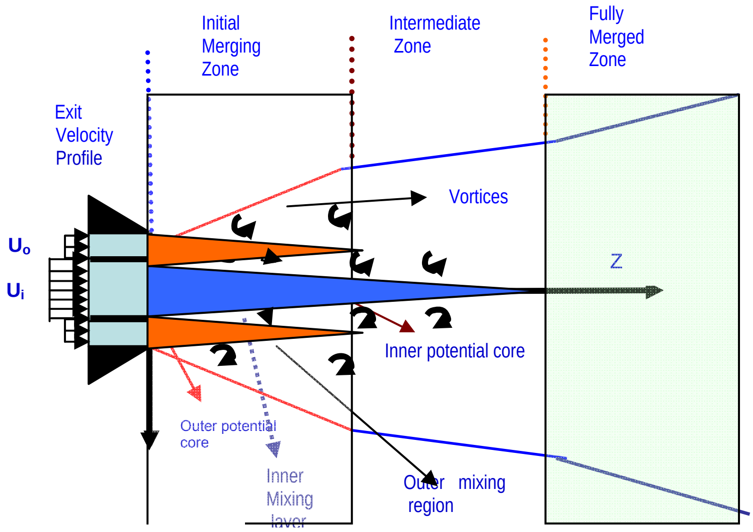


Fig.1. Schematic Representation of flow structure in a Co flow jet

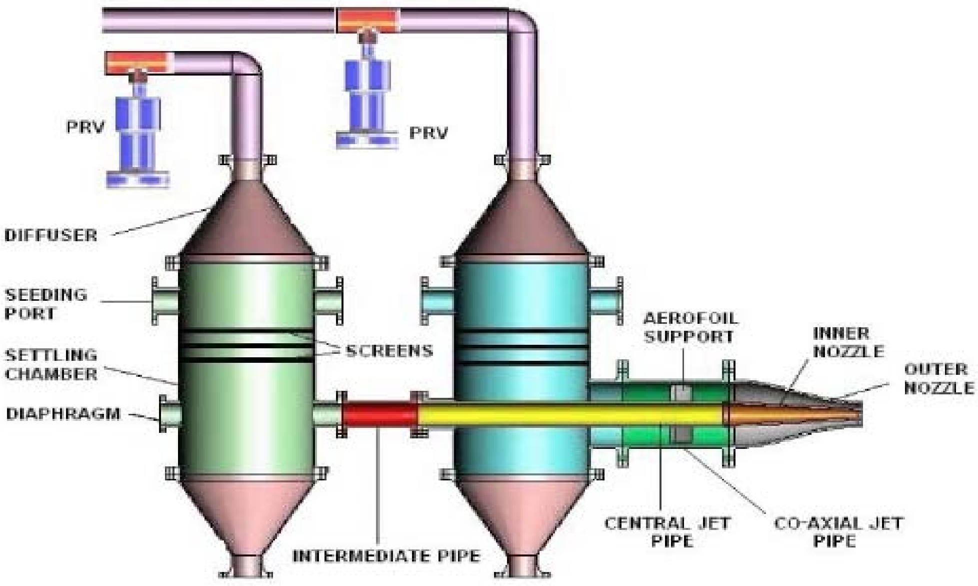
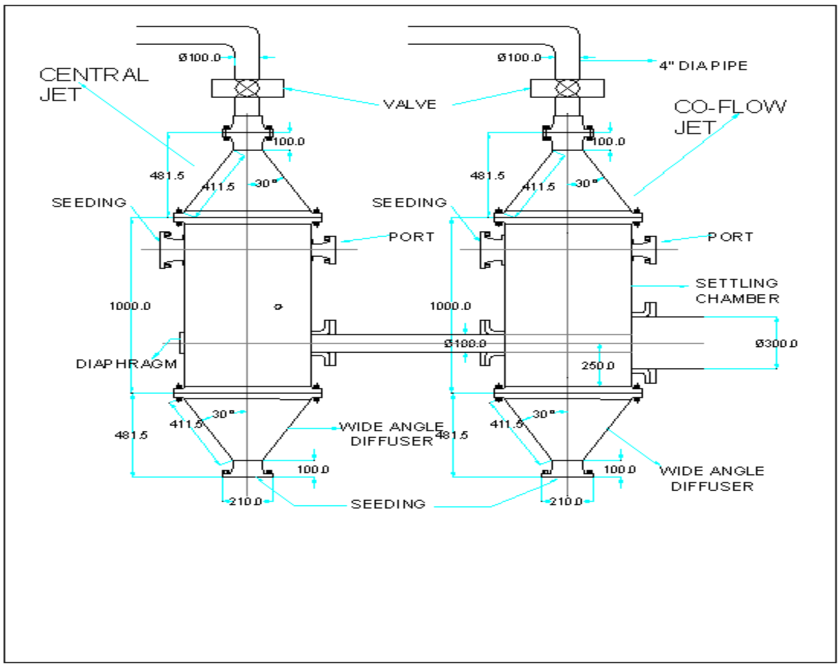
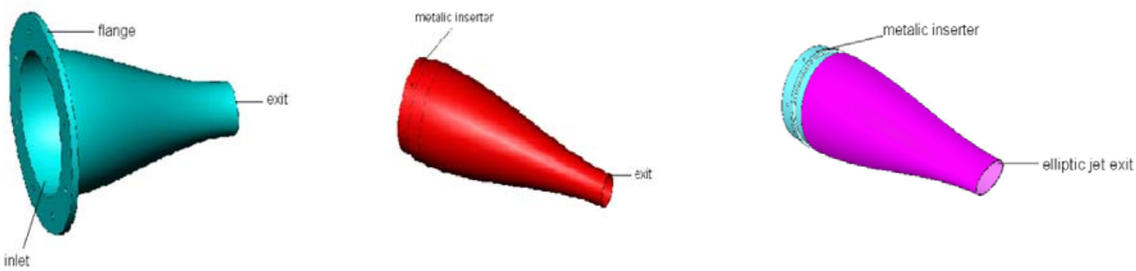


Figure 2: The Schematic of the Co Flow Jet Facility



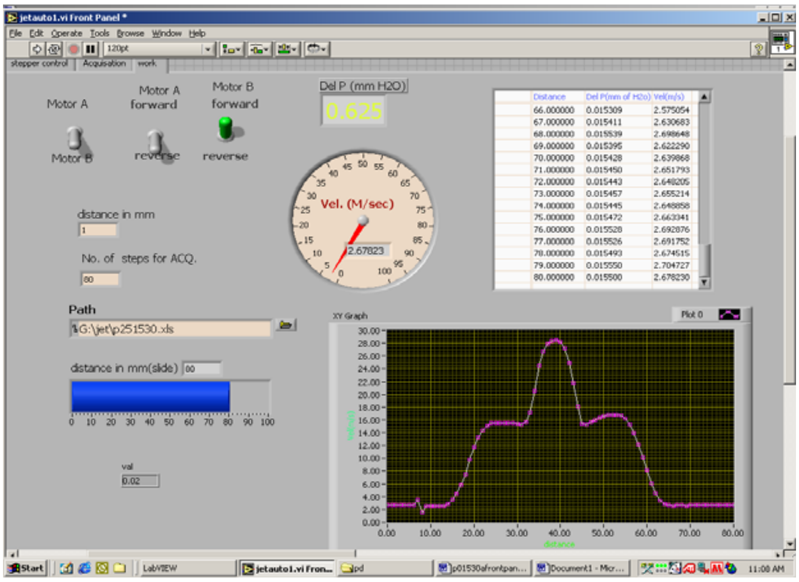
.Fig.3. Dimensional Details of Settling Chamber

Fig.4. .Wodden Master of Settling Chamber for the CFRP fabrication.



(a) Outer nozzle (b) Inner Nozzle (circular) (c) Inner Nozzle (Elliptic)

Fig.6. Nozzles for outer and inner jets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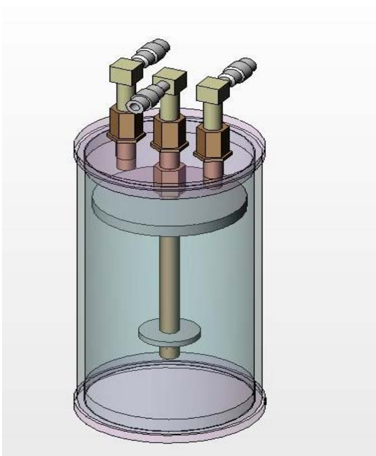

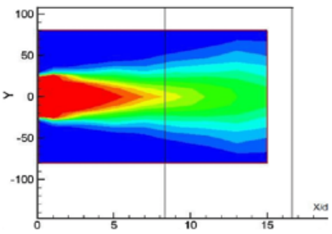
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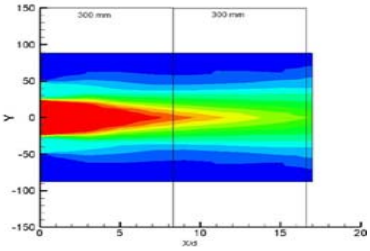
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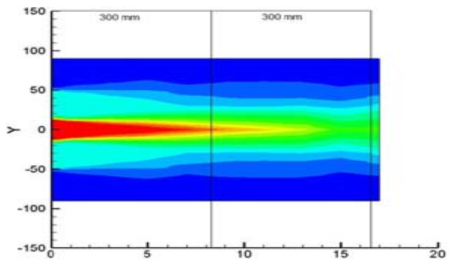
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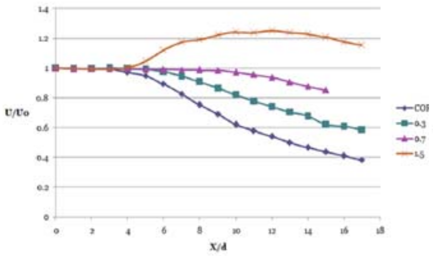
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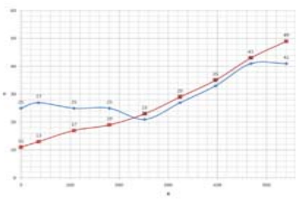

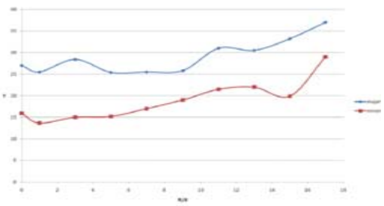

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Title Investigation of near Field Flow of an Elliptic Jet in a Co-flowing Outer Stream using 2D PIV

Author/s G.Ramesh, S.B. Verma

Division EAD

NAL Project No. E-1-231

Document No.

Date of issue April 2009

Contents Pages Figures Tables References

External Participation

Sponsor AR & DB, Aerodynamics Panel

Approval Head, Experimental Aerodynamics Division

Remarks

Keywords Elliptic Jet, Axis-switching, Co-flow, PIV, Jet growth

Abstract

To study the near field of a small aspect ratio elliptic jet in the presence of annular flow at subsonic speed a coaxial jet facility is developed in the Experimental Aerodynamics Division of NAL. The Jets are driven by compressed air from the central compressor. The two jet velocities are independently controlled using pressure regulating valves to set the required pressure in settling chambers. A virtual Instrumentation based controls and data acquisition system was developed for the pressure and velocity measurements. The top hat jet exit velocity profile and the low exit turbulence intensity measured using hotwire prove the design efforts taken in building this facility.

A study of the near field of an elliptic jet in the presence of external co flow using Particle Image Velocimetry (PIV) is carried out for two chosen velocity ratio. PIV being a unique tool that provides both time averaged flow statistics as well as the instantaneous flow field has brought out various flow features of the near field elliptic jet in the presence of annular co flow that are discussed in this report.