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Investigation of Turbulent Characteristics of a Subsonic Jet Using 3D RANS Simulation

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ABSTRACT: Jet aerodynamics is highly dependent on the fluctuating quantities in a flow and determination of these quantities experimentally is very expensive and time consuming. The flow fluctuations associated with turbulence give rise to additional transfer of momentum, heat and mass. In the present work numerical simulations of a turbulent compressible subsonic circular jet of 50mm diameter and Mach number 0.75 using RANS is carried out. Simulations are performed in a three dimensional computational domain and the turbulent model used is SST k-ω. The flow is investigated for axial and radial profiles of velocity components and all the turbulent characteristics. The results are found agreeable with the available results from referred journals. In this work modelling and meshing are done in GAMBIT and the simulations using FLUENT.

KEYWORDS: RANS , Subsonic , Jet , Simulation , Mach number , Turbulence model

I . INTRODUCTION

Theoretical analysis and prediction of turbulence has been, and to this date still is, the fundamental problem of fluid dynamics, particularly of computational fluid dynamics (CFD). The major difficulty arises from the random or chaotic nature of turbulence phenomena. Because of this unpredictability, it has been customary to work with the time averaged forms of the governing equations, which inevitably results in terms involving higher order correlations of fluctuating quantities of flow variables.

All flows in engineering practices , simple ones such as two-dimensional jets, wakes ,pipes flows and more complicated three-dimensional ones, become unstable above a certain Reynolds number (UL/v). At low Reynolds number flows are laminar. At higher Reynolds number flows are observed to become turbulent. A chaotic and random state of motion develops in which the velocity and pressure change continuously with time within substantial regions of flow. The velocity fluctuations are found to give rise to additional stresses on the fluid, so called Reynolds stresses.

Turbulent flows possess irregularity or randomness. A full deterministic approach is very difficult. Turbulent flows are usually described statistically. Turbulent flows are always chaotic. But not all chaotic flows are turbulent. Turbulent flows are rotational; that is, they have non-zero vorticity. Mechanisms such as the stretching of three-dimensional vortices play a key role in turbulence. The diffusivity of turbulence causes rapid mixing and increased rates of momentum, heat, and mass transfer. A flow that looks random but does not exhibit the spreading of velocity fluctuations through the surrounding fluid is not turbulent. If a flow is chaotic, but not diffusive, it is not turbulent. Turbulent flows are dissipative. Kinetic energy gets converted into heat due to viscous shear stresses. Turbulent flows die out quickly when no energy is supplied. Random motions that have insignificant viscous losses, such as random sound waves, are not turbulent.

An LES or DNS can be used to obtain the non-linear near-field, which in the jet noise case corresponds to the

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hydrodynamic jet region. Freund [6] investigated sources of sound in a Mach 0.9 jet at a Reynolds number of $Re_D = 3.6\times10^3$ using DNS.Bogey and Bailly[3][5] investigated the effects of inflow conditions on the flow field and the radiated sound of a high-Reynolds-number, $Re_D=4.0\times10^5$, Mach 0.9 jet.

In DNS, all scales of the turbulent flow field are computed accurately, which requires a mesh fine enough to capture even the smallest scales in the flow, whereas in LES, only the large scales of the flow are resolved and the influence on these large scales of the smaller, unresolved scales is modelled using a subgrid scale model. With the computational resources available today, DNS is restricted to fairly simple geometries and low Reynolds number flows. Moreover, it is believed, Mankbadi et al [4] , that large scales are more efficient than small ones in generating sound, which justifies the use of LES for sound predictions. Another approach is to use a less computationally expensive RANS calculation to obtain a time-averaged flow field. Information about length and time scales in the time-averaged flow field can then be used to synthesis turbulence in noise source regions.-This method is promising since simulations of high Reynolds number flows are possible with reasonable computational efforts. In contrast to a RANS calculation, where all turbulent scales in the flow are modelled and only a time-averaged flow field is obtained, DNS and LES directly provide information about turbulent quantities and sources of noise. Since sound predictions are not considered it will be fine to investigate turbulence characteristics using RANS.This is the objective of present work.

II. MODELLING

In the present study a RANS of a Mach 0.75 nozzle/jet configuration has been performed . The Reynolds number based on the nozzle exit diameter and the jet velocity at the nozzle exit plane, ReD, was $5.0 *10^4$. An isothermal jet is simulated, i.e. the static temperature in the nozzle exit plane, T_j , is equal to the static temperature of the ambient air, T_∞. The table below show the flow properties. The geometry was created in gambit and was simulated in fluent.

Properties	Jet
U_j / C	0.75
T_j / T**Error! Reference source not found.**	1.0
P (pa)	101325
ρ (kg/m^3)	1.225561
C (m/s)	340.174
U (m/s)	0.0
T (K)	288
T_{0j} (K)	320.4
Re D	$5*10^4$

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The geometry of 3dimensional circular jet was created in gambit and simulations were conducted in fluent. Simulations were performed on mesh containing 4,27,940 nodes.

Computational Set up

Figure 1 gives an overview of computational set up used Anderson et al [1]. In order to minimize the effect of reflections at the domain outlet of the predicted flow field, a damping zone was added at the domain outlet. The axial extent of the physical part of the domain downstream of the nozzle exit is 2.5 meters, which is equal to 50 nozzle diameters (D_j = 50mm). The radial exit is 10 Dj at the nozzle exit plane and 20 Dj at the domain outlet.

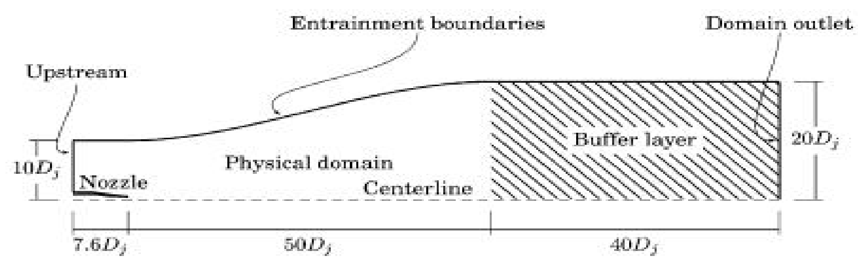

Figure 1 : Computational domain[N.Anderson et.al].

Stagnation conditions were specified at the nozzle inlet and static conditions, equal to ambient conditions were specified at all other places.

III . GOVERNING EQUATIONS

The turbulent flow equations for compressible flows are shown below. The extra turbulent stresses that appear on Reynolds equation are called Reynolds stresses. The normal stresses involve The respective variances of the x, y and z velocity. They are always non-zero because they contain squared velocity fluctuations. The shear stresses contain second moments associated with correlations between different velocity components.

Continuity

$$\frac{\partial \rho}{\partial t} + div(\rho \mathbf{U}) = 0$$

Reynolds equations

$$\frac{\partial(\rho U)}{\partial t} + div(\rho U \mathbf{U}) = -\frac{\partial P}{\partial x} + div(\mu \ grad \ U) + \left[-\frac{\partial\left(\rho \overline{u'^2}\right)}{\partial x} - \frac{\partial(\rho \overline{u'v'})}{\partial y} - \frac{\partial(\rho \overline{u'w'})}{\partial z} \right] + S_{Mx}$$

$$\frac{\partial(\rho V)}{\partial t} + div(\rho V \mathbf{U}) = -\frac{\partial P}{\partial y} + div(\mu \ grad \ V) + \left[-\frac{\partial(\rho \overline{u'v'})}{\partial x} - \frac{\partial\left(\rho \overline{v'^2}\right)}{\partial y} - \frac{\partial(\rho \overline{v'w'})}{\partial z} \right] + S_{My}$$

$$\frac{\partial(\rho W)}{\partial t} + div(\rho W \mathbf{U}) = -\frac{\partial P}{\partial z} + div(\mu \ grad \ W) + \left[-\frac{\partial(\rho \overline{u'w'})}{\partial x} - \frac{\partial(\rho \overline{v'w'})}{\partial y} - \frac{\partial\left(\rho \overline{w'^2}\right)}{\partial z} \right] + S_{Mz}$$

Scalar transport equation

$$\frac{\partial(\rho \Phi)}{\partial t} + div(\rho \Phi \mathbf{U}) = div(\Gamma_\Phi \ grad \ \Phi) + \left[-\frac{\partial(\rho \overline{u'\varphi'})}{\partial x} - \frac{\partial(\rho \overline{v'\varphi'})}{\partial y} - \frac{\partial(\rho \overline{w'\varphi'})}{\partial z} \right] + S_\Phi$$

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IV. RESULTS AND DISCUSSIONS

The simulations on isothermal mach 0.75 circular jet were performed. Axial extent of computational domain is 2.5 m. The model used is sst K-W and pressure based solver with steady conditions were used. The stagnation pressure corresponding to mach 0.75 was specified at inlet. The orthogonal quality of mesh was 0.9.

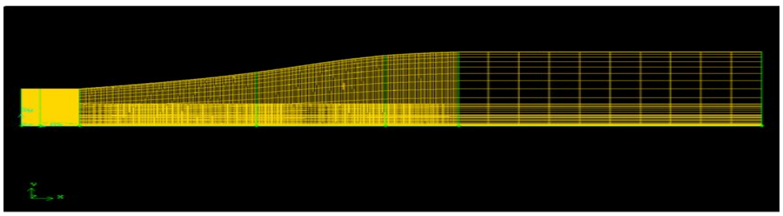


Figure 2 : 3 dimensional mesh

It is very clear from the velocity contour that there exists a region outside the nozzle exit where the velocity remains constant for some time. This region of constant velocity is called potential core.

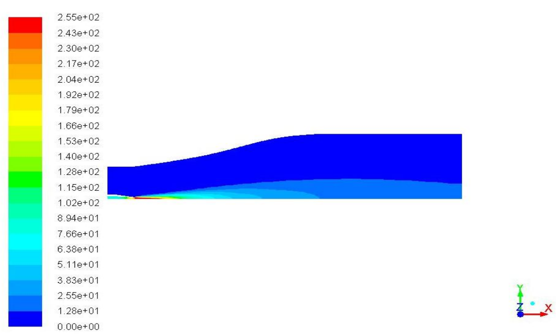
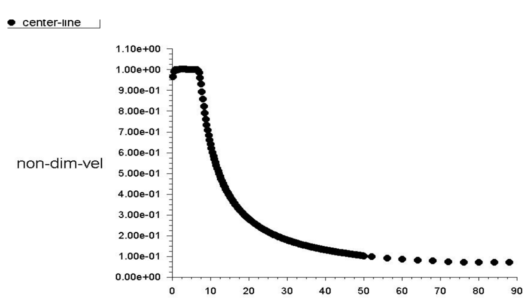


Figure 3 : Velocity contour

Velocity magnitude along the center line throughout the axial distance (4.8 m) is shown in fig 4. The steady line from the nozzle exit clearly mention a region of constant velocity, called as potential core.



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In figure 4 below,the black dotted lines indicate the correlation curve and the red dots indicate experimental values [N.Anderson et.al].The velocity is non- dimensionalised at y axis and axial distance is non-dimensionalised at x axis. It is clear that the maximum velocity is witnessed at the potential core region.The measured values are slightly over predicted compared to experimental values.

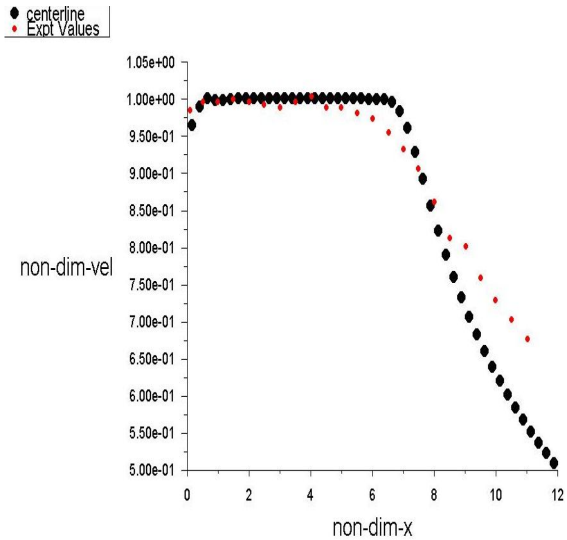

Figure 5 :Center line profiles of time averaged axial velocity

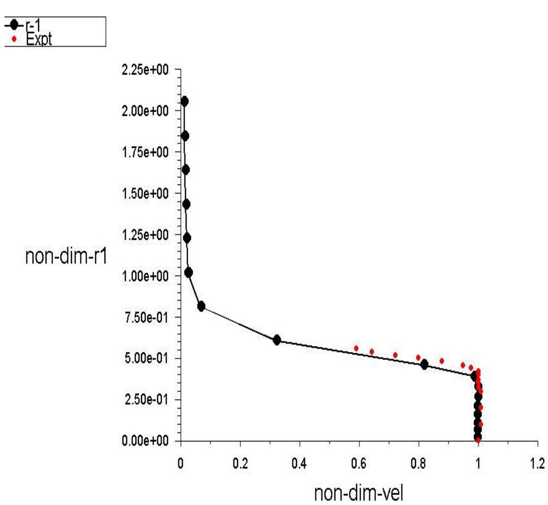

Figure 6 : Radial profiles of axial velocity at X/Dj =1

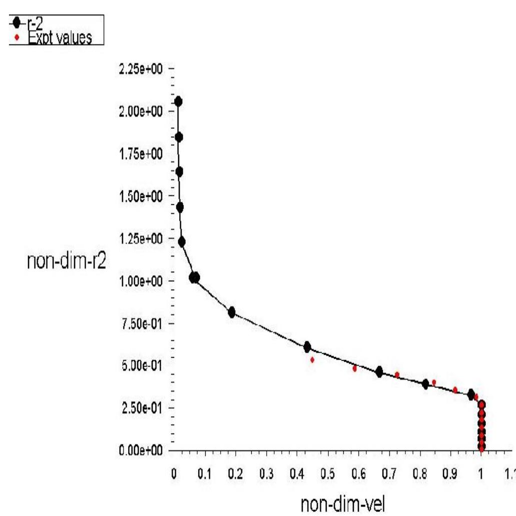

Figure 7 : Radial profiles of axial velocity at X/Dj =2.5

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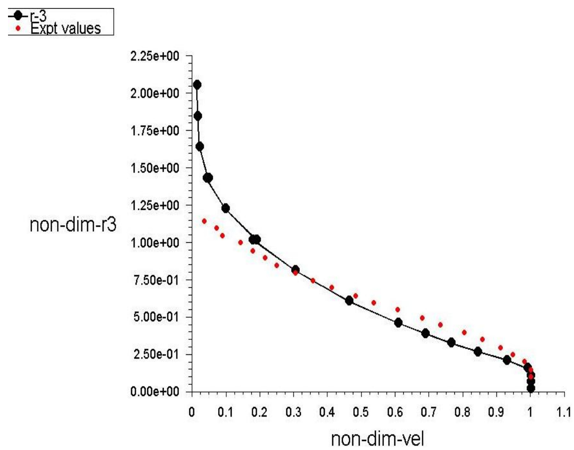

Figure 8: Radial profiles of axial velocity at X/Dj =5

Radial profiles are plotted at three different sections along x axis(X/Dj) namely ; 1,2.5 and 5.There is a decrement in the peak of velocity from X/Dj=1 to 5 ie, the velocity will be maximum at the potential core region some where near to nozzle exit and goes on decreasing as the flow progresses

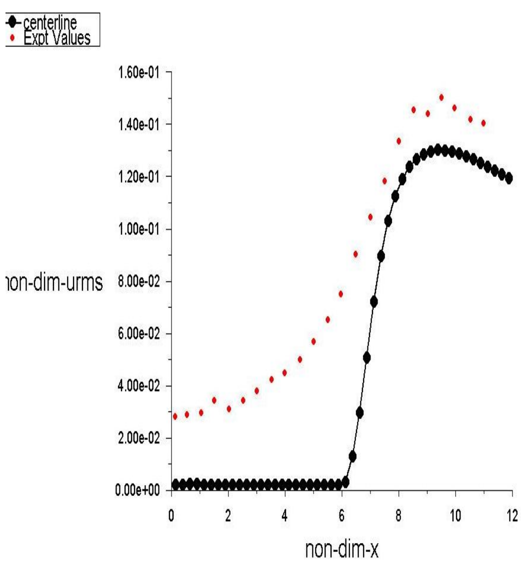

Figure 9 : Axial profile of turbulent intensity : u_{rms}

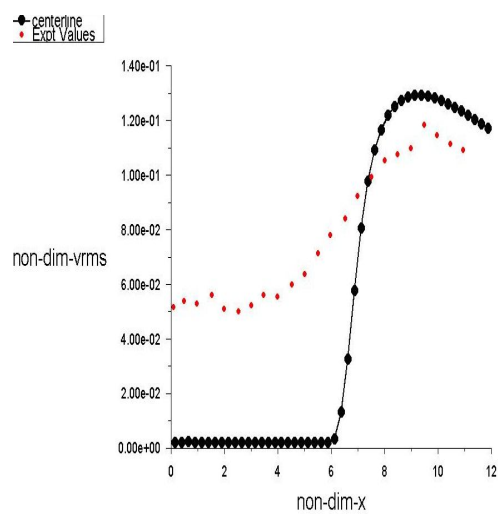

Figure 10 : Axial profile of turbulent intensity : v_{rms}

Figures 9 and 10 shows the non dimensionalized u_{rms} and v_{rms} axial profiles along the centerline. The red dotted points indicate the experimental values Andersson, N.et al [2] and black dotted points indicate the measured values. The difference in levels of u_{rms} and v_{rms} indicate that turbulence anisotropy is captured. The peak levels of turbulent intensity is

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shifted towards the nozzle exit,which is consistent with the underprediction of potential core lengths because maximum turbulent intensity is found where the potential core closes. The variation of measured and experimental values of turbulent intensity , especially at the peak is due to the reason that experimental values are taken from LES calculation which is more accurate compared to RANS, but computationally time consuming and expensive.

V. CONCLUSION

Reynolds Averaged Navier Stokes Equation (RANS) of a compressible Mach 0.75 nozzle/jet configuration is performed. The Reynolds number based on jet velocity and nozzle diameter was $5*10^4$ .Axial and radial profiles of velocity was calculated. Although some deviations occur, the results are generally in good agreement with experiments. The good results are probably attributed to the homogeneity of the mesh used and the fact that a nozzle geometry has been included in the calculation domain. The maximum levels of turbulence intensity was also captured. The initial jet spreading and the potential core lengths are however not predicted correctly. A comparison of heated and isothermal jet can be conducted as a part of future work Anderson et al [1]. More over certain modifications can be made at the nozzle exit to obtain a better mixing characteristics.

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Nomenclature :

c	Speed of sound
D_j	Nozzle outlet diameter
p	Pressure
T	Temperature
L_c	Potential core length
u,v,w	Axial, radial and tangential component of velocity
R_{eD}	Reynolds number based on jet diameter
r	Radial coordinate or distance from the source to observer
x	Flow field location
ρ	Density

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Subscripts

∞	Free stream or ambient condition
0	Total condition
c	Center line
j	Jet ,nozzle exit condition
rms	Root-mean-square
t	Turbulent quality