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CFD Analysis of Supersonic Coaxial Jets on Effect of Spreading Rates

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ABSTRACT

Prevailing high-speed air-breathing propulsion systems invariably banks on coaxial jets which plays a vigorous role in stabilization of flames and combustion emission. Coaxial jets have applications in supersonic ejectors, noise control techniques and enhancement of mixing. Coaxial jet nozzles regulate spreading rates by developing virtuous mean flow and shortening primary flow potential core length. In the present paper, two-dimensional coaxial jet profiles of different area ratios are designed and analyzed. The models were designed in ANSYS Design Modeler and the numerical simulation was done in ANSYS FLUENT 14.5 using the two dimensional density based energy equation and k- ε turbulence model with primary supersonic flow and secondary subsonic flow. The contours of turbulence intensity, acoustics power level and axial-velocity are investigated along the flow direction. This study shows that increasing the area ratio results in less turbulence which in turn increases the potential core length,acoustics power level, turbulent kinetic energy and generates more noise.

Keywords- Coaxial jets, spreading rates, potential core length, noise control, turbulence model, acoustics.

I. Introduction

The study of behavior of fluids developing from coaxial jets is of major concern in many engineering applications. Coaxial jets are simple configurations from which an inner supersonic flow and an outer subsonic flow deliver as shown in fig. 1. From past two decades massive research has been performed over coaxial jets due to their capability to reduce noise, improve combustion and thrust augmentation. They even enhance the mixing flow issuing from the exhaust with ambient air. Even though the fluid mechanics of coaxial nozzle has been studied, the effect of spreading rates has not yet been massively investigated. In ref [1], the compressible spreading rate of supersonic jet flow into the high-speed coflowing secondary jet for circular and triangular nozzles were studied experimentally and numerically.

In general, today’s aircraft engines possess dual stream jets in which a hot high-speed primary flow is surrounded by a cold secondary flow. Compared with single jets, coaxial jets with round nozzles can develop flow structures of very different topology, depending on environmental and initial conditions and, of course, on the temperature gradient between the core (inner) stream and the bypass stream. In the coaxial jet, mixing is achieved mainly due to the velocity ratio, density ratio, compressibility and turbulence levels of the two streams, swirl, pressure gradient and free shear flows.In single jet engines, the spreading rate will be higher which results in generation of more noise and reduction in thrust. The mixing rate of flow with ambient air will be poor. The potential core length (length up to which the effect of shock waves exists from the nozzle exit) will be more.

Coaxial jets are effective in producing turbulence. They control the spreading rates by reducing the growth rate of compressible mixing layer. Entraining of jet flow with atmospheric air is improved by increasing the turbulence. They reduce noise by providing shielding effect to potential flow. They also increase the thrust by reducing potential core length of primary flow.

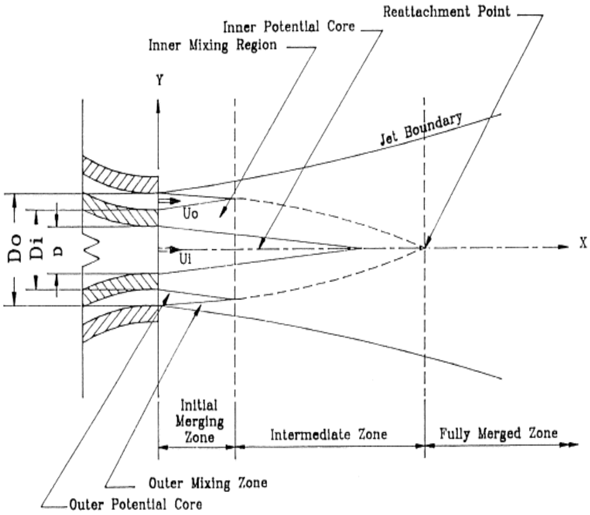


Figure 1- Simple Coaxial Nozzle Configuration

In the present study, detailed characteristics of coaxial jet nozzle shapes of four different area ratios (0.9, 1.8, 2.9 and 4.3) for the effect of flow spreading were analyzed. For all cases, a single axisymmetric convergent divergent nozzle and three conical secondary flow nozzles were examined. The primary and secondary nozzles are provided with Mach numbers 2.7 and 1 respectively.

II. Literature Review

A detailed literature survey of coaxial jets has been studied and some of the important work is specified. In ref. [2], Seung-Cheol Baek, Soon-Bum Kwon, Byeong-Eun Lee, investigated the detailed characteristics of supersonic dual coaxial jets flow issuing from an inner supersonic nozzle and an outer sonic nozzle with various ejection angles. J. Philip Drummond [3] describes a numerical study of mixing strategies to enhance fuel-air mixing and reaction in scramjet engines.

Nicholas J. Georgiadis and Dimitri Papamoschou [4] investigated a series of coaxial dual-streams issuing into ambient air using Reynols-averaged Navier-Stokes calculation with linear two-equation explicit algebraic stress turbulence modelling. Nevin Celik, Daniel W. Bettenhausen and Ryan D. Lovik [5], in their review performed a comprehensive numerical simulation to inter-relate the fluid mechanics of the formation of coaxial jets and their development downstream of the plane of jet emergence.

Marco Debiasi and Dimitri Papamoschou[6], characterized the acoustics of axisymmetric high-speed jets at a variety of Mach numbers and velocities and at pressure-matched, overexpanded and underexpanded conditions.

Looking through the various research works conducted previously, the effect of spreading rates is not yet fully investigated. So, the primary motive of this study is to analyse coaxial jets of various area ratios and get clear idea about the influence of spreading rates on noise and thrust by comparing results of various parameters.

III. Methodology

A.Geometry

The four coaxial nozzle shapes were designed using ANSYS Design Modeler 14.5. Coaxial nozzle arrangements employed a fixed inner (primary) nozzle and outer (secondary) nozzles of different diameters. The primary nozzle has an exit diameter of D_P= 12.7 mm and is designed using Area-Mach number relation for Mach 2.7. Four conical secondary nozzles are used with exit diameters D_S= 17.8, 21.6, 25.4, 29.2 mm. The secondary nozzle has inner and outer converging angle of 11^0 and 23^0. The total length of the nozzle arrangement is 80 mm. Fig. 2 depicts nozzle configurations for the coaxial arrangement with D_s= 29.2 mm. The different coaxial nozzle configurations are summarized in TABLE 1.

Table 1: Coaxial Nozzle Configurations

Nozzle	Secondary Exit Diameter (mm)	D_S/D_P	A_S/A_P
Model 1	17.8	1.4	0.9
Model 2	21.6	1.7	1.8
Model 3	25.4	2.0	2.9
Model 4	29.2	2.3	4.3

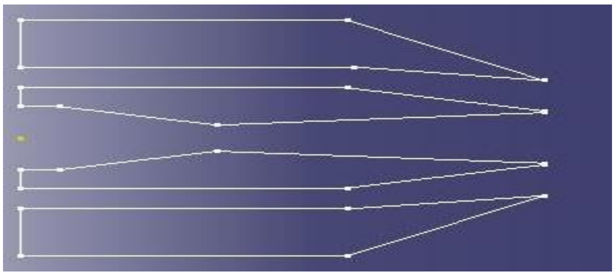


Figure 2- Two-Dimensional Coaxial Nozzle Model

B. Computational Grids

For all the coaxial nozzle configurations listed in Table 1, four zone quadrilateral elements mesh are used. For each of the cases proximity and curvature sizing functions, fine grids are used. All quadrilateral elements constructed have 89950 total points. The grids are extended by $45D_P$ downstream of the nozzle exit and 8 D_P vertically from the axis of symmetry.

C. Computational Method

The solver used in this study is ANSYS FLUENT- Version 14.5. In the current study, linear two-equation formulations are employed to calculate the jet flows. The linear two equation model used here is k- ε standard model and standard wall functions. For every models implicit formulation, AUSM flux type solution methods are used. Flow spatial discretization used is of the order of one.

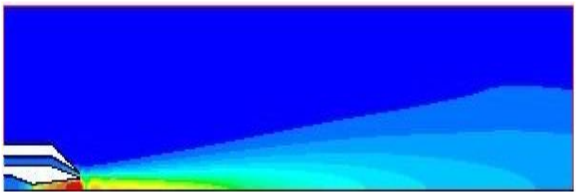
D. Boundary Conditions

Air from reservoir at calculated temperature was supplied to primary and secondary nozzles. The air used here is ideal-gas. The inflow boundary conditions of primary and secondary nozzle flows corresponds to under expanded Mach number of the flow condition. The primary and secondary downstream static pressure is set to 0.9 atm and ambient pressure respectively.

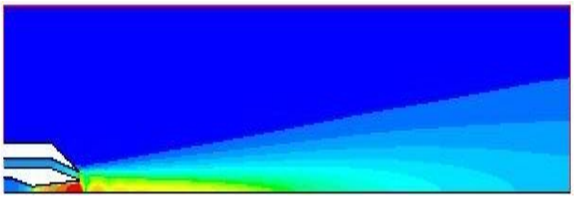
IV. Results and Discussion

The analysis was done till the residuals attain a steady state. The four models analyzed were used to study the effect of spreading rates of flow. In all the cases, the flow from primary nozzle results in under expanded condition at nozzle exit where the observed Mach is 2.69 which is less than the design Mach number 2.7. This is due to displacement of turbulent boundary layer thickness which reduces the effective ratio of nozzle exit area to throat area.

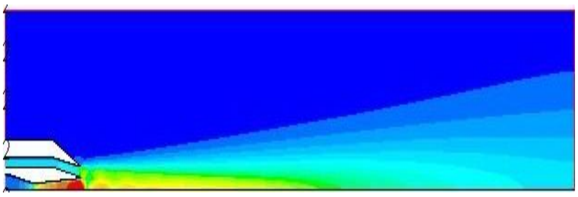
Contours of axial velocity for all the four models are shown in fig. 3. From the figure, we could see that velocity of the flow is large at the exit of the nozzle. Further, downstream the velocity of flow decreases due to rapid mixing with the surrounding air. From this, the primary jet velocity decay rate can be understood. The potential core length of the flow will be more, if jet decays at a slower rate and viceversa.



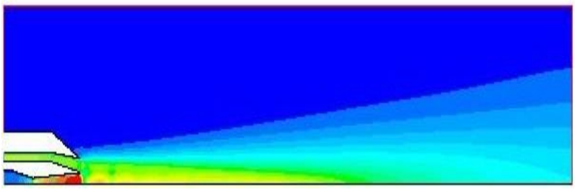
Area Ratio- 0.9



Area Ratio- 1.8



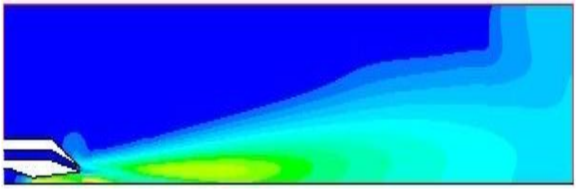
Area Ratio- 2.9



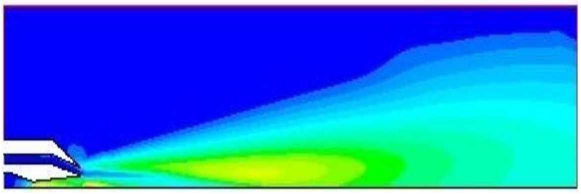
Area Ratio- 4.3

Figure 3- Axial Velocity

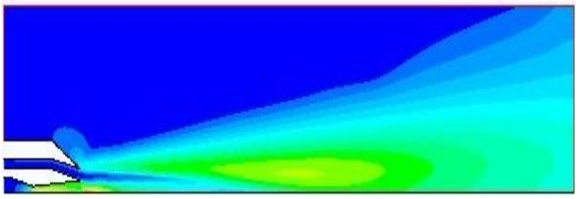
Contours of turbulence intensity are depicted in fig. 4. The model of area ratio 0.9 has a shorter potential core with a region of peak turbulence at upstream of the flow than the others. From the figure, we could see that the flow mixes rapidly at the upstream of the nozzle exit. Figure shows magnitude of turbulence intensity decreases with increasing area ratio. The secondary lip line also shows little difference in the initial region with a fairly constant intensity.



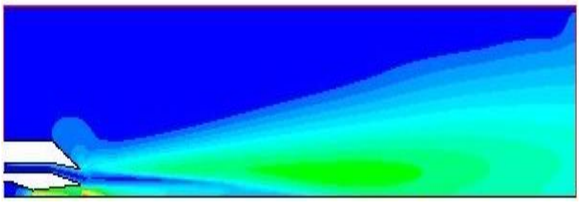
Area Ratio- 0.9



Area Ratio- 1.8

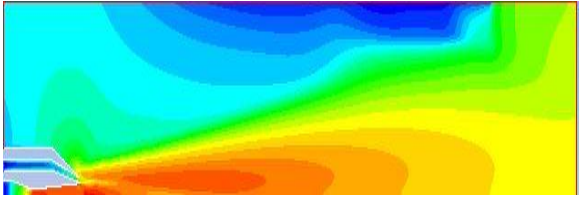


Area Ratio- 2.9

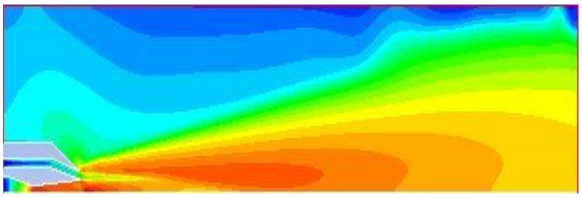


Area Ratio- 4.3
Figure 4- Turbulence Intensity

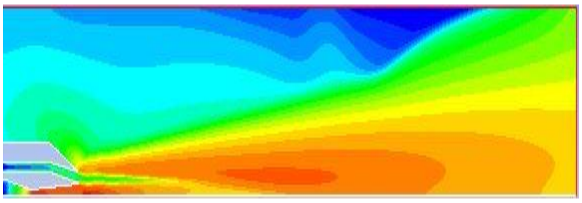
Contours of acoustics power level are shown in fig. 5. It is evident from the fig. that the level of acoustics increases from with area ratio. The model 4 has less acoustics power than the other three models.



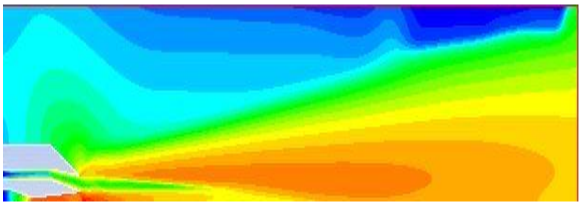
Area Ratio- 0.9



Area Ratio- 1.8



Area Ratio- 2.9



Area Ratio- 4.3
Figure 5- Acoustics Power Level

The profiles of various parameters for all the models were depicted below and discussed. Fig. 6.a depicts velocity profile of model 1. This model has a maximum Velocity 766 m/s.

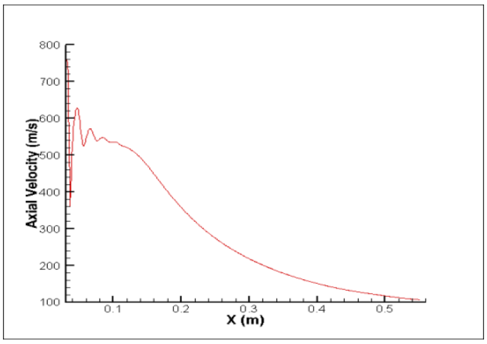


Figure 6.a- Axial Velocity

Fig. 6.b shows acoustics power level for mode 1. This model has a maximum acoustic power level 183 db.

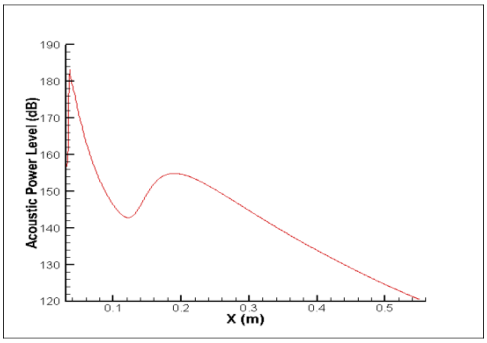


Figure 6.b- Acoustic Power Level

Fig. 6.c shows turbulent intensity profile of model 1. This model has a maximum turbulent intensity 17.7%.

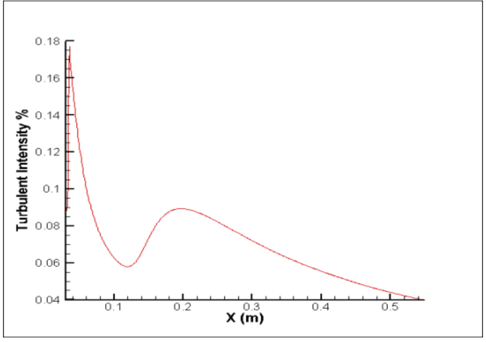


Figure 6.c- Turbulent Intensity

Fig. 7 depicts the flow properties for model 2. Fig. 7.a shows velocity profile of model 2. This model has a maximum Velocity 765 m/s.

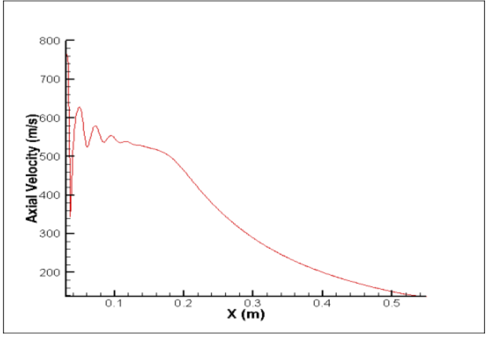


Figure 7.a- Axial Velocity

Fig. 7.b shows acoustics power level for model 2. This model has a maximum acoustic power level 181 db.

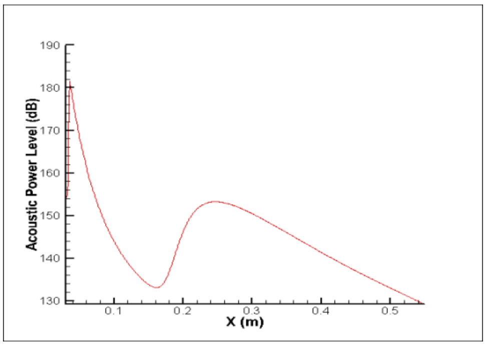


Figure 7.b- Acoustic Power Level

Fig. 7.c shows turbulent intensity profile of model 2. This model has a maximum turbulent intensity 16.5%.

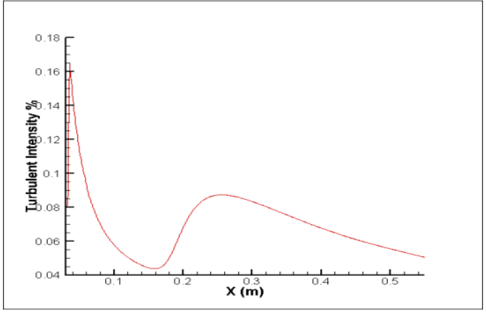


Figure 7.c- Turbulent Intensity

Fig. 8 depicts the flow properties for model 3. Fig. 8.a shows velocity profile of model 3. This model has a maximum Velocity 764 m/s.

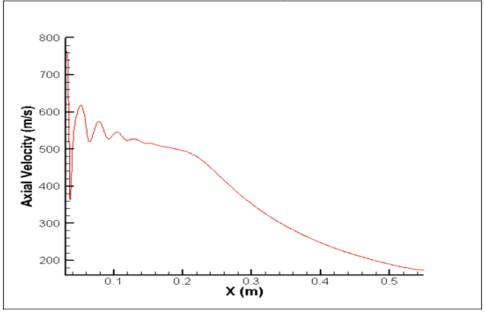


Figure 8.a- Axial Velocity

Fig. 8.b shows acoustics power level for model 3. This model has a maximum acoustic power level 182 db.

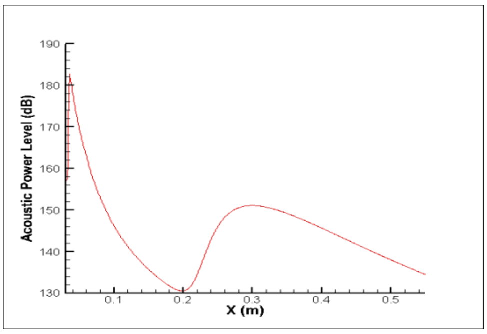


Figure 8.b- Acoustic Power Level

Fig. 8.c shows turbulent intensity profile of model 3. This model has a maximum turbulent intensity 29.5%.

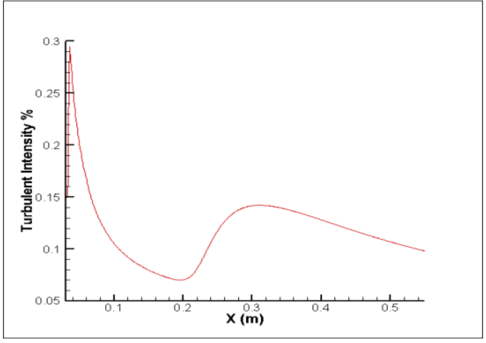


Figure 8.c- Turbulent Intensity

Figure 9 depicts the flow properties for model 4. Figure 9.a shows velocity profile of model 4. This model has a maximum Velocity 763 m/s.

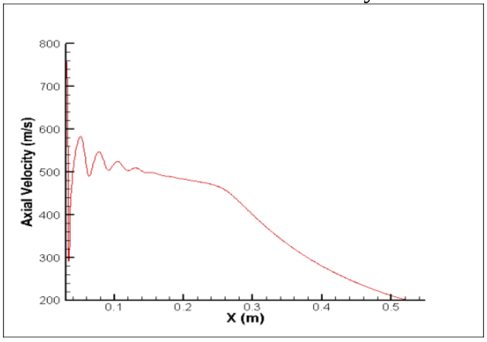


Figure 9.a- Axial Velocity

Fig. 9.b shows acoustics power level for model 4. This model has a maximum acoustic power level 187 db.

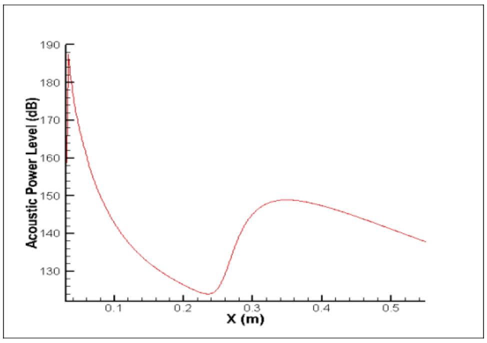


Figure 9.b- Acoustic Power Level

Fig. 9.c shows turbulent intensity profile of model 4. This model has a maximum turbulent intensity 19.15%.

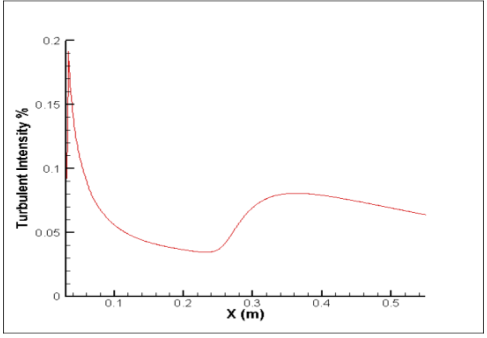


Figure 9.c- Turbulent Intensity

V. COMPARISON

Detailed comparisons of axial velocity, turbulence intensity and acoustic power level are shown in figure 10.The graphs plotted for various variables are from the nozzle exit along the flow direction. It is evident from fig. 10 that the flow properties reaches the peak value at the nozzle exit and decays along downstream direction.

The axial velocity profile shows that increasing the area ratio reduces the exit velocity. The nozzle shape with minimum exit diameter has larger exit velocity. The model of secondary exit diameter D_S= 12.7 mm delivers more velocity 766 m/s whereas the model of secondary exit diameter D_S = 29.2 mm has less velocity than the other three models.

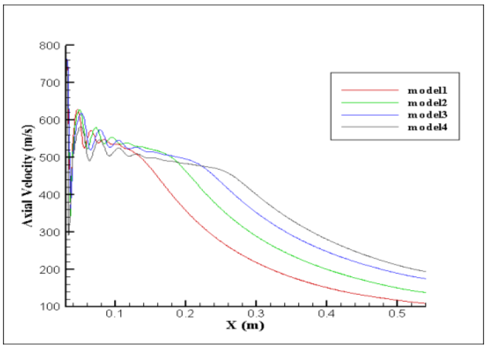


Figure 10- Axial Velocity

The acoustic power level is depicted in fig. 11. From the graph, it is summarized that model 2 generate less noise 181 db and model 4 produces huge amount of noise 187 db.

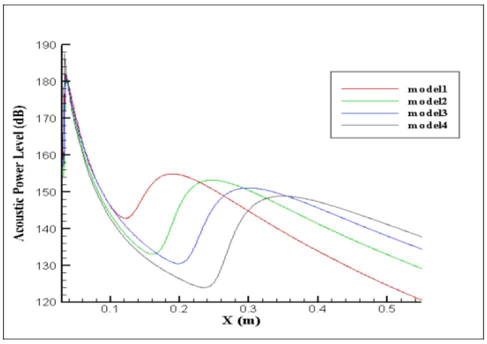


Figure 11- Acoustic Power Level

Fig. 12 depicts turbulence intensity comparison. Model 1 has more turbulence intensity of 19%. This depicts the enhanced mixing of flows from both nozzles and ambient air. The peak of intensity moves along downstream direction.

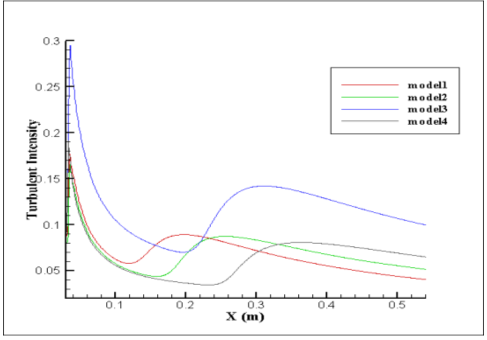


Figure 12- Turbulent Intensity

VI. CONCLUSION

The results of this study indicate that analysis employing linear two-equation turbulence modeling can predict the effect of spreading rates of high-speed coaxial jets reasonably well. The knowledge gained in the computational approach enabled the examination of turbulent kinetic energy in the developing jet.

It was observed that peak kinetic energy magnitude decreased and the location of the peak moved downstream with increasing secondary nozzle diameter. Finally, we can conclude that increasing the area ratio of secondary to primary nozzle increases the spreading rate. This results in less turbulence which results in larger potential core length which in turn reduces the thrust and generation of huge amount of noise. Thus, the model 4 has less turbulence which in turn has less turbulence intensity. So, the model 4 generates less thrust, more acoustic power and huge amount of noise.

VII. Acknowledgement

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