Numerical Characterization of Lip Thickness on Subsonic and Correctly Expanded Sonic Co-flowing Jets*

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Characteristics of co-flowing jets at subsonic and correctly expanded sonic Mach numbers were investigated numerically for three different lip thicknesses namely, 0.2\(D_p\), 1.0\(D_p\) and 1.5\(D_p\) (where \(D_p\) is the exit diameter of the primary nozzle which is 10 mm). Comparisons of numerical flow-field characteristics were made with experimental data. Lip thickness is defined as the thickness of the wall separating primary jet and the secondary jet. It has been found that co-flow with 0.2\(D_p\) lip thickness retards the mixing of the primary jet, leading to potential core elongation. For 1.0\(D_p\) and 1.5\(D_p\) lip thickness, the presence of lip thickness creates a recirculation zone between the primary jet and the secondary jet, which increases turbulence intensity in the near-field region of the co-flowing jet thereby influencing the properties in the near-field, such as potential core length reduction, static pressure rise, etc. Variation in Mach number has less significance in the flow-field characteristics of co-flowing jet.

Key Words: Co-flowing Jets, Lip Thickness, Potential Core, Recirculation Zone

Nomenclature

CFD: computational fluid dynamics
\(D\): nozzle exit diameter
\(M\): Mach number
\(P\): pressure
\(R\): co-ordinate along jet radial direction
\(X\): co-ordinate along jet axial direction
2D: two dimension
\(\nu\): viscosity

Subscripts
\(\text{atm}\): atmospheric conditions
\(e\): primary jet exit condition
\(o\): stagnation chamber condition
\(p\): primary jet exit diameter
\(s\): static condition
\(t\): pitot reading
\(T\): turbulence

1. Introduction

In the evolution of co-flowing jets, lip thickness which separates the main jet and the co-flowing jet, plays an important role in determining the characteristics of co-flowing jets. The behaviour in the near-field of coaxial jets could be considered as wake dominated if lip thickness is crucial. 1) Velocity variations along the axial and radial directions were studied up to \(X/D_p = 2\). The 5 mm spacing between the main jet and co-flowing jet acts as a bluff body that produces a wake. When lip thickness is finite, the near-field behaviour of co-flowing jets becomes wake dominant. By decreasing the lip thickness, wake dominance disappears, as evident in the measurements with a small lip thickness of Ko and Kwan. 2) Beginning from Olsen and Karchmer, 3) a large number of investigations indicate the effect of lip thickness on altering the characteristics of co-flowing jets in an incompressible flow regime such as static pressure rise (which is constant for co-flowing jets with minimum values of lip thickness), turbulence intensity variation in the near field, etc. 4-11) A large recirculation zone was recognized behind the lip region for large values of lip thicknesses, for co-flowing jets with incompressible flow fields at low subsonic Mach numbers ranging from 0.1 to 0.3. 12) Additionally the centerline velocity decay and the intensity of the turbulence were profoundly affected by co-flowing jets with large values of lip thickness. It should be noted here that the co-flowing duct exit diameter was very high when compared to the primary nozzle exit diameter, with an outer to inner diameter ratio of 19.23. Hence, the co-flowing jet has a large influence on the main jet even in low subsonic Mach numbers. In the present study, at high subsonic compressible Mach numbers and at finite values of lip thicknesses, the co-flowing jet influences the characteristics of the main jet even at an outer to inner diameter ratio of 4 and 5 for lip thicknesses 1.0\(D_p\) and 1.5\(D_p\) respectively. For compressible co-flowing jets with small values of lip thickness, say a lip thickness of 0.7 mm, an 80% increase in potential core length was obtained when compared to a single jet. 13) Lovaraju and Rathakrishnan 14) experimentally studied co-flowing jets with a lip thickness 2.65 mm, and reported that co-flow inhibits mixing compared to the single jet at high subsonic and sonic underexpanded levels. The characteristic decay region of the central jet was also retarded in the presence of co-flow. This is because the co-flowing jet, which surrounds the main jet, shields the jet from interacting

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with the surrounding atmosphere, thereby inhibiting mixing. Srinivasarao et al.\textsuperscript{15}) demonstrated that the lip thickness of a co-flowing jet can be effectively used to enhance free-jet mixing considerably. However, in their investigation they studied only the mixing enhancement characteristics by comparing the potential core length of a thick lip and a thin lip. The thick lip was found to be more efficient in promoting mixing of the primary jet when compared to the thin lip. The potential core length reduced to 45% and 58% for the thin and the thick lip, respectively, when compared to the single jet. In other words, when lip thickness increases, the core length decreases and vice versa. But, characteristics like static pressure variation, turbulent viscosity ratio, etc. were not addressed. A nozzle with a thick lip promotes better mixing than a thin lip for sonic underexpanded co-flowing jets.\textsuperscript{16) Sukumar et al.\textsuperscript{17}} reported reduction in core length by varying the velocity ratio between the main jet and the co-flowing jet. A 33% reduction in the potential core length was achieved and the lip thickness was cited as a factor in enhancing mixing. Here the lip thickness was 16.15 mm for Mach 0.4 and 0.5 in both main and co-flowing jets.

The present study numerically investigates a detailed study on the flow characteristics of co-flowing jets for high subsonic and sonic Mach numbers with three different lip thicknesses, motivated from the earlier research based on the effect of lip thickness under compressible flow regimes.\textsuperscript{15–17) Flow characteristics such as static pressure variation, increase in turbulence in the near-field, are discussed.

2. Experimental Configurations

The experiments were conducted at the High Speed Jet Laboratory of Madras Institute of Technology, Anna University in Chennai, India. A convergent circular nozzle surrounded by an annular constant area duct is used in the present investigation. Three lip thicknesses, namely 2 mm (0.2$D_p$), 10 mm (1.0$D_p$) and 15 mm (1.5$D_p$), are used in the present study, as shown in Figs. 1, 2 and 3 respectively. The primary nozzle exit inner diameter is 10 mm ($D_p$) and the co-flowing duct width is 5 mm (0.5$D_p$) for all lip thicknesses.

A Pitot probe is used for measuring the total pressure of the jet emanating from the nozzle. Compressed air is ducted to the settling chamber, where the flow reaches a settled equilibrium. The required stagnation pressure in the chamber can be maintained with the pressure regulating valve. The stagnant air from the chamber expands through the convergent nozzle and the annular duct passage. The pressure in the chamber is controlled to achieve the desired Mach number at the nozzle exit. Free jet flow arrangement is used to carry out the experiments. The Pitot tube mounted on a traverse mechanism is aligned at the centre of the nozzle exit and moved downstream. The Pitot tube is connected to a scanivalve for pressure measurements. The total and static pressure of the co-flow jet is measured along both the axial and radial directions.

3. Computational Method

The computations are performed on a structured grid generated by GAMBIT 2.3.1, as illustrated in Fig. 4. There are a total of about 43,300 cells distributed among the computational domain. Grid points are clustered near the nozzle and at the exit of the nozzle to resolve the near field characteristics such as the recirculation zone, the potential core, etc. The computational flow conditions matched the experimental conditions, that is, the flow through the nozzle comes from a single feed system, with a settling chamber, nozzle and a duct. After the nozzle exit, a domain of 10$D_p$ × 40$D_p$...
is chosen for analyzing the jet mixing at the exit of the nozzle for all three types of jets. Figure 4 shows the sample domain geometry for co-flowing jets with lip thickness 1.0D_p.

### 3.1 Grid independence study

Three sets of grid cells, a coarse grid of about 24,000, a medium grid of about 43,300, and a fine grid of 171,800, are used for the grid-independence study.

The predicted axial decay for the total pressure in the central jet plume is shown in Fig. 5 together with the experimental data, for lip thickness 1.0D_p using Spalart–Allmaras (SA) model (details for choosing the SA model is presented in Sec. 4.1). The results indicate that all types of grids adequately capture the flow field characteristics in the jet plume. The RANS equations are solved using the commercial code FLUENT-6.3.2. The computations are made using a density based solver and in an axisymmetric domain. The inflow boundaries of the primary and secondary nozzle flows specify the nozzle stagnation pressure that corresponds to the ideally expanded Mach number of the flow conditions and are set as per isentropic relations. For Mach 0.6, 0.8 and 1.0, the inlet pressure is set as 1.2755, 1.5243 and 1.893 bar, respectively. The stagnation temperature is set to the ambient static temperature in order to correspond to the conditions of the experiment. The downstream static pressure is set to the ambient pressure. A density based solver is used, and the problem is set to axisymmetric. Green-Gauss cell based gradient option is implemented with an implicit formulation (ref. Fluent 6.3 manual). The Courant–Friedrichs–Lewy number of 0.5 is used for all computations over a few thousand iterations. Converging the momentum equation typically required about 5,000 iterations to reduce the residual by 2–3 orders of magnitude.

### 4. Results and Discussion

#### 4.1 Validation of CFD with experimental results

Before conducting a detailed computation, test cases are run by means of different turbulence models. An extensive set of turbulence models exist, all of which fall into the set of eddy-viscosity formulations. The turbulence models are comprised of a one-equation Spalart–Allmaras (SA) model,\(^{18}\) the linear two-equation k-ε model of Chien,\(^{19}\) and the shear-stress transport (SST) model of Menter,\(^{20,21}\) a two-equation realizable k-ε model,\(^{22}\) Wilcox’s standard k-ω model,\(^{23}\) and the Reynolds-stress model\(^{24}\) (RSM). The SST model employs a k-ε formulation in the inner region of the wall boundary layers and switches to a transformed k-ε formulation in the outer region of the boundary layers and in the free shear layer/mixing regions. It should be noted that the intention here is not so much as to make a detailed evaluation of the different models and their different variants in computing the present flow field. Rather, it is to select one that can represent flow among these models.

The primary jet potential core length (PCL) is defined as the axial extension until the primary exit nozzle velocity prevails for subsonic jets.\(^ {14}\) Figure 6 plots centerline total pressure variation for lip thickness 0.2D_p co-flowing jet, Mach 0.6, for the seven different turbulence models and for the experiment. It is evident that the SA model produces data that agrees well with the experimental data, consistent with its advantage in predicting the flow field characteristics, and the k-ε standard model decays slower than the experiment in the characteristic decay region. Figure 7 plots centerline total pressure variation for the lip thickness 1.0D_p co-flowing jet, Mach 0.6, where recirculation appears behind the lip that dominates the flow field, for the seven different turbulence models and for the experiment. It is again evident that the SA model produces data that agrees well with the experimental data; and for this reason, the SA model is used for the computations in the remainder of this paper.

#### 4.2 Axial Pitot pressure decay

Potential core length, which was defined in Sec. 3.1, primarily determines the mixing characteristics. This means, the faster the decay, the faster the jet mixing is with the entrained fluid mass. The centerline decay can clearly show the extent of the jet core. It can be stated that the potential core of a jet is the distance from the nozzle exit at which the characteristic decay begins. The comparison plot of centerline ve-
locity for lip thicknesses 0.2\(D_p\), 1.0\(D_p\) and 1.5\(D_p\) at Mach 0.6, 0.8 and 1.0 is presented in Fig. 8(a), (b) and (c), respectively. The mixing is inhibited at lip thickness 0.2\(D_p\) and enhanced at lip thicknesses 1.0\(D_p\) and 1.5\(D_p\). The lip thickness 0.2\(D_p\), Mach 0.6 co-flowing jets core becomes elongated and extends up to 8.7\(D_p\). This is because co-flow protects the main jet from interacting with the atmosphere thereby inhibiting mixing.14) For lip thicknesses 1.0\(D_p\) and 1.5\(D_p\), core length gets shortened up to 2.8\(D_p\) and 2.4\(D_p\) with a percentage reduction of 68 and 72% compared to lip thickness 0.2\(D_p\), respectively, due to the formation of the recirculation zone. The effect of lip thickness is well pronounced both in the potential core and characteristic decay region. As the lip thickness is increased from 0.2\(D_p\) to 1.0\(D_p\), due to the presence of significant lip thickness, a recirculation zone is formed in between the main jet and the co-flowing jet, which plays a major role in reducing the potential core and promoting mixing in the near field. The flow field of a co-flowing jet with lip thickness is shown in Fig. 9.

The mixing between two streams is controlled by the dynamics and interaction of vortical structures present in the shear layer developed between the two jets and between the outer jet and the ambient fluid. When lip thickness increases, a large recirculation zone is recognized behind the nozzle wall, specifically in the inner mixing region.12) The intensity of turbulence becomes high due to the wake behind the nozzle wall. Due to the occurrence of high turbulent intensity in the intermediate region, a large momentum transfer between two streams takes place. Hence, if the recirculation zone becomes larger then the mixing enhancement increase occurs between the two streams.25) Thus, a co-flowing jet with a finite lip thickness enhances mixing. A similar trend is observed for Mach 0.8 and 1.0 co-flowing jets and these data are tabulated in Table 1, where lip thickness 0.2\(D_p\) is kept as the base for the analysis of potential core reduction for co-flowing jets with higher values of lip thickness.

The potential core length for lip thicknesses 0.2\(D_p\), 1.0\(D_p\) and 1.5\(D_p\) for Mach 0.6, 0.8 and 1.0 co-flowing jets are tabulated in Table 1, which has almost same value for all three types of jets. Additionally there is not much deviation found in the characteristic decay region. Hence, the effect of Mach numbers stet less pronounced in altering the characteristics of co-flowing jets with lip thicknesses 0.2\(D_p\), 1.0\(D_p\) and 1.5\(D_p\).

### 4.3 Radial Mach number decay

The significant differences between the flow fields corresponding to the three lip thicknesses, 0.2\(D_p\), 1.0\(D_p\) and 1.5\(D_p\) co-flowing jets (Fig. 10), along the axial stations \(X/D_p = 0.1, 1, 2, 3, 4, 6, 8\) and 10, can be deduced from the radial profiles of the non dimensionalised radial Mach number with respect to the exit Mach number of the central jet (\(M/M_c\)).
These plots clearly show the effect of lip thickness in the radial direction. In Fig. 10(a), due to a small value of lip thickness, a minimum Mach number value between the main jet and the co-flowing jet, which almost indicates a wake region, is felt at the particular radial location $R/D_p = 0.6$. At a downstream location, the co-flow begins to interact with the main jet as seen in the plot for $X/D = 1$. With a progressive increase in axial distance, the co-flow and the main jet join together, attaining an equal Mach number. In the stations further downstream, the co-flow jet and the main jet combine to form a single jet. Hence, even in the far-field, the co-flowing jet with lip thickness $0.2D_p$ possesses more kinetic energy compared to a single jet. This implies that co-flow, with relatively lower values of lip thickness, inhibits the jet mixing of the main jet both in the near and far fields significantly.

For a co-flowing jet with lip thickness $1.0D_p$, Fig. 10(b), at $X/D = 0.1$, potential core is recognized until $R/D_p = 0.4$ and in the further radial locations velocity starts decreasing. From $R/D_p = 0.6$, very low velocity prevailed because of the lip region, which almost causes a wake region, and can be clearly seen from the plot. The lip/wake region has only 6 to 12% of the exit Mach number of the primary jet. It extends from $R/D_p = 0.6$ to $R/D_p = 1.4$. Then due to the interference of the co-flowing jet, the radial profile shows an increase after $R/D_p = 1.4$ and attains 91% velocity, as that of the main jet at $R/D_p = 1.7$. After $R/D_p = 1.7$, the radial velocity decreases in further radial locations. The $X/D = 0.1$ shows a velocity bucket-like structure which is almost symmetrical. The base of the velocity bucket shrinks in further axial locations. A similar trend is observed for a co-flowing jet with lip thickness $1.5D_p$.

**4.4. Distribution of static pressure**

As the turbulent mixing of two jets behind the nozzle wall intensifies, a rapid increase of static pressure occurs in the near field. Figure 11 shows the static pressure variation for different lip thicknesses along the central axis. It is clear from the plot that static pressure decreases near the exit due to wake and then increases to attain a peak in the near field and becomes constant after a downstream axial distance.

<table>
<thead>
<tr>
<th>Type of Jet</th>
<th>Mach 0.6 % reduction in potential core</th>
<th>Mach 0.8 % reduction in potential core</th>
<th>Mach 1.0 % reduction in potential core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lip thickness 0.2$D_p$</td>
<td>8.7</td>
<td>8.8</td>
<td>8.8</td>
</tr>
<tr>
<td>Lip thickness 1.0$D_p$</td>
<td>2.8</td>
<td>68%</td>
<td>68%</td>
</tr>
<tr>
<td>Lip thickness 1.5$D_p$</td>
<td>2.4</td>
<td>72%</td>
<td>72%</td>
</tr>
</tbody>
</table>

Table 1. Comparison of co-flowing jets with different lip thicknesses.
The static pressure in this study has the magnitude of gauge pressure which is non-dimensionalised with atmospheric pressure. For lip thickness 0.2\textit{D}_p, non-dimensionalised static pressure at the nozzle exit is 0.998, after which it slowly decreases. There is not much variation in slope and it can be concluded that static pressure variation is negligible for lower values of lip thickness like 0.2\textit{D}_p. For lip thickness 1.0\textit{D}_p, non-dimensionalised static pressure at the nozzle exit 1.006 decreases to 0.974 at an axial distance of \textit{X}/\textit{D}_p = 0.5. After that it starts increasing until \textit{X}/\textit{D}_p = 2.0 and attains a value of 1.032. After this axial location, it again starts decreasing and becomes constant after \textit{X}/\textit{D}_p = 7.0. This shows a static pressure rise of 5.5% atm, which shows a considerable increase when compared to lip thickness 0.2\textit{D}_p. A similar trend is observed for a co-flowing jet with lip thickness 1.5\textit{D}_p. For lip thickness 1.0\textit{D}_p, static pressure rise is at a near field location (\textit{X}/\textit{D}_p = 2.0) when compared to lip thickness 1.5\textit{D}_p (\textit{X}/\textit{D}_p = 2.7). This is due to the formation of a larger recirculation zone for higher values of lip thickness. There is a shift in the occurrence of peak static pressure. This shows a presence of a dominant recirculation zone for lip thickness 1.5\textit{D}_p.

### 4.5. Velocity contour plots

Velocity contour plots are given in Figs. 12(a) to (c), for co-flowing jets with lip thicknesses 0.2\textit{D}_p, 1.0\textit{D}_p, and 1.5\textit{D}_p, respectively, at Mach 0.6. The mirror planes option is used to display contours in both sides of the axis. The result for the lip thickness 0.2\textit{D}_p co-flowing jet is shown in Fig. 12(a). It is evident from this plot that the co-flow with lip thickness 0.2\textit{D}_p protects the main jet core because of the reduced mixing caused by it, thus elongating the potential core. But for lip thicknesses 1.0\textit{D}_p and 1.5\textit{D}_p, Figs. 12(b) and (c), respectively, a recirculation zone is formed between the main jet and the co-flowing jet in the near field region which increases turbulence, thereby reducing the potential core length of the main jet. Further, it is also recognised that the merging position of two streams is far from the nozzle and the recirculation zone becomes larger as lip thickness increases. A similar trend is observed for Mach 0.8 and 1.0 co-flowing jets.

### 4.6. Distribution of turbulent viscosity ratio

As mentioned in Sec. 4.4, the mixing process of both jets is being affected by wake behind the nozzle wall and turbulence intensity increases as the lip thickness increases.\textsuperscript{12} The maximum value of turbulence intensity is high in the case of large values of lip thickness. The turbulent viscosity ratio is defined as the ratio of eddy viscosity (\textit{v}_T) to the molecular viscosity (\textit{v}). A comparison between the turbulent viscosity ratio (\textit{v}_T/\textit{v}) for different lip thicknesses along axial distance is plotted in Fig. 13. For lip thickness 0.2\textit{D}_p, there is only a minimum variation until \textit{X}/\textit{D}_p = 10. But in the region further downstream i.e. \textit{X}/\textit{D}_p > 9, the turbulent viscosity ratio again begins to increase by the effect of joining together with the external stream. In the case of large values of lip thickness, the turbulent viscosity ratio in the near-field (2 < \textit{X}/\textit{D}_p < 9) is largest and it drops as \textit{X}/\textit{D}_p increases. These results are similar to those of Matsumoto et al.\textsuperscript{12} Hence, the turbulent viscosity ratio increases as lip thickness increases. When compared to lip thickness 1.0\textit{D}_p and 1.5\textit{D}_p, at \textit{X}/\textit{D}_p = 5, the difference in peak value of the turbulent viscosity ratio is 32%, which is phenomenal.

### 4.7. Contours of turbulent viscosity ratio

As the lip thickness increases the turbulence intensity behind the nozzle wall increases.\textsuperscript{9} The result for lip thickness 0.2\textit{D}_p co-flowing jet is shown in Fig. 14(a).

It is evident from this contour that the turbulent viscosity ratio behind the nozzle wall is less (attains least value of tur-
bulence) for the lip thickness $0.2D_p$ co-flowing jet when compared to lip thickness $1.0D_p$ and $1.5D_p$, shown in Figs. 14(b) and (c), respectively. In Fig. 14(b), the turbulent viscosity ratio has a higher value behind the nozzle wall when compared to lip thickness $0.2D_p$ (Fig. 14(a)) and a minimum value on the central axis. Similarly, in Fig. 14(c), the turbulent viscosity ratio has a higher value behind the nozzle wall when compared to lip thickness $1.0D_p$ (Fig. 14(b)).

4.8. Near-field axial Mach number profiles

Figure 15 shows the near-field axial Mach number variation of co-flowing jets with different lip thicknesses at Mach 0.6 until $X/D_p = 8$. The variation of both the static pressure and Mach number is caused due to the presence of a recirculation zone in the near-field of co-flowing jets with a significant lip thickness. When the lip thickness is smaller, say $0.2D_p$, no dominant recirculation zone will be formed between the main jet and the co-flowing jet. When the lip thickness increases to a finite value, $1.0D_p$ and $1.5D_p$, the recirculation zone formed between the main jet and the co-flowing jet will be dominant. The Mach number variation in the near-field is primarily due to static pressure variation in the near-field, which is due to the presence of the recirculation zone. Thus, the phenomenon behind Mach number variation is due to the fact that the recirculation zone becomes dominant when lip thickness increases.

5. Conclusion

The computations are able to replicate the experimental observations of the flow field characteristics. The results of this work indicate that RANS calculations employing linear one-equation turbulence modeling (SA) can predict the development of high subsonic and sonic co-flowing jets reasonably well.

Co-flowing jets with lip thickness $0.2D_p$ elongates potential core length. This is because the co-flowing jet protects the main jet from directly interacting with the atmospheric still air, thereby inhibiting mixing. On the other hand co-flowing jets with lip thicknesses of $1.0D_p$ and $1.5D_p$ reduce, the potential core length due to the formation of a recirculation zone between the main jet and the co-flowing jet, thereby enhancing mixing. With lip thickness $1.0D_p$ and $1.5D_p$ potential core length reduction of 68% and 72% are achieved, respectively. Static pressure varies in the near-field for greater values of lip thickness, namely $1.0D_p$ and $1.5D_p$ co-flowing jets, and for $0.2D_p$ co-flowing jets it is almost constant. Similarly, the turbulent viscosity ratio rises in the near-field
for higher values of lip thickness and is constant for lower value lip thickness. Moreover, variation in Mach number for higher values of lip thickness and is constant for lower potential core and in the characteristic decay region.

References


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