Effect of nozzle inlet geometry on underexpanded supersonic jet characteristics

N. Menon and B.W. Skews

School of Mechanical Engineering, University of the Witwatersrand, Johannesburg, Private Bag 3, WITS - 2050, South Africa

Summary. A numerical study has been undertaken on underexpanded sonic jets issuing from nozzles of varied inlet geometries. The Mach stem height in the jet issuing from the contoured nozzle has been the greatest over the range of pressure ratios investigated. A vena-contracta effect has been noted in the jet flow field in the cases of nozzles with sharp inlet geometries. The effect of the inlet geometry is to delay the onset of the typical barrel shock structure seen in underexpanded jets. The distortion of the jet boundary results in a smaller Mach stem for the same pressure ratio and exit Mach number.

1 Introduction

Jet flows are an important part of various mixing and thrust producing propulsion systems. Problems associated with combustion and jet noise have been shown to be associated with the jet structure, particularly the existence of shock waves within the jet. The structure of jet flows from underexpanded axisymmetric nozzles have been investigated fairly rigorously over the past half century commencing with the work carried out by Love et al. [1]. Pack [2] provided a method of characteristics approach as early as 1948 to determine the flow field characteristics of an underexpanded jet. A significant amount of work has also been concentrated on the production of noise as a result of the interaction of the shock wave with the turbulent shear layer of the jet (some of the work can be found in [3], [4], [5], [6], [7], [8], [9] and [10]). In the past work has also been concentrated on understanding the initial inclination of the underexpanded supersonic jet as it exhausted from the nozzle. The inclination of the jet boundary was calculated using a method of characteristics based approach for underexpanded jets at moderate pressure ratios exhausting into a quiescent medium [11], for an underexpanded jet at large pressure ratios exhausting into a quiescent medium [12], and for the case of an underexpanded jet exhausting into a supersonic ambient stream [13], [14]. A number of researchers have utilised the approach of solving the Euler [15] or the Navier Stokes ([6], [16], [17] and [18]) equations in cylindrical coordinates to obtain the flow field within an underexpanded axisymmetric jet.

The underexpanded jets were generated by utilising nozzles that were conically divergent (for supersonic underexpanded jets) or smooth contoured nozzles (for sonic underexpanded jets). The effect of conically convergent inlet geometry on the characteristics of the sonic underexpanded jets has not been investigated in the same detail as the cases mentioned earlier. Addy [19] has provided an empirical relation to predict the location and the size of the Mach stem formed in a sonic jet issuing from a conically convergent sonic nozzle. It was observed that the pressure ratio at the onset of the Mach disk formation increased smoothly and continuously with the convergence angle of the nozzle inlet and the Mach disk structure was observed to be stable when the ratio between the stagnation pressure in the nozzle and the ambient pressure was greater than 5.

2 Numerical set-up

The numerical simulation of the underexpanded jet impingement flow was carried out using the commercially available code Fluent 6. The flow was modeled as a viscous flow, with the one equation Spallart-Allmaras turbulence model for closure of the Reynolds Averaged Navier-Stokes equations. The simulation was performed in steady state and convergence was monitored by the log of the residuals of the equations and using a mass flux balance across the inlet and the outlet boundaries of the model. The computational grid was adapted based on the gradient of pressure to obtain the results of adequate resolution.

3 Results and Discussion

The following nozzle inlet geometries were analyzed to determine the effect of the inlet geometry on the underexpanded jet: contoured inlet, , 45^o inlet and an orifice inlet. The nozzles were analyzed to have sonic exits, with the ratio between the exit plane and the ambient atmosphere being varied between 2 and 10 (the ratio is henceforth referred to as PR).

3.1 General description of the flow field

For small underexpansion ratios of the jet (PR = 2), the contoured nozzle results in a well defined barrel shock structure appearing in the flow field as can be seen in figure 1(A). The barrel shock reflects along the jet centerline as a Mach reflection. For the case of the non-contoured inlets (Figure 4 (B) and (C)), the flow field is markedly different. The expansion waves forming at the nozzle exit reflect at the sonic line in the jet boundary as compression waves. These compression waves do not coalesce to form a shock wave before the reflection point as can be seen in figure 1(B) and (C). As the pressure ratio is increased the strength of the barrel shock increases as can be seen in figure 2. The formation of a Mach stem occurs in all of the examined nozzle inlet geometries. The strength of the barrel shock is at its strongest for the case of the contoured nozzle. The formation of the barrel shock in the jet flow stream is nearest to the nozzle exit in the case of the contoured nozzle (Figure 2 (A)). The height of the Mach stem in the nozzle flow field is lower in the case of the 45^o inlet and the orifice nozzle cases (Figure 2 (B) and (C)). Upon increasing the pressure ratio to PR = 10, the shape of the jet flow field remains

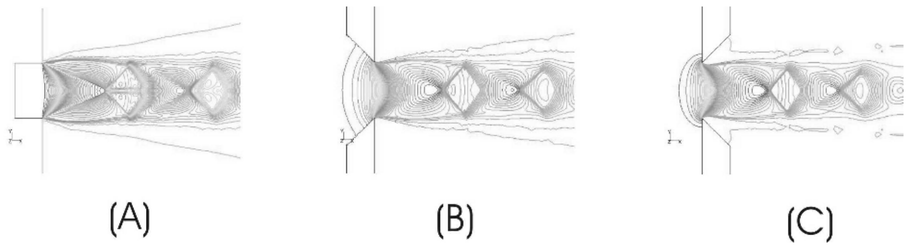

Fig. 1. Density contours of the flow field, M = 1, PR = 2 (A) Contoured inlet (B) 45^o inlet (C) Orifice inlet

essentially similar for the cases of the contoured nozzle and the 45^o inlet nozzle (Figure 3 (A) and (B)). In the case of the nozzle with the orifice inlet however, the expansion of the jet flow as it exits the nozzle is such that the jet boundary touches the nozzle exit face. This causes the jet to expand along the nozzle exit face and not along the jet boundary. The jet boundary in this case originates from the edge of the orifice exit nozzle as can be seen in 3 (C).

3.2 Mach stem heights

A comparison of Mach stem heights non-dimensionalized by the nozzle exit height is shown in Figure 4. The Mach stem height is consistently the greatest for the case of the contoured nozzle. The Mach stem height of the 45^o nozzle inlet is the smallest across the range of pressure ratios examined. The orifice inlet Mach stem height is comparable to the 45^o inlet case until a pressure ratio of 5, after which the Mach stem height for the orifice inlet is greater for pressure ratios of 7 and 10 in comparison the that of the 45^o inlet case. This is as a result of the jet boundary merging with the nozzle exit at higher pressure ratios for the orifice inlet as shown in figure 2 (C). The analytical expressions for the orifice inlet and the contoured nozzle as developed by [19] have also been presented in figure 4 and it is important to note that the analytical expressions under predict the Mach stem height as compared to the simulation results. This is due to the fact that the boundary layer growth in the nozzle geometry has not been accounted for in the case of the contoured nozzle simulation resulting in a flow field that is closer to an inviscid case. The effect of viscosity is evident in the prediction with the analytical expressions as they were developed from experimental results. The effect of inlet turbulence in the development of the jet flow field needs further investigation to ascertain its exact influence.

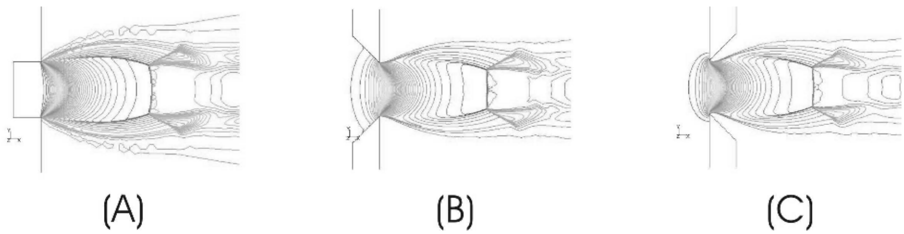

Fig. 2. Density contours of the flow field, M = 1, PR = 5 (A) Contoured inlet (B) 45^o inlet (C) Orifice inlet

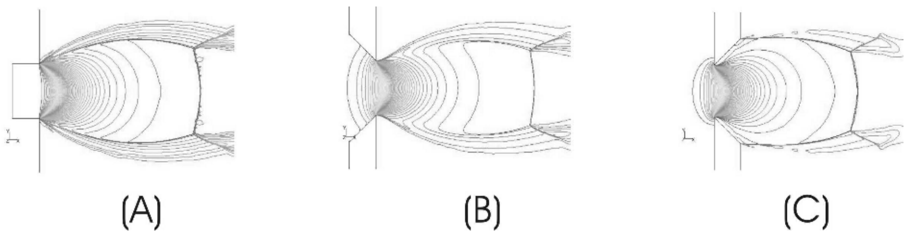

Fig. 3. Density contours of the flow field, M = 1, PR = 10 (A) Contoured inlet (B) 45^o inlet (C) Orifice inlet

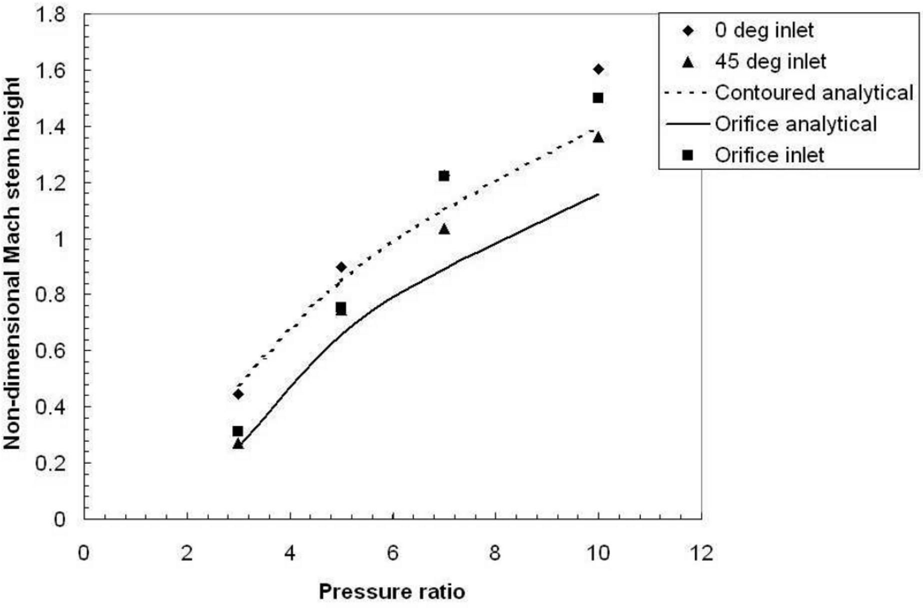

Fig. 4. Non-dimensional Mach stem heights as a function of pressure ratio for various inlet angles

3.3 Effect on jet boundary

The contoured nozzle results in a jet boundary that leaves the nozzle at an angle orthogonal to the nozzle exit face. In the case of the sharp edged nozzle, there is a defined vena-contracta effect that can be seen at the nozzle exit. The vena-contracta effect is most pronounced for the orifice nozzle exit (Figure 5 and 6). There is no discernible change in the shock structure between the jets issuing from the orifice inlet and the 45^o inlet. The vena-contracta in the jet flows results in a narrowing of the jet boundary as it leaves the nozzle exit. This results in a sonic line that is not orthogonal to the nozzle exit

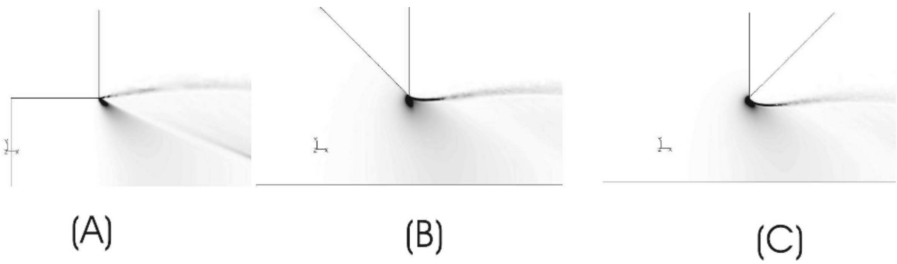

Fig. 5. Pseudo-schlieren images of the flow field in the vicinity of the nozzle exit, M = 1, PR= 2 (A) Contoured inlet (B)45^o inlet (C)Orifice inlet

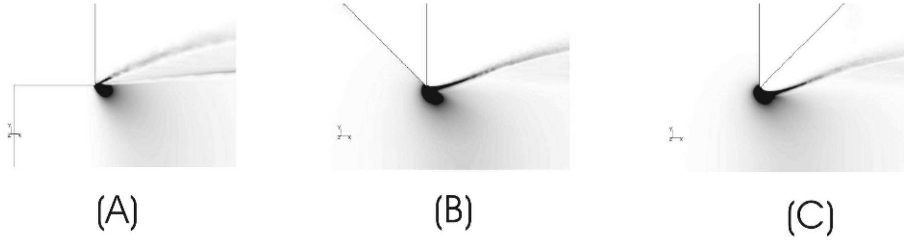

Fig. 6. Pseudo-schlieren images of the flow field in the vicinity of the nozzle exit, M = 1, PR= 5 (A) Contoured inlet (B)45^o inlet (C)Orifice inlet

plane, but curved in space downstream of the nozzle exit. Hence for the case of the 45^o inlet nozzle and the orifice inlet nozzle the flow reaches sonic conditions a small distance downstream of the nozzle exit and not at the nozzle exit in the case of the contoured nozzle.

4 Conclusions

A computational study on underexpanded jet flows issuing from nozzles having varied geometries has been carried out. The main conclusions of the study are:

- The formation of the barrel shock in the jet flow field occurs at the lower pressure ratio in the case of the contoured nozzle in comparison to the other nozzle geometries that have been investigated.
- The Mach stem height is greatest for the case of the contoured nozzle in comparison to the other nozzle geometries that have been investigated over the pressure ratio range between 2 and 10. There is a curvature of the Mach stem in the direction of the flow and the curvature is more pronounced as the pressure ratio is increased.
- The formation of a vena-contracta resulting in a narrowing in the jet boundary is observed in the case of the 45^o and the orifice inlet nozzles.
- The effect of nozzle inlet turbulence needs to be investigated to account for the differences between the analytical prediction of Mach stem height in comparison to the Mach stem height predicted by simulation.

References

1. Love E. S., Grigsby C. E., Lee L. P., and Wooding M. J.: Experimental and Theoretical Studies of Axisymmetric Free Jets, NACA TR R-6 (1959)
2. Pack D. C.: Journal of Mechanics and Applied Mathematics, 1 pp. 1 - 17 (1948)
3. Powell A.: The Aeronautical Quarterly IV pp. 103 - 122 (1953)
4. Powell A.: Proceedings of the Physics Society 66 pp. 1039 - 1057 (1953)
5. Umeda Y. and Ishii R.: Recent Developments in Acoustics 1 pp. 69 - 96 (2003)
6. Siener J. M., Dash S. M., and Wolf D. E.: AIAA Journal, 23 5 (1985)
7. Panda J.: Journal of Fluid Mechanics 363 pp. 173 - 198 (1998)
8. Panda J. and Seasholtz R. G.: Physics of Fluids, 11, 12 (1999)
9. Tam C. K. W., and Jackson J. A.: Journal of Fluid Mechanics, 153 pp. 123 - 149 (1985)

10. Tam C. K. W.: Journal of Sound and Vibration, 121 1 (1988)
11. Love E. S., Woodling M. J., and Lee L. P.: Boundaries of supersonic axisymmteric free jets NACA RM L56G18 (1956)
12. Love E. S, and Lee L. P, Shape of the initial portion of boundary of supersonic axisymmetric free jets at large pressure ratios NACA TN 4185 (1958)
13. Love E. S.: Initial inclination of the mixing boundary separating an exhausting supersonic jet from an ambient supersonic stream NACA RM L55J14 (1956)
14. Vick A. R., Andrews E. H. Jr., Dennard J. S., and Craidon C. B.: Comparisons of experimental free jet boundaries with theoretical results obtained with the method of characteristics NASA TN D-2327 (1964)
15. Katanoda H., Miyazato Y., Masuda M., and Matsuo K.: Shockwaves 10 pp 95 - 101 (2000)
16. Dash S. M., Wolf D. E, and Siener J. M.: AIAA Journal, 23 4 (1985)
17. McDaniel J., Glass C., Staack D., and Miller C.: In Proceesings of the 40th AIAA Aerospace Sciences Meeting and Exhibit (2002)
18. Gribben B. J., Badcock K. J., and Richards B. E.: AIAA Journal 38 2 (2000)
19. Addy A. L.: AIAA Journal 19 1 (1981)