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Aspect Ratio Effect on Mach 1.5 Rectangular Jet Mixing

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ABSTRACT An experimental investigation on the mixing characteristics of Mach 1.5 rectangular jet emanating from aspect ratios (*AR*s) 2 and 3 convergent-divergent nozzles is carried out at nozzle pressure ratios (*NPR*s) 3, 3.69, 4 and 5, respectively. At overexpanded (*NPR* 3), correctly expanded (*NPR* 3.69) and underexpanded (*NPR*s 4, 5) levels of Mach 1.5 jet, the Pitot pressure measured along the centerline of *AR*2 and *AR*3 rectangular jets showed that the influence of aspect ratio on the jet mixing is not as strong as expected. The effect of aspect ratio is noticeable only in the core of both the jets. The core length of *AR*2 jet is shorter than *AR*3 jet at all the *NPR*s, which indicates faster mixing of *AR*2 jet with ambient fluid as compared to *AR*3 jet. But after core, the decay of *AR*2 and *AR*3 jets in the characteristic decay region remained almost same at all the *NPR*s except at correctly expanded *NPR* of 3.69, the *AR*3 jet decays slightly faster than *AR*2 jet. For all the cases, the jets have become fully developed together at far downstream location. The pressure profiles taken along major axis and minor axis of Mach 1.5 rectangular jets confirm the faster spreading of *AR*2 and *AR*3 jets along minor axis than along major axis. Both the jets are found to switch axes between $8D_e$ to $10D_e$. The shadowgraph visualization reveals the complex structure of waves present in the major axis and minor axis planes of *AR*2 and *AR*3 rectangular jets.

INDEX TERMS Core length, jet mixing, rectangular jet, aspect ratio.

I. INTRODUCTION

It is well known that the evolution of jet is strongly dependent on the initial conditions at the exit of nozzle. The jet flow field can be affected by the exit shape of the nozzle, aspect ratio, initial turbulence level and Reynolds number [1]. The study of noncircular jets emerging from square, triangular, rectangular or elliptical nozzles has proved their superiority over equivalent circular jet, in terms of improved mixing characteristics, jet noise reduction, increased entrainment and faster mean velocity decay along the jet axis [1]. The use of noncircular geometry as a passive control essentially aims at modifying the mixing and acoustic characteristics of jets. A passive jet control is preferred over active control due to its simplicity, and it doesn't require an auxiliary power source like active control methods. It is well proved that controlling the jet can greatly improve the performance of many systems. For instance increasing fuel–air mixing in combustion chamber, reducing infrared signature and noise level, gas dynamics lasers, thrust vector control are some of the applications of jet control.

Compared to other noncircular jets, rectangular jets combine the aspect ratio feature and azimuthal asymmetry of an elliptic jet along with vertex features of the square jet [1]. Earlier experiments on incompressible rectangular jets showed that the flow field of rectangular jets is characterized by three distinct regions namely potential core, two-dimensional and axisymmetric regions [2], [3]. The extent of these regions is found to be functions of both the initial geometry and aspect ratio of the nozzle [3]–[5]. The beginning of second region (two-dimensional region) is the location where shear layer separated by short dimension of the nozzle meet [6]. Several experimental studies on noncircular jets (which include rectangular jet) confirm the occurrence of axis switching in noncircular jets [7]–[13]. Axis switching is a phenomenon in which the cross section of a noncircular jet evolves in such a manner that, after a certain distance from the nozzle, the major and minor axes are interchanged [14]. This phenomenon of axis switching in noncircular jets is the reason for their increased entrainment properties [1].

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The mixing characteristics of noncircular supersonic jets are found to be similar to subsonic noncircular jets [1]. For underexpanded rectangular jet from moderate aspect ratio convergent nozzle, the increased growth rate of jet along minor axis than along major axis is observed for pressure ratios 3 to 4.5 [15]. With increase of aspect ratio from 2 to 4 for underexpanded rectangular jet, the shape of rectangular jet boundary is more affected along minor axis than along major axis at pressure ratios 2 and 3 [16].

The cold and hot-flow tests on small aspect ratio (3:1) elliptical and rectangular jets from convergent nozzles showed that the rectangular and elliptic jets spread faster than the equivalent circular jet at subsonic, sonic and supersonic conditions [17]. The higher spreading is due to self-induction process [1] which resulted in enhanced mixing of noncircular jets. An extensive experimental investigation [18] on the spreading characteristics of compressible jets from different asymmetric convergent nozzles (which includes rectangle nozzle of aspect ratio 3:1) at Mach number, M = 0.3 to 2 showed that the asymmetric jets spread only slightly faster at subsonic Mach number compared to relatively faster spreading at supersonic conditions. For elliptic and rectangular jets at supersonic condition, the axis switching occurred by 10 equivalent diameters from the nozzle exit [18].

For a small-scale model of F-22 jet engine rectangular nozzle (M = 1.5) of *AR*1.75, a detailed Pitot survey confirmed the axis switching of rectangular jets as well as the influence of shocks on the location of axis switching [19]. The imperfectly expanded rectangular jets from F-22 jet engine nozzle model switched their axes at 4.5 times the average height of the rectangular jet, whereas perfectly expanded jet switched axes at an average height of 6.5 from the nozzle exit. The location of axis switching, thus the jet mixing characteristics can be modified by the use of flow control. The location of axis switching for rectangular jet is found move upstream when two delta-tabs are used along the major axis of rectangular nozzle exit [18]. A diagonally placed ramp is also proved to be effective in controlling the mixing characteristics of Mach 1.8 rectangular jet from AR2 convergent-divergent nozzle [20]. In addition to modifying the mixing characteristics of jets, a jet control can also modify the jet acoustic characteristics. For perfectly expanded supersonic rectangular jets (M = 1.5, 1.75 & 2) [21], an annular coflow is said to eliminate Mach wave radiation which is considered as a dominant source of supersonic jet noise. For screeching Mach 1.44 rectangular jet of AR4, the dominant source of acoustic waves is detected at the end of the fifth shock-cell [22]. It is observed that the screech tones found in the near field of underexpanded rectangular jet can affect the overall jet flow field leading to increased spreading of the rectangular jet [15]. The effect of temperature on screech is found to be significant particularly at elevated temperature. For high temperature ratio of 3, the screech is eliminated for Mach 1.5 rectangular jet of aspect ratio 2 at all the levels of expansion [23]. Unlike screech the dependence of shock-cell structure on temperature is weak. The shock-cell structure remains unaffected near the exit of nozzle but the shock-cells decay faster with increasing temperature indicating a weak dependence on the temperature [24].

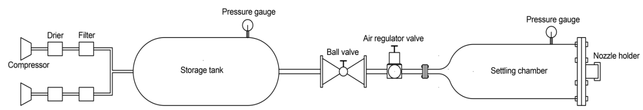


FIGURE 1. Layout of jet facility.

The supersonic rectangular jet literature showed that most of the experimental investigations are mainly focused on the underexpanded rectangular jets from convergent nozzles/orifices of rectangular shape. Few works on supersonic rectangular jets from convergent-divergent rectangular nozzles are mainly focused on understanding their acoustic characteristics rather than the effect of aspect ratio on the mixing characteristics of supersonic rectangular jets. The need for investigating the effect of aspect ratio on supersonic rectangular jet mixing is clear from the literature. Also, the individual works on different aspect ratio rectangular jets cannot be compared directly as their Mach number, Reynolds number and test conditions are different from each other. Therefore, in the present work, the Mach 1.5 rectangular jets from aspect ratios 2 and 3 convergent-divergent rectangular nozzles are studied experimentally at different levels of expansion. For both the nozzles, the experiments are conducted for nozzle pressure ratios (*NPRs*) 3, 3.69, 4 and 5, covering overexpanded (*NPR* 3), correctly expanded (*NPR* 3.69) and underexpanded (*NPRs* 4, 5) levels of Mach 1.5 jet. A detailed Pitot pressure measurement is made to quantify the mixing characteristics of Mach 1.5 rectangular jets from *AR*2 and *AR*3 nozzles. The waves present in the Mach 1.5 rectangular jets are visualized using shadowgraph technique.

II. EXPERIMENTAL DETAILS

A. OPEN JET FACILITY

The experiments are carried out in the open jet facility available at High Speed Aerodynamics Lab, SRM Institute of Science and Technology (SRMIST), Kattankulathur, India. The schematic layout of the jet facility at SRMIST is shown in Figure 1. The air from the two compressors of 20 horsepower capacity each, is dried, filtered and stored in the cylindrical storage tank of 14 m^3 capacity. The compressed air at 10 bar from the storage tank is supplied to the settling chamber through a ball valve and air pressure regulator and then it is made to pass through Mach 1.5 convergent-divergent (C-D) rectangular nozzle model mounted (using nozzle holder) at the settling chamber end. The required nozzle pressure ratio (*NPR*) is achieved by controlling the settling chamber pressure (P_0) using the pressure regulator.

B. NOZZLE MODELS

The convergent-divergent rectangular nozzle models of the present study are made of brass. The models include *AR*2 and *AR*3 C-D nozzles with design Mach number of 1.5. For both the models, the cross-section is rectangular from inlet to exit,

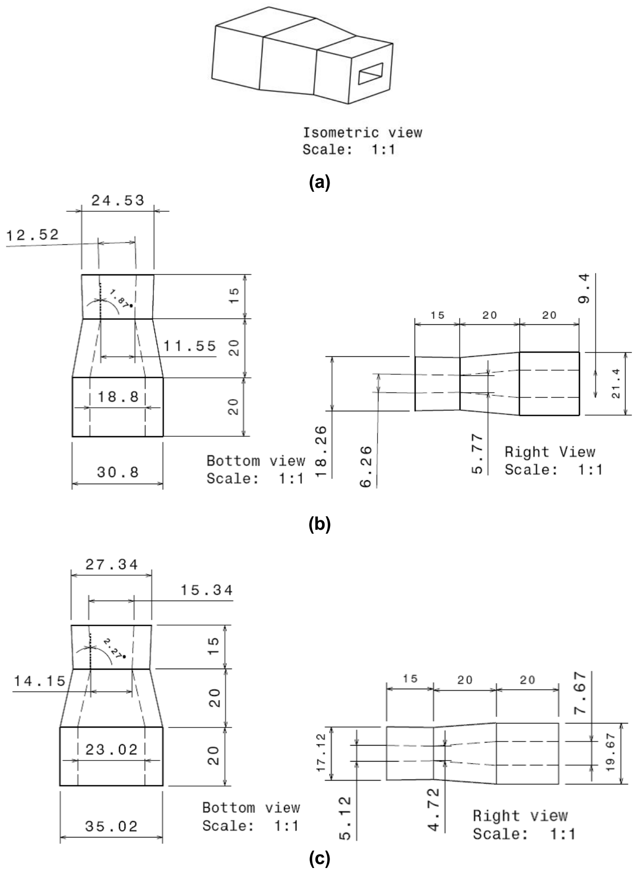


FIGURE 2. **(a) Nozzle isometric view, (b) *AR*2 nozzle dimensions (in mm), (c) *AR*3 nozzle dimensions (in mm).**

with the same inlet, throat and exit areas. Both the nozzles delivered uniform supersonic flow of Mach 1.5 ± 0.02 at all the *NPR*s. An isometric view of a nozzle and the dimensions of *AR*2 and *AR*3 C-D nozzles are shown in Figure 2.

C. INSTRUMENTATION AND DATA ACCURACY

A Pitot tube with outer diameter 1 mm and inner diameter 0.8 mm is used along with the pressure scanner (Sunshine Measurements Pvt. Ltd.) to make detailed pressure measurement in the jet field. The blockage due to probe is said to be negligible if the ratio of the nozzle exit area to the pitot probe area is greater than 64 [25]. For the probe of outer diameter 1 mm in the present work, this ratio is found to be 100, which is well above the limiting value for neglecting the blockage effects due to probe. The piezoresistive pressure transducer has a range of 0 to 10 bar. The response time of the pressure sensor is 1 ms. The pressure measurement is done at a sampling frequency of 100 Hz which is later averaged to get a single value of pressure. Hence, each measured pressure value in the present study is an average of 100 samples. The pressure transducer is calibrated regularly by supplying a known pressure from a pneumatic pump. The accuracy of the transducer is ± 0.5% full-scale. The repeatability of the pressure measurements is within ± 3%. For the present investigation, the settling chamber pressure is maintained within

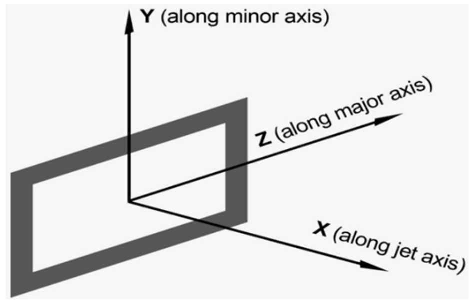


FIGURE 3. **Schematic of coordinate system.**

± 2% for all the *NPR*s studied. The movement of the Pitot probe along jet centerline, major axis and minor axis is carried out with the help of a traverse with a resolution of ±0.1 mm in the linear translation. The coordinate system used for the measurement is shown in Figure 3. The waves in the core of Mach 1.5 rectangular jets are visualized using shadowgraph technique. The visualization setup includes a helium spark arc light source which is used in conjunction with a concave mirror of 200 mm diameter and 2.2 m focal length. The visualization is carried out with continuous illumination and the shadowgraph images projected on a screen are recorded using a still camera.

III. RESULTS AND DISCUSSION

The measured Pitot pressure in a supersonic jet field is not the actual total pressure but the total pressure behind the bow shock standing in front of the probe. The Pitot pressure cannot be corrected for shock loss as the total pressure changes from point to point in all the directions in the supersonic jet field due to the presence of compression and expansion waves. Therefore, the measured pitot pressure cannot be used to calculate the Mach number as in the case of subsonic jets. However the Pitot pressure data is accurate enough to study the overall characteristics of supersonic jet [26]. The measured Pitot pressure is nondimensionalized with respect to settling chamber pressure and used as such to discern the mixing and spread characteristics of jets. It is worth mentioning that the settling chamber pressure is the main control parameter dictating the nozzle pressure ratio, thus the expansion level of the supersonic jet.

A. CENTERLINE PITOT PRESSURE DECAY

The Pitot pressure measurement along the jet centerline up to $25D_e$ is done to understand the decay characteristics of Mach 1.5 rectangular jets of *AR*2 and *AR*3. The measured centerline Pitot pressure (P_t) nondimensionalized with settling chamber pressure (P_0) is plotted against nondimensionalized axial distance (x/D_e) for all the *NPR*s. The comparison of centerline Pitot pressure decay (*CPD*) of Mach 1.5 rectangular jets of *AR*2 and *AR*3 for *NPR* 3, 3.69, 4 and 5 is shown in Figures 4, 5, 6 and 7 respectively. The presence of Pitot pressure oscillations up to certain distance in the plots is due to the presence of compression and expansion waves in the core of supersonic jet. The end of this oscillation indicates

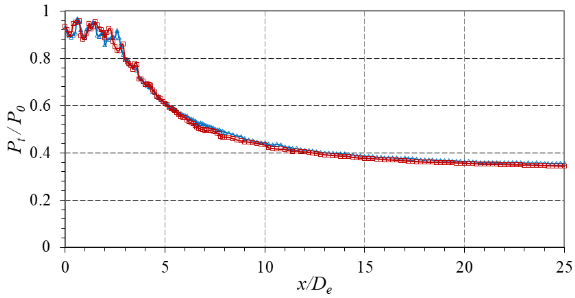


FIGURE 4. ***CPD* of rectangular jets at *NPR* 3, △ – *AR*2, □ – *AR*3.**

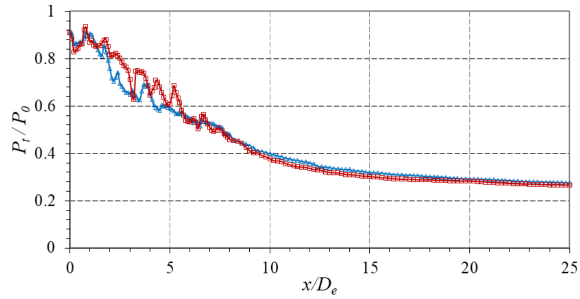


FIGURE 6. ***CPD* of rectangular jets at *NPR* 4, △ – *AR*2, □ – *AR*3.**

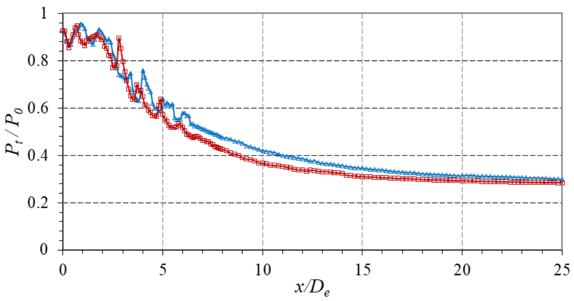


FIGURE 5. ***CPD* of rectangular jets at *NPR* 3.69, △ – *AR*2, □ – *AR*3.**

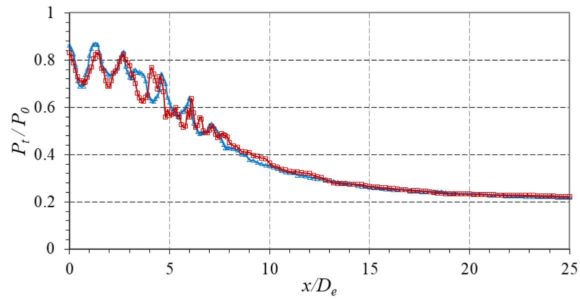


FIGURE 7. ***CPD* of rectangular jets at *NPR* 5, △ – *AR*2, □ – *AR*3.**

the end of supersonic core length. The core of supersonic jets does not possess constant centerline velocity like subsonic jets because of the wave dominated supersonic jet field. Hence, the core for a supersonic jet is usually taken as the axial extent up to which the supersonic flow prevails [26]. The length of this supersonic core is usually referred as supersonic core length in literature [27]–[29]. The supersonic core length is an important parameter that quantifies the jet mixing; shorter the core, faster is the jet mixing with the ambient fluid [26]. The distance between two successive peaks of pressure corresponds to the shock-cell length. Also, the pressure oscillations in the core reflect the strength of the shock-cell structure in the jet field.

At *NPR* 3 (Figure 4), the Mach 1.5 jet is said to be overexpanded. For *NPR* 3, the core length of *AR*2 is about $3.3D_e$ as compared to $4D_e$ for *AR*3 jet. From the pressure oscillations it is seen that only the first shock-cell of *AR*2 and *AR*3 jets are of same strength and length. After the first shock cell the pressure oscillations are different for both the jets. Immediately after the core, both *AR*2 and *AR*3 jets decay at the same rate to become fully developed at around $13D_e$. When the *NPR* is increased from 3 to 3.69 (Figure 5), the core length of *AR*2 and *AR*3 jets increased to about $6D_e$ and $6.6D_e$, respectively. The *NPR* 3.69 for Mach 1.5 jet corresponds to correct expansion. It is seen that at correct expansion also, the *AR*3 jet has longer core than *AR*2 jet. The waves in both the jets are of different strengths as evident from the noticeable difference in pressure oscillations. It is interesting to note that *AR*3 jet is found to decay slightly faster than *AR*2 jet from $5D_e$ onwards, but both the jets become fully developed at around $15D_e$. At *NPR* 4 (Figure 6), the jet is said to be marginally underexpanded as the correct expansion for Mach 1.5 jet is 3.69. At this *NPR* also, the core length of *AR*2 jet is shorter than *AR*3 jet as in *NPR*s 3 and 3.69. The core lengths of *AR*2 and *AR*3 jets are found to be $6.8D_e$ and $7.4D_e$, respectively. Like *NPR* 3.69, the *AR*3 jet at *NPR* 4 shows slightly faster decay than *AR*2 jet after core, but not as evident as in *NPR* 3.69. The larger magnitude of pressure oscillation in *AR*3 jet compared to *AR*2 jet is an indication of stronger waves in *AR*3 than *AR*2. At the highest studied *NPR* of 5, the jet is moderately underexpanded. At *NPR* 5 (Figure 7), the core of *AR*3 jet extends up to $7.7D_e$ whereas for *AR*2 jet, it is only $7.1D_e$. From $10D_e$, both the jets decay gradually at the same rate to become fully developed after $15D_e$. The variation of nondimensionalized core length (L_c/D_e) of *AR*2 and *AR*3 jets with *NPR* is presented in Figure 8. It is seen that the core length of both the jets increases with *NPR*. The core length of *AR*3 jet is longer than *AR*2 jet at all the *NPR*s. It is interesting to note that the rate of increase of core length with *NPR* for *AR*2 and *AR*3 jets remains same.

The centerline Pitot pressure decay of *AR*2 and *AR*3 jets at *NPR*s 3, 3.69, 4 and 5 showed that the aspect ratio has a clear effect on the core length. The aspect ratio effect is minimal in the characteristic decay and fully developed zones of the Mach 1.5 rectangular jets. At all the *NPRs*, the *AR*2 jet is found to possess shorter core than *AR*3 jet which is an indication of better mixing of *AR*2 jet immediately after exiting the nozzle. However, the shorter core of *AR*2 jet doesn't lead to faster decay after the core. After core both the jets decay almost at the same rate. At *NPR*s 3 and 5, the pressure curves of *AR*2 and *AR*3 jets are found to even overlap each other. The difference in pressure oscillations in the core of both the jets confirms the presence of compression and expansion waves of varying strengths. From the present work, it is clear that

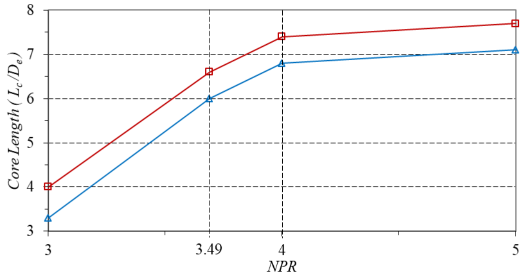


FIGURE 8. Variation of core length with *NPR*, △ – *AR*2, □ – *AR*3.

the aspect ratio has an influence only in the near field of the Mach 1.5 rectangular jet not in the far field.

It is well known that the rectangular jet exhibits better mixing characteristics than the equivalent circular jet because of the mixed size of vortices shed from the rectangular nozzle exit. The higher mixing and entrainment of the rectangular jet lead to shorter jet core compared to equivalent circular jet [24]. The large-scale azimuthal vortices generated at flat sides of nozzle exit along with the small-scale streamwise vortices from the sharp corners result in better mixing promotion compared to an equivalent circular jet [1]. The change of aspect ratio in the present study manipulated the complex interaction of these large and small-scale vortices, thereby by modifying the mixing characteristics of the jet. This in the case of *AR*2 jet resulted in better mixing than the *AR*3 jet, though the better mixing is only in the near field of the jet as evident from the *CPD* results.

B. PRESSURE PROFILES

To understand the spread characteristics and development of Mach 1.5 rectangular jets of *AR*2 and *AR*3, the pressure measurement is carried out along *y* (minor axis) and *z* (major axis) directions at different axial locations.

The profile plots along *y* and *z* axes at selected axial locations for *AR*2 and *AR*3 jets at *NPR* 3.69 alone are shown in Figures 9 and 10, respectively. The results confirm that the rectangular jets spread differently along *y* and *z* directions. Both the jets spread faster along minor axis than along major axis. The jet width along *y* axis increases at a faster rate than along *z* axis. For all the *NPR*s, the pressure profiles within the core showed fluctuations because of the presence of shock-cells. The off-center peaks in the pressure profiles confirm the presence of shock-cells in the supersonic core. From Figures 9 and 10, it is seen that from $8D_e$ onwards, both the jets show only one peak and the pressure profiles along *y* and *z* axes of *AR*2 and *AR*3 jets coincide, indicating the jet has become axisymmetric. This location is usually taken as axis switching location. Axis switching is the outcome of faster growth rate of the jet shear layers in the minor axis plane than in the major axis plane [1]. In the present work, both *AR*2 and *AR*3 jets are found to switch their axes between $8D_e$ and $10D_e$.

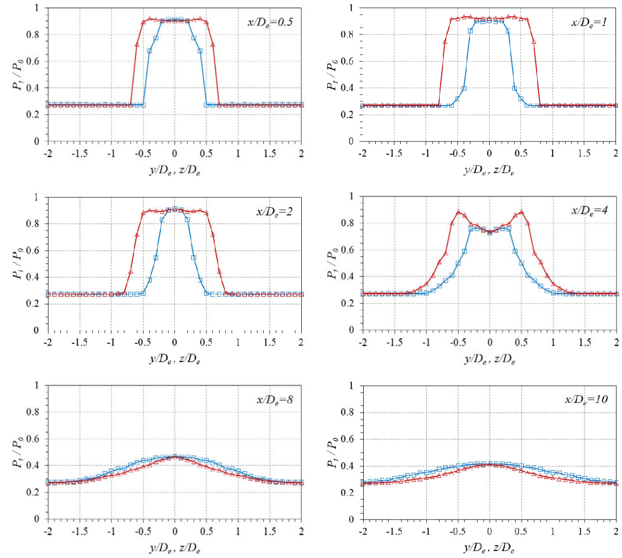


FIGURE 9. Pressure profiles of *AR*2 jet at *NPR* 3.69, △ – along *y* axis, □ – along *z* axis.

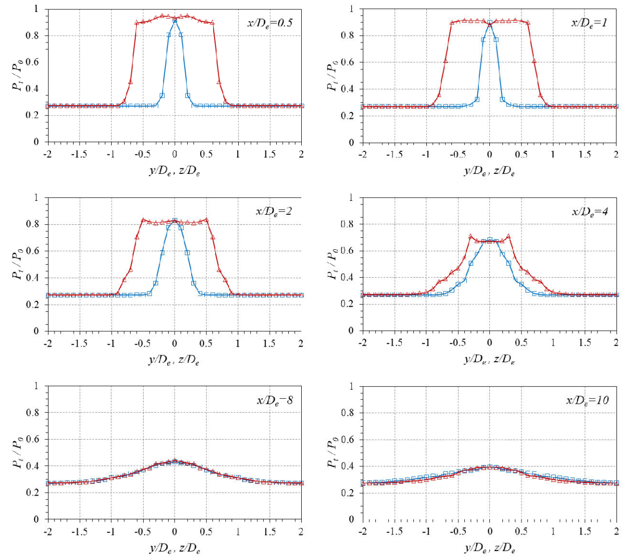
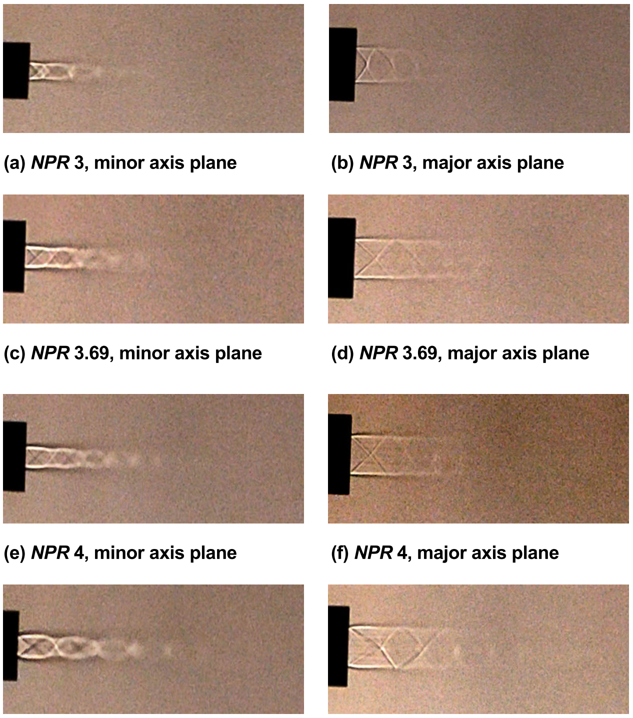


FIGURE 10. Pressure profiles of *AR*3 jet at *NPR* 3.69, △ – along *y* axis, □ – along *z* axis.

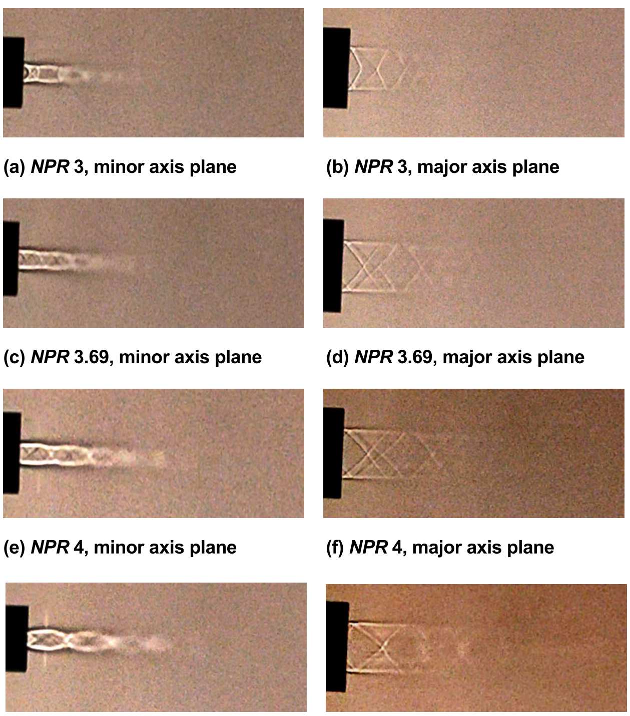
C. FLOW VISUALIZATION

The waves in the Mach 1.5 rectangular jets of *AR*2 and *AR*3 are visualized using a shadowgraph setup. The visualization is done along *y* and *z* axis of the jets. The shadowgraph results of *AR*2 and *AR*3 jets at *NPR*s 3, 3.69, 4 and 5 presented in Figures 11 and 12 show that the core length of both the jets increases with increasing *NPR* and at the same time the wave strength increases with *NPR*. This confirms the discussion based on jet centerline pressure decay results. It is also seen that the length of shock-cells visible in the shadowgraph pictures being shorter at lowest studied *NPR* 3 increases with increasing *NPR*. The wave structure is different in major axis



(a) *NPR* 3, minor axis plane (b) *NPR* 3, major axis plane
(c) *NPR* 3.69, minor axis plane (d) *NPR* 3.69, major axis plane
(e) *NPR* 4, minor axis plane (f) *NPR* 4, major axis plane
(g) *NPR* 5, minor axis plane (h) *NPR* 5, major axis plane

FIGURE 11. Shadowgraph visualization of *AR*2 jet.



(a) *NPR* 3, minor axis plane (b) *NPR* 3, major axis plane
(c) *NPR* 3.69, minor axis plane (d) *NPR* 3.69, major axis plane
(e) *NPR* 4, minor axis plane (f) *NPR* 4, major axis plane
(g) *NPR* 5, minor axis plane (h) *NPR* 5, major axis plane

FIGURE 12. Shadowgraph visualization of *AR*3 jet.

and minor axis planes of jets which is quite common in the case of noncircular jets. The shock structure in the jets is very complex due to asymmetric nature of rectangular jets. At overexpanded *NPR* 3, a Mach disk kind of wave is visible only in the major axis plane of both the jets. The same was observed at overexpanded *NPR* of 4 for Mach 2 elliptic jet in the literature [29]. For *NPR*s 3.69, 4 and 5 there is no occurrence of Mach disk, both in minor and major planes. When the *NPR* increases from 3.69 to 5, the Mach 1.5 jet becomes underexpanded. At marginally underexpanded *NPR* 4, a barrel type shock started appearing in the minor axis plane of the jets and it becomes very evident at *NPR* 5 which corresponds to moderate underexpansion.

IV. CONCLUSION

The present experimental investigation of Mach 1.5 rectangular jets from rectangular C-D nozzles of *AR*2 and *AR*3 clearly shows that the influence of aspect ratio is dominant in the near field. With increasing aspect ratio, the jet mixing is found to decrease in the near field as reflected in the core length of the jets. The *AR*2 jet has shorter core than *AR*3 jet at all the *NPR*s. After core, both the jets decay almost at the same rate indicating the absence of aspect ratio effect. The phenomenon of axis switching is clearly seen in both the jets. The present study is focused in understanding the effect of only two aspect ratios, 2 and 3 on Mach 1.5 rectangular jet mixing. Extending this work for more number of aspect ratios (like *AR*4, 5 & 6) in future would give a lot of information on the aspect ratio effect on Mach 1.5 rectangular jet mixing.

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