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CFD Letters

Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

Experimental and Numerical Simulations at Sonic and Supersonic Mach Numbers for Area Ratio 7.84

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ARTICLE INFO

Article history:
Received 2 April 2019
Received in revised form 4 May 2019
Accepted 18 May 2019
Available online 20 May 2019

ABSTRACT

Sudden expansion is a common phenomenon found in automobiles, aerospace vehicles and in combustion chambers. Flow separation occurred in the sudden expansion area will influence base pressure either the flow is sonic or supersonic. Therefore, an experimental and numerical works were carried out to evaluate the base pressure variation with nozzle pressure ratio (NPR) in the range from 2 to 8 for a fixed L/D ratio. The experimental investigation and simulations were performed at Mach numbers ranging from 1 to 2.5 for suddenly expanded square duct of 28 mm side. The results indicate that there is marginal discrepancy in the simulation and experimental results. It is found that the base pressure continues to decrease with the increase in NPR, and this trend continues even when the jets are under-expanded due to the vast area ratio of the enlarged duct. The base pressure values obtained from numerical simulations are marginally higher than the experimental values even though all the other parameters are the same, as the values of the simulation were taken for the entire region of the base whereas, the experiments were conducted at selected points in the base area. Another reason for the discrepancy is the error in the measurements as well as the losses occurring during the flow through the taps.

Keywords:
Nozzle Pressure Ratio (NPR), Base Pressure, Mach number

1. Introduction

Sudden expansion is a common phenomenon which takes place in automobiles, aerospace vehicles, and in the combustion chambers. In case of the aircraft fuselage or at the base of the projectiles and rockets, a sudden increase in the area (i.e., at the backward facing step) will occur. The flow separation will take place followed by the reattachment of the flow with the wall. At the endpoint when the flow is separating at the backward facing step the flow will be associated with the immense pressure gradient, shock waves, and later in the downstream, from the reattachment point, there will be the growth of the boundary layer. In the case of the boundary layer separation, due to the presence of an adverse pressure gradient near the duct wall, there will be a reverse flow towards the base region. The base region which is enveloped by the dividing streamline will depend upon the

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upstream Mach number, the level of expansion and the step height of the backward facing step. Due to this flow separation and low pressure at the base, the resulting base drag is only ten percent of the skin friction drag for shells, aircraft bombs, missiles, and unguided rockets which flying at subsonic Mach number. However, at transonic Mach number, the base drag created due to the low pressure at the base is around sixty-six percent of the net drag of the aerodynamic vehicles which is very high value. Hence, many researchers are working in the area of sudden expansion, and they have tried to control the base pressure which has more general applicability. For instance, if the application is for the combustion chamber, then we aim to decrease the base pressure as low as possible to achieve proper mixing of the air with fuel leading to efficient combustion and generating maximum thrust, and ultimately saving the energy. However, for external aerodynamics application, the aim is to increase the base pressure very close to the ambient atmospheric pressure so that the base drag component is almost zero. In some application, there is a need to increase the base pressure by manifolds to that of the ambient pressure, and that also can be achieved by controlling the base pressure. Hence, the application of suddenly expanded flow problems can be found in many engineering problems where the aim is to control the base pressure for reduction of the aerodynamic drag. Many investigations are carried out both theoretically and experimentally in order to reduce the aerodynamic drag. In order to reduce the base drag, there is a need to control the base pressure [1-12].

Many researchers have applied active control in the form of micro-jets as well as passive control in the form of ribs or cavities in order to break the vortex at the base in the recirculating zone [13]. For highly over expanded jets, the micro-jets in supersonic regime become useful for NPR 5 and above depending upon the flow regime. During the flow, the flow field is dominated by both weak and strong waves, and this depends on the level of expansion. The flow becomes highly oscillatory due to the presence of these waves which results in reflection, recombination, and recompression that are taking place in the base region as well as in the duct wall. During the flow process, the NPR plays a vital role in deciding the magnitude of the base pressure in the supersonic regime too. Micro-jets are proven to be an active controller increasing the base suction to the high value may be equal to or greater than ambient pressure for some combination of the flow parameters [14].

Ambareen *et al.,* [15-16] numerically simulated the flow field at supersonic Mach number for area ratio 3.24 at Mach 1.87. They compared their numerically simulated result with the experimental results of Khan *et al.,* [7]. Simulation results were in a good agreement with experimental data. The discrepancy between the computed and simulation results was within the acceptable limit,and this type of method has been used in Ref. [17-19]. Vignesh *et al.,* [18]perform experimental work to investigate the base flow at low as well as high supersonic Mach number for four area ratios. From their result, it is found that the micro-jets are effective at low supersonic Mach numbers. With the increase in the Mach number, the control effectiveness is reduced. Chaudhary *et al.,* [20] experimentally investigated using the micro-jets as an active control mechanism to control the base pressure and the flow development in the enlarged duct. Their results revealed that the control effectiveness is at best at low supersonic Mach number and control does not aggravate the flow field in the duct.

When the cavity is employed as the passive control mechanism to control the base pressure results in an increase of the pressure at the base corner, the reason for this trend is the less interaction between the recirculation zone and shear layer and also due to the less effect of low pressure due to the vortex shedding at the base region. There will be an increase in the base pressure with the increase in the base cavity length. The average value of the base pressure is found to increase due to the presence of the ventilated cavity [21,22].

Dimples which is another passive control results in an increase of base pressurethat could be used to reduce the base drag by controlling the base pressure. The control becomes highly sensitive with the variations in the duct length. The sensitivity of the base pressure with duct length is attributed to the influence of the back pressure on the flow field. When dimples were employed for low duct length, the wall pressure gets affected. There will be a maximum increase or decrease in the base pressure for a given Mach number and NPR to arrive at the optimum duct length [23]. Pathan *et al.,* [24-28] optimized the area ratio, L/D, and Mach number for different NPR in a suddenly expanded CD nozzle using the finite element method. *Khan et al.,* [29] investigated the flow field around a two-dimensional wedge considering the pressure and velocity flow and validated the numerical simulation results with analytical and theoretical work. *Umair et al.,* [30, 31] and *Hamizi et al.,* [32] numerically studied heat transfer augmentation using pulse jet impinging on pin fin heat sink. *Khan et al.,* [33] experimentally investigated the grooved cavity as a passive controller behind the backward-facing step.

Based on the previous works done by the researchers on the sudden expansion and the control method to control the base pressure, there are no information on the influence of Mach number (from sonic to supersonic) on the base pressure for suddenly expanded duct was presented. Therefore, this study is performed to investigate the effect of sonic and supersonic Mach number on the base pressure for the suddenly expanded duct without any control mechanism. This investigation is crucial before any control methods (active or passive) should be applied to control the base pressure.

2. Methodology

2.1 Experimental Set-up

Figure 1 shows a view of the converging-diverging nozzle of the square cross-section along with the enlarged square duct of the 28 mm side indicating the wall pressure tappings. Figure 2 shows a view of the nozzle assembly with the enlarged duct mounted on the experimental setup indicating the settling chamber with other attachment and accessories being used during the experiment.

Fig. 1. A view of the nozzle along with the duct attached with the settling chamber of the open jet facility

Fig. 2. A view of the Nozzle and the duct assembly

3. Results

3.1 CFD Analysis

Academic licensed ANSYS Workbench 18.0 version is used for modeling and meshing the geometry while the flow simulation was performed using ANSYS Fluentsoftware. Figure 3 shows structured mesh of the expanded nozzle model performed in ANSYS. Table 1 shows sensitivity analysis performed to ensure the independency of the grid size and the accuracy of the simulation result. Coarse, medium and fine tetrahedron with different number of elements was performed. Time taken until the simulation was converged was recorded. Percentage difference of the back pressure and atmospheric pressure ratio between experimental data and CFD was calculated. Among these three type of meshes, fine mesh shows closer percentage difference with the experimental data. Therefore, this mesh was selected for further evaluation.

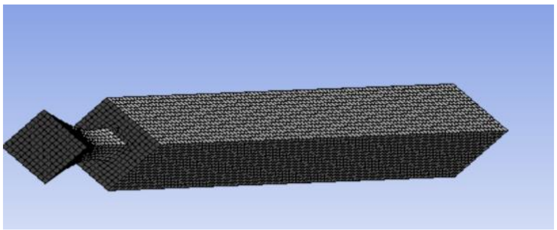


Fig. 3. Structured mesh

Table 1
Mesh independence check

	Coarse	Medium	Fine
Number of Elements	14223	16556	20790
Time taken until converge	2 hrs 25 min	2 hrs 30 min	3 hrs 20 min
Percentage difference with experimental data	8%	8%	7%

The nozzles were modeled for Mach numbers 1.2, 1.6, 2.0 and 2.5. The model is imported in the ANSYS Fluent for CFD analysis. A Reynolds Averaged Navier-Stokes Equations (RANS) with turbulent models has been solved numerically. A k-ε viscous turbulent model is used for the analysis. For numerical analysis, the density based steady-state solver was considered. The convergence criterion for continuity and velocities were set to 10^{-6}, and for energy also it was set to 10^{-6} to get accurate results. Iterations were carried out till convergence was reached. The clock hours taken to converge single case was approximately 2–4h and all the cases were converged within 6000 iterations. During the analysis, the air is considered as the ideal gas and Sutherland law is used. The initialization of boundary conditions is done before simulation. The inlet pressure is set to $(NPR)_{gauge,}$ and the outlet pressure is set to zero. The gauge pressure is calculatedfor the respective Nozzle Pressure Ratio (NPR). For various flow and geometrical variables, the simulation is carried out, and the outcome of the investigation is compared with experimental data and analyzed. The simulation was performed for Mach numbers in the range as stated above and at various NPR. The velocity and pressure contours are obtained and analysed. The pressure and velocity contour for Mach number 2 and NPR 6 is shown in Figure 4 and Figure 5 below.

Figure 4 depicts the pressure contour for Mach number 2. It is shows that pressure at the corner of the enlarged duct is minimum which leads to an increase in the base drag. In general, with the increase in the Mach number in supersonic regimes, there will be a decrease in base drag with the increase in base pressure. This trend continues until the correct expansion is obtained. Velocity contour as shown in Figure 5 depicts that the velocity is maximum in the middle of the duct which is required for the main jet and this proves that the velocity contour is on the expected lines.

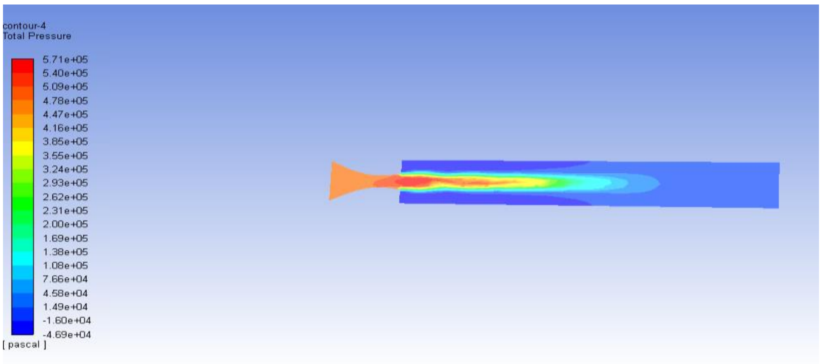


Fig. 4. Pressure contour for Mach 2 NPR 6

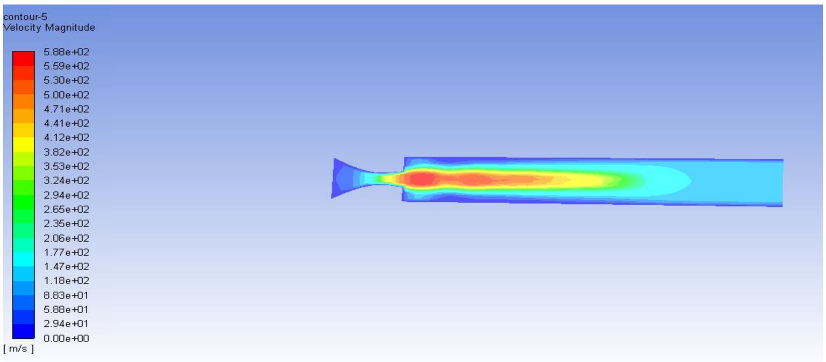


Fig. 5. Velocity Contour for Mach 2 NPR 6

The present study focusses on the numerical analysis, and then these results are compared with the experimental results for suddenly expanded square duct of side 28 mm. The parameters considered in the present study are the area ratio of the pipe, L/D ratio, jet Mach number and the level of expansion (NPR). The Mach numbers considered in the present investigation are 1, 1.2, 1.6, 2.0, and 2.5. The measured base pressures have been non-dimensional by dividing them by the atmospheric pressure.

Base pressure variation as a function of NPR at various Mach numbers of the present study is presented in Figure 6 to 8. Initially, we are discussing the comparison of numerical and experimental investigations for supersonic flow and later at sonic Mach number. Non-dimensional base pressure with nozzle pressure ratio (NPR) is shown in Figure 6 for Mach numbers 1.2 and 1.6. The NPR for correct expansion at these Mach numbers is 2.42 and 4.3. The figure indicates that at Mach number

M = 1.2 and 1.6 at NPR 2 the value of base pressure is high and its non-dimensional values are 0.81 and 0.82. With the further progressive increase in the expansion level, the base pressure continues to decrease. Whereas, in the ordinary circumstances it is expected that base pressure would increase after specific NPR that is required for correct expansion. Also, it is seen that with an increase in the Mach number from 1.2 to 1.6, the influence of Mach number is marginal. The physics for this trend in base pressure is due to the relaxation available to the flow where the flow after exiting from the nozzle proceeds in the downstream and the base pressure continues to decrease, and NPR is unable to influence the base pressure. The physics of this trend in the flow is that when the shear layer is exiting from the converging-diverging nozzle, the flow undergoes through the expansion fan located at the nozzle exit. Later the flow separates, and the flow is dividedinto two zones; one is the main jet, and the second is the recirculation zone. The separated flow is getting attached again with the enlarged duct wall. From the point of reattachment, the boundary layer will start to grow again.

The reason for this trend is due to an increase of the area ratio is beyond certain limits, the flow from the nozzle discharged into the enlarged duct tend to attach with reattachment length other than the optimum for an active vortex at the base. This process makes the NPR effect on base pressure to become insignificant for higher area ratio. When we observeand compare the base pressure values obtained by experiments and the numerical simulation, the experimental results are lower than the results obtained by the numerical simulations. The values obtained by numerical simulation are marginally higher than the experimental values. In case of numerical simulations, the base pressure values are the average values on the entire base area whereas, in the case of experiments the measurements were made at specific locations, hence; the value measured during the experiments will be marginally lowerthan the simulation values. This may be the reasons for this difference in the magnitude of the base pressure. Moreover, in the case of the results from experiments, there are errors involved in measurements, friction creeping in at the measurement points as well as due to the friction at the wall.

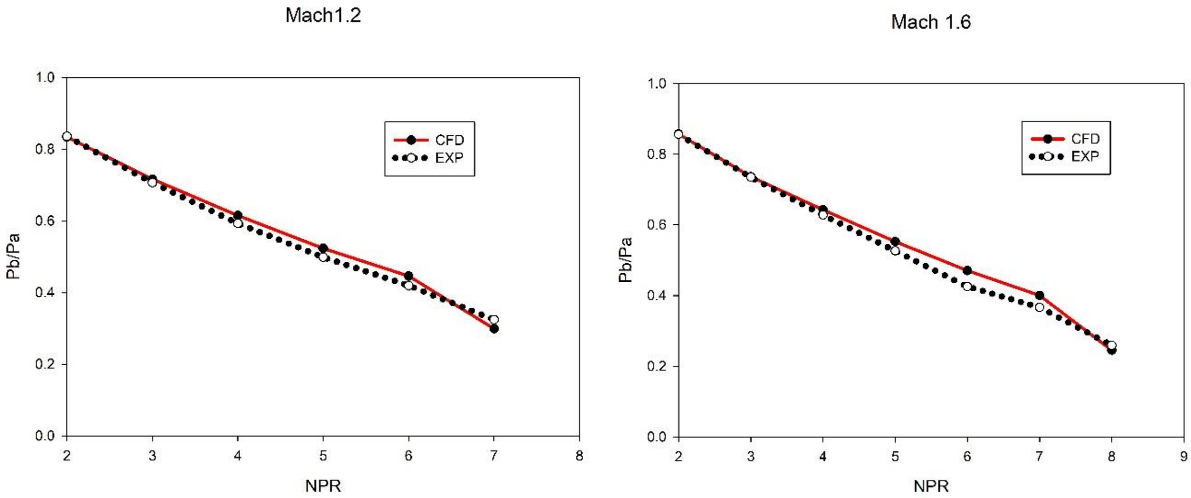


Fig. 6. Base pressure variation with NPR for Mach 1.2 and Mach 1.6

Base pressure results for Mach 2 and 2.5 are shown in Figure 7. The NPR needed for correct expansion at these Mach numbers are 7.82 and 17.09. For Mach 2 and 2.5, the jets are correctly expanded and over-expanded. When the jets correctly expanded,the Mach waves will be position at the nozzle exit where the flow will be isentropic. However, when the jets are over expanded, there will be an oblique shock at the nozzle exit which will result in larger base pressure values as compared to the values before the shock wave case. It is seen that at NPR = 2, the base pressure values are 0.98

and 0.99. At NPR = 9, the base pressure values are 0.3 and 0.5. This variation in the base pressure values is attributed to the level of expansion. When we compare the results obtained by experiments and by the numerical simulations, there are marginal variations in the values obtained by experiments. The reason for this discrepancies has been discussed earlier as above.

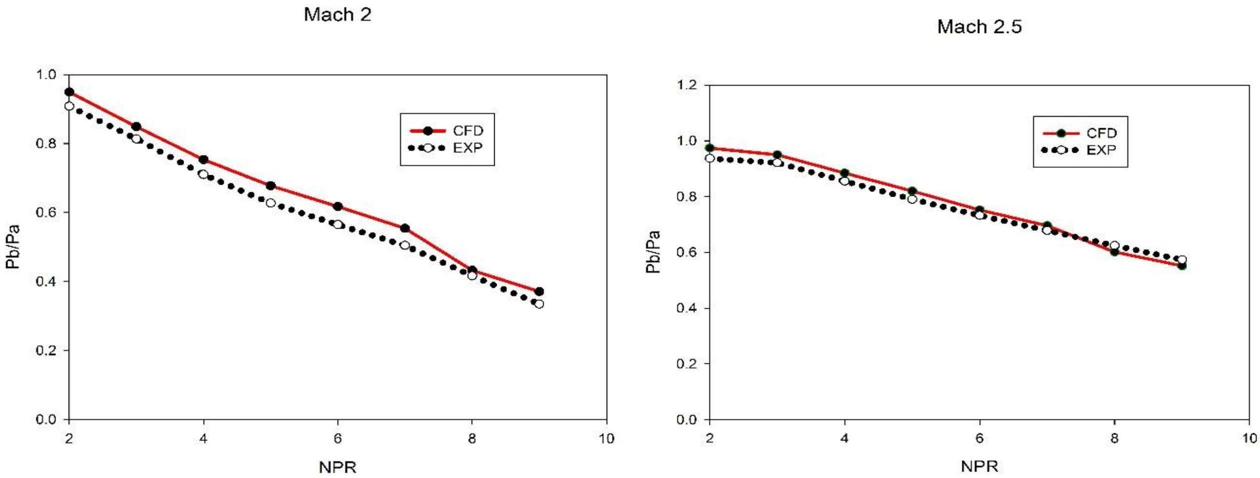


Fig. 7. Base pressure variation with NPR for Mach 2 and Mach 2.5

Base pressure results for Mach 1 are shown in Figure 8 for the converging nozzle at Mach M = 1. For choked flow conditions the NPR needed is 1.89. In the figure, the base pressure results are shown from NPR 2 to 7. The results indicate that even at a very high level of under expansion the base pressure continues to decrease. The discrepancy between experimental and CFD results are more at the sonic Mach number. As we know that to simulate the flow at the sonic Mach number numerically is very difficult. Other reasons for the discrepancy are the same as having already been discussed.

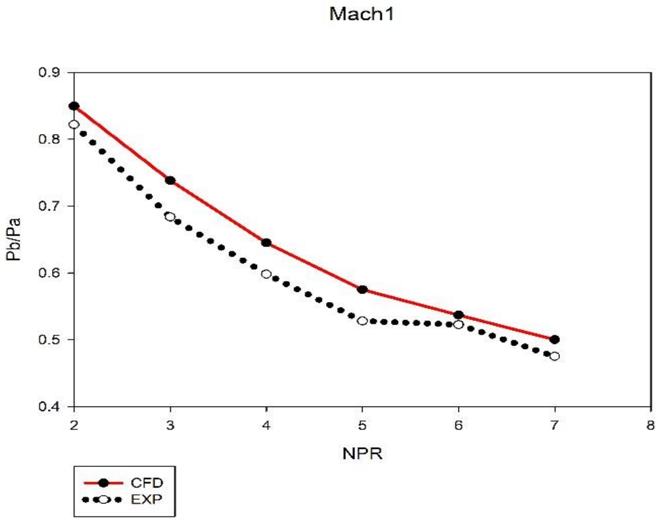


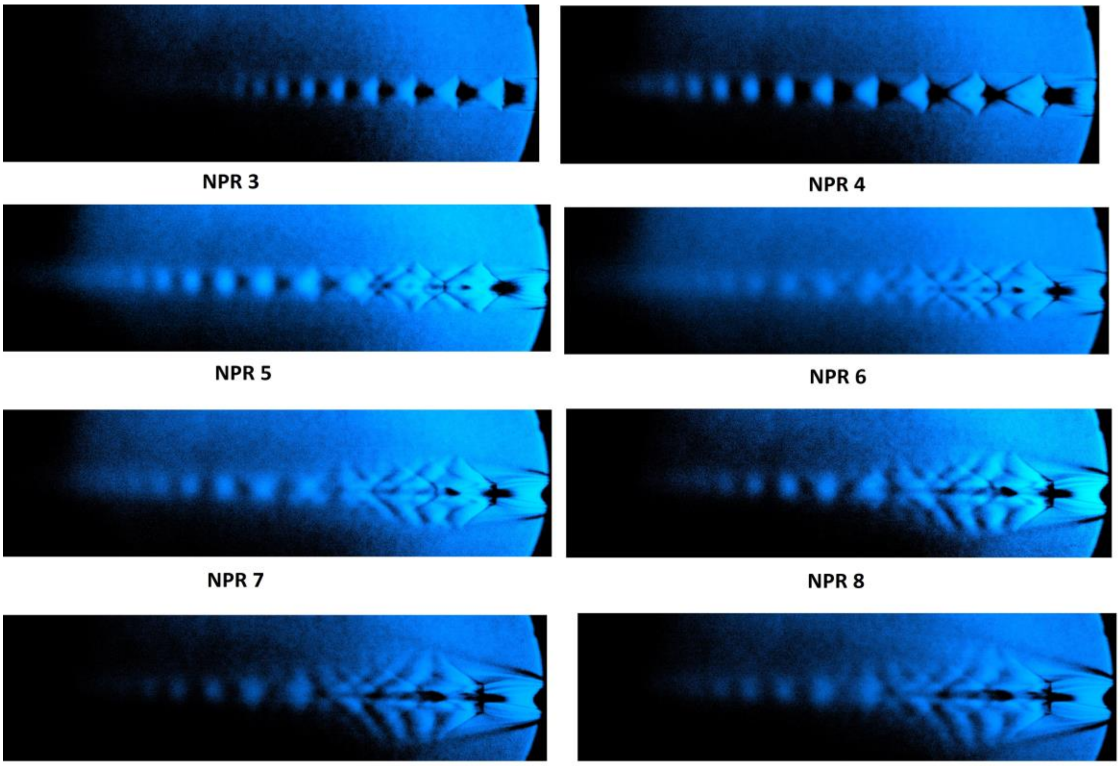
Fig. 8. Base pressure variation Mach number 1

From the above results, it can be stated that with the increase in NPR there is a decrease in base pressure. Further, the matching of the CFD simulation results with the experimental results are excellent, and discrepancy in the results is within 10 %.

3.2 Flow Visualization

Figure 9 shows the Schlieren images from the converging nozzle at Mach number M = 1 at NPR = 3, 4, 5, 6, 7, 8, 9, and 10. It is worth to be noted that the clarity of the Schlieren images has been done using the ImageJ software.

Now, when the flow is exiting from the converging nozzle, the NPR needed for the chocking condition is 1.89 assuming the flow to be isentropic. However, in the real situation, the flow will not be isentropic due to the viscous effects and hence the presence of the boundary layer. Hence, in practice during the experiments, we take NPR slightly more than the NPR needed for the correct expansion. Schlieren images indicate that when the jets are under-expanded they are accompanied by the expansion wave and the formation of the expansion waves, barrel shock, and diamond shock will continue till the jets reaches the ambient conditions.



NPR 3
NPR 4
NPR 5
NPR 6
NPR 7
NPR 8
NPR 9
NPR 10

Fig. 9. Schlieren Pictures from Converging Nozzle at Sonic Mach Number

Schlieren pictures for Mach 2.5 for various NPR are shown in Figure 10. Since the requirement of NPR at Mach 2.5 is around 17. Due to the limitation of the experimental setup, it was not possible to conduct the experiments as well as the flow visualization at Mach 2.5. However, the experiments, as well as the flow visualization, was done at NPR lower than that required for correct expansion. In this case, the maximum NPR tested was NPR = 10. The level over expansion at Mach 2.5 is 0.59. In view of the overexpandedjet, the flow will be accompanied by the oblique shock which tries to increases the pressure so that quickly the jets are able to attain the pressure needed for correct expansion. From Figure 10 it is seen that initially, the oblique shock wave at the exit of the nozzle is powerful, and later it becomes weak, and this phenomenon continues till the jets re correctly expanded.

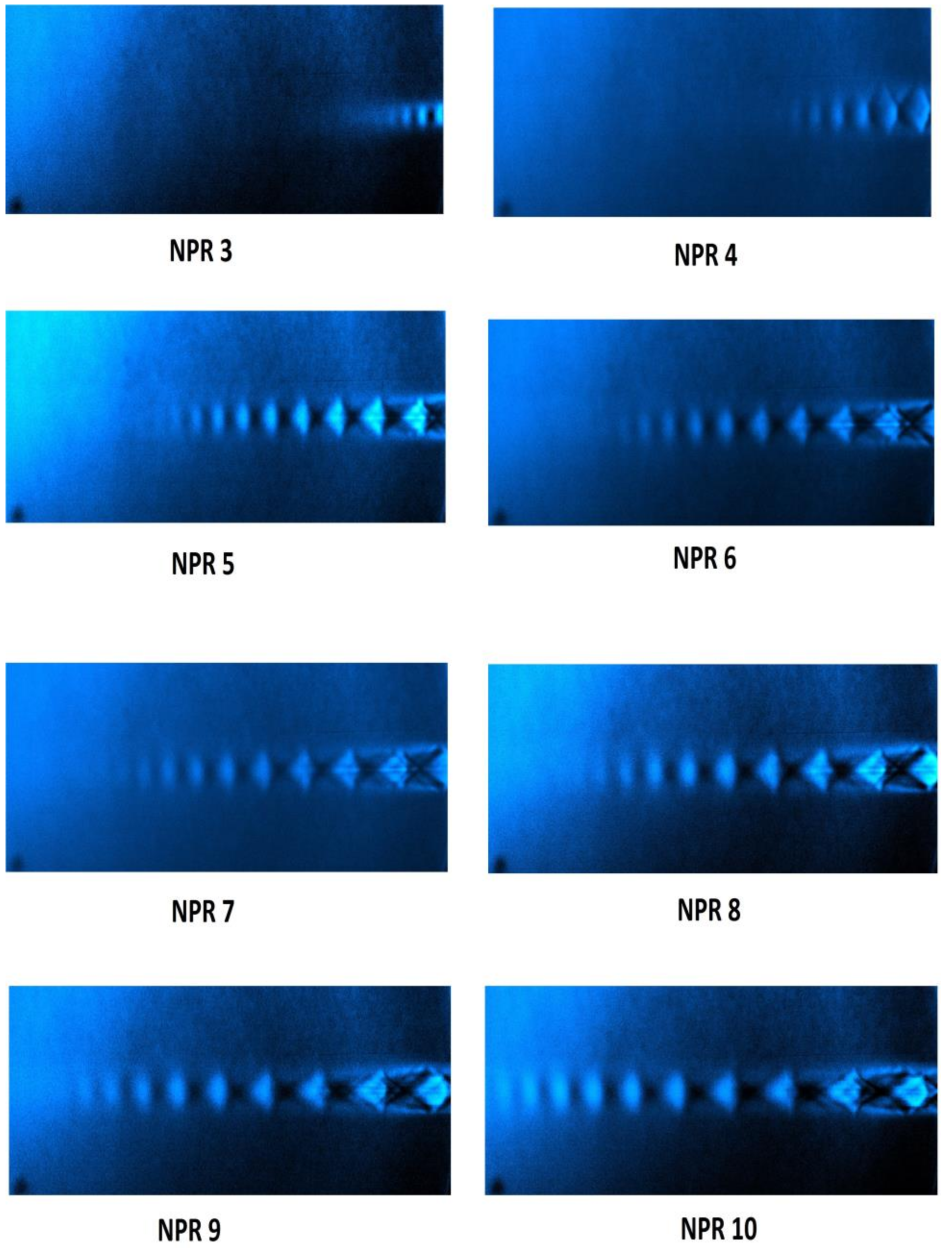

NPR 3
NPR 4
NPR 5
NPR 6
NPR 7
NPR 8
NPR 9
NPR 10

Fig. 10. Schlieren Pictures from Converging-Diverging Nozzle at Mach Number M = 2

4. Conclusions

Based on the above discussions, the following conclusions were obtained:

I. The discrepancy in experimental and the simulation results are marginal. However, the discrepancy between experiments and simulation are maximum at sonic Mach numbers. The discrepancy is attributed due to the instability and oscillations in the flow at sonic Mach number.
II. The discrepancy in experiments and simulation results are in within acceptable limits.
III. Since the area ratio is high which; will result in the substantialconsiderable value of base pressure.

IV. In view of the above, there will be a considerable increase in the reattachment length and hence, high values of the base pressure.
V. Increased reattachment length results in the significant area of the re-circulation zone resulting in the weak influence of the base vortex in creating suction at the base area.
VI. Highly under-expanded jets at all the Mach number and NPR's tested are unable to influence the base pressure value due to the vast area ratio at a fixed inertia level.
VII. Due to the combined effect of the area ratio, the level of expansion, and the inertia level are responsible for the ineffectiveness of the high level of under expansion.
VIII. The flow visualizations complement and reiterate the findings of the base pressure through experiment and numerical methods.
IX. The base pressure values obtained from numerical simulations are marginally higher than the experimental values even though all the other parameters are the same.
X. This may be due to the values of the simulation were taken for the entire region of the base whereas, the experiments were conducted at selected points in the base area.
XI. Another reason for the discrepancy is the error in the measurements as well as the losses occurring during the flow through the taps.

Acknowledgment

Authors would like to thank UniversitiSains Malaysia Research University grant (1001/PAERO/8014019) and Bridging Grant (304/PAERO/6316111) for sponsoring this work.

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