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AN INVESTIGATION OF EFFECT OF CONTROL JETS LOCATION AND BLOWING PRESSURE RATIO TO CONTROL BASE PRESSURE IN SUDDENLY EXPANDED FLOWS

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ABSTRACT

The drag force is an essential factor in any projectile, from road vehicles to rocket or aircraft. The total drag includes skin friction drag, wave drag, and base drag. The base drag is the drag due to low pressure in the base region of the projectile. In the case of suddenly expanded flows, due to the sudden expansion of flow from the nozzle into the enlarged duct, the low pressure is created in the base region of the enlarged tube, which results in base drag and hence overall thrust reduced. In this paper, Computational Fluid Dynamic (CFD) analysis is used to analyze the effect of secondary air blowing jets called control jets to control base pressure in the base region of suddenly enlarged duct. These control jets are placed at different Pitch Circle Diameters (PCD) on the base face of the enlarged pipe. The objective of this work is to increase the base pressure up to atmospheric pressure and hence reduces the base drag. Mach number 3.0 is considered for analysis. The CFD analysis is done for different combinations of Area Ratios (AR) (2, 5 and 8), Nozzle Pressure Ratios (NPR) (2, 5 and 8), and PCD (d_1, d_2, and d_3).

Further analysis is done for different air blowing pressure ratios (BPR) to optimize air blowing pressure. The analysis results are plotted for different area ratios, nozzle pressure ratios, and PCD of control jets. By observing results, it can be concluded that the base pressure is strongly influenced by AR, NPR, and PCD of control jets. The air blowing pressure should be optimum to save energy, and the optimum values can be selected from the results.

Keywords: *Area ratio, base pressure, blowing pressure ratio, Mach number, nozzle pressure ratio*

INTRODUCTION

Suddenly expanded flow is a complex phenomenon characterized by flow separation, flow recirculation, and reattachment. A shear layer into two central regions may divide such a flow field, one being the flow recirculation region and the other the primary flow region. Reattachment point is the point at which the dividing streamline strikes the wall of the enlarged duct. The features of the suddenly expanded flow field are illustrated in Figure 1 [1-5].

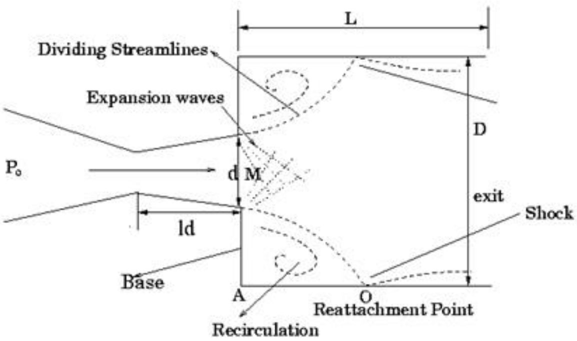

Figure 1. Suddenly expanded flow field [1]

A review on drag shows that 50% of the total drags of high-speed objects, such as a missile in jet-off condition is due to base drag. Base drag is in the form of pressure drag that dominates at very high speeds and

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creates a zone of depression behind the bluff bodies [8,13-18]. In this search of reducing drag, scientists have come up with passive, active, and reactive controls [9]. Active control techniques are instrumental, such as suction [10] and blowing [1, 4, 5, 11], and reactive in the form of rotating cylinders [12]. The various studies on the flow through nozzle and diffuser are available in the literature [19-21].

The study of base pressure in suddenly expanded flows from nozzle finds applications in many areas like a rocket, aircraft, etc. The base pressure for a rocket nozzle is reduced due to expansion fans provided in the base. Thus the hot gases coming out of the nozzle tends to fill this region. This is undesirable since the high temperature of the gases is continuously felt in the base area.

Based on the literature, it is essential to increase the base pressure up to atmospheric pressure to reduce drag. In this study, the active control technique in the form of control jets is used for blowing pressurized air in the base region of the enlarged duct as a secondary jet provided in the base region of the enlarged tube. In this study, different cases are analyzed by varying area ratio, nozzle pressure ratio, pitch circle diameter of control jets, and blowing pressure ratio. This analysis does not simulate the exact flow conditions of a rocket nozzle completely. Still, the results can give an excellent idea to control the base pressure.

MODELING AND MESHING

For modeling and meshing, academic licensed ANSYS Workbench 16.2 is used. The geometry is modeled using the dimensions for Mach number 3. Following figure 2 shows the geometry of the nozzle and enlarge duct.

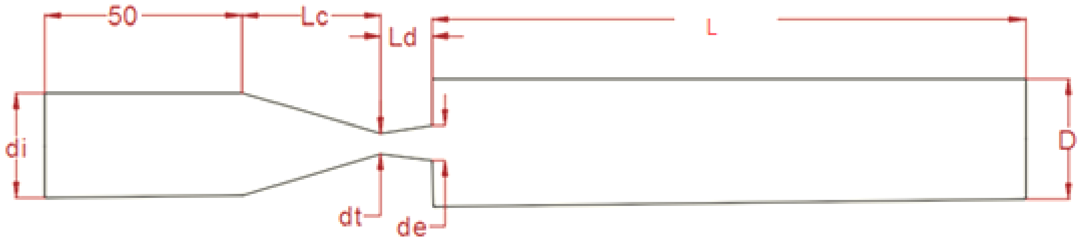

Figure 2. Dimensions of the nozzle and enlarged duct

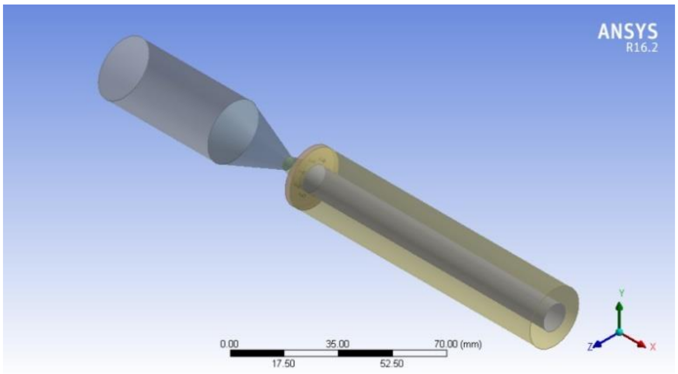

Figure 3. 3D geometry

An extra length of 50 mm length is added before the nozzle inlet to develop the exact inlet flow condition at the inlet of the nozzle. Area ratios, i.e., the proportion of enlarged duct area to nozzle exit area for all the cases, are 2, 5, and 8. According to area ratio, enlarged duct diameter (D) is calculated. The length to diameter ratio of the enlarged duct is kept constant for all the cases as 5.

The mesh should be structured to get accurate results. The model is divided into many parts, as shown in figure 3, and each section has meshed separately with the structured grid. Maximum hexahedral elements have been selected to generate mesh, as shown in Figure 4.

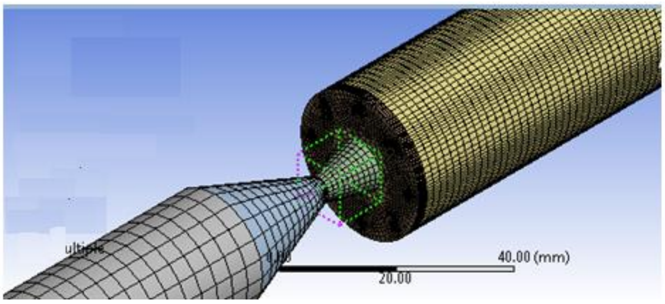

Figure 4. Structured meshed 3D geometry

ANSYS Fluent is used for the analysis, and the investigation is done by varying the geometry and flow parameters.

CFD ANALYSIS

CFD analysis has many flow assumptions and considerations to be set for better results. In the analysis setting, the air is considered as an ideal gas, and Sutherland's law is used to calculate the viscosity of air at different temperature values [6-7]. Sutherland's equation to calculate the dynamic viscosity of the air at different temperature values is given in equation (1) [8].

$$\frac{\mu}{\mu_0} = \frac{T_0 + T_s}{T_0 + T}\left(\frac{T}{T_0}\right)^{\frac{2}{3}} \tag{1}$$

k-epsilon turbulent model is used for the analysis. Nozzle pressure ratios, i.e., the proportion of stagnation pressure or inlet pressure to backpressure or atmospheric pressure, considered for analysis are 2, 5, and 8. Three different pitch circle diameters concerning the difference of radii of an enlarged duct and nozzle exit are used to install control jets in the base region of an enlarged tube. As the blowing pressure is extra energy supplied to the system to control the base pressure, it should be optimum. Further analysis is done for blowing pressure ratios, i.e., the ratio of control jet's blowing pressure to atmospheric pressure is considered as 2, 3, 4, 5, 6, 7, and 8 to optimize the blowing pressure. Pitch circle diameters d_1, d_2, and d_3 can be calculated using the following equations (2), (3), and (4).

$$d_1 = d_e + 2\times(0.25\times C) \tag{2}$$

$$d_2 = d_e + 2\times(0.50\times C) \tag{3}$$

$$d_3 = d_e + 2\times(0.75\times C) \tag{4}$$

RESULTS AND DISCUSSION

Results are extracted with the help of ANSYS Fluent software. The contours of total pressure and velocity are shown in figure 5 and figure 6, respectively, for area ratio 8.0, nozzle pressure ratio 8.0, and PCD of control jets d_3.

A plane is created parallel to the base face of the enlarged duct at a distance of 2 mm from the base face. Contours of total pressure for Area Ratio = 5, Nozzle Pressure Ratio = 5, and PCD of control jets d_3 is plotted on the XY plane, and a plane 2 mm from the base face is shown in figures 7.

The total average pressure is calculated with the help of a fluent post-processor on this new plane for all the cases without control jets, and with control, jets and graphs are plotted to observe the effectiveness of control jets. All the values of absolute pressure are divided by atmospheric pressure and plotted the graphs to get a clear idea about the pressure variations in the base region. The results of this dimensionless pressure values at different nozzle pressure ratios are shown in figure 8.

Figure 8 is plotted for the ratio of base pressure to atmospheric pressure versus nozzle pressure ratio for Area ratio 2. From figure 8, it is observed that, for area ratio 2, the base pressure is less than atmospheric pressure for nozzle pressure ratios 2 and 5. When the nozzle pressure ratio becomes 8, the base pressure increases and becomes more than atmospheric pressure. The objective of this analysis is to increase the base pressure up to atmospheric pressure. When the nozzle pressure ratio is 8, then there is no need of control jets as already the base pressure is more than atmospheric pressure. However, when the nozzle pressure ratio is five, the base pressure is almost half of atmospheric pressure; in this case, the control jets play an essential role in increasing base pressure. From figure 8, it can also be observed that, for ratio 2, the control jets are more effective at pitch circle diameter d_1.

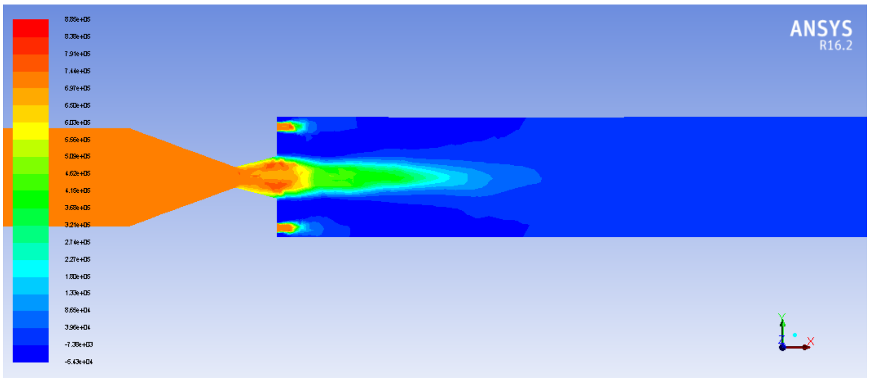

Figure 5. Pressure contour for NPR=8, AR=8, PCD=d_3

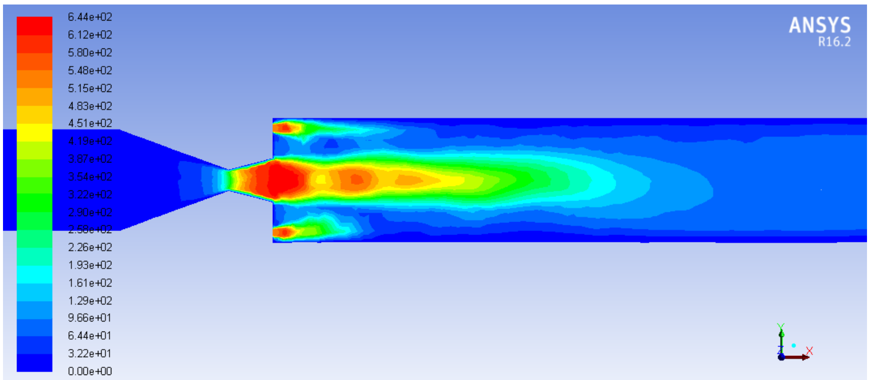

Figure 6. Velocity contour for NPR=8, AR=8, PCD=d_3

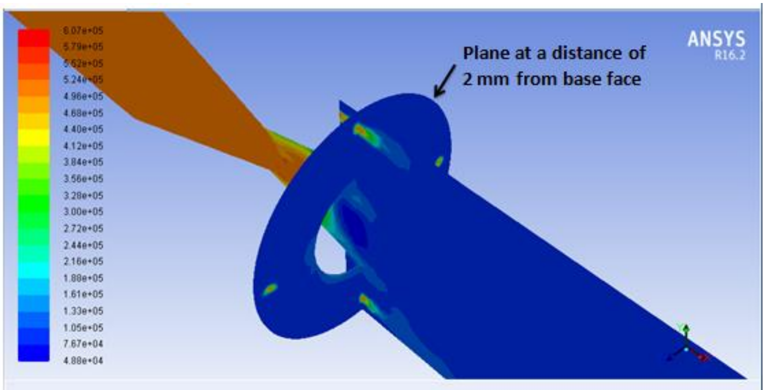

Figure 7. Pressure contour for AR = 5, NPR = 5, and PCD=d_3

As the area ratio increases, the diameter of enlarged duct increases; this results in a rise in reattachment length, and hence base region increases. From above figure 9, it is observed that, for area ratio 5, the base pressure is less than atmospheric pressure for all the values of nozzle pressure ratios. In this case, for all nozzle pressure ratios, the control jets are very useful to increase base pressure. From the above graph, it can also be observed that for area ratio 5, the control jets have approximately the same effectiveness at pitch circle diameters d_1, d_2 than d_3 at NPR 2 and 5, but for NPR 8 the control jets are more effective at PCD d_1.

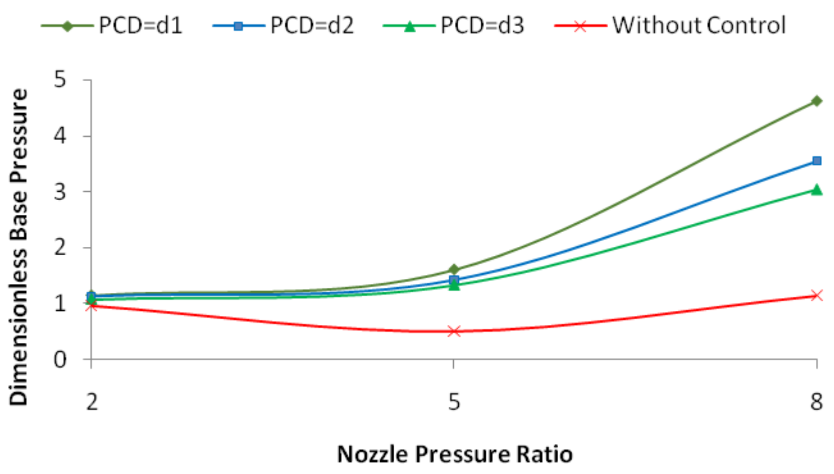

Figure 8. P_b/P_a Vs. nozzle pressure ratio for AR=2

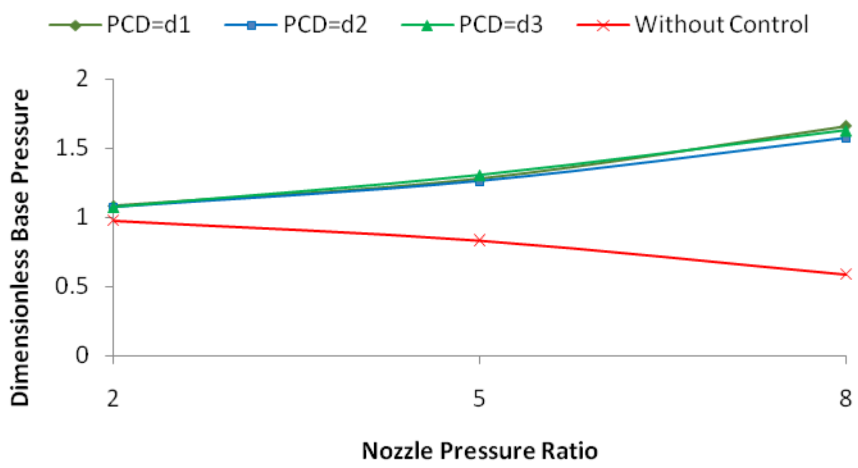

Figure 9. P_b/P_a Vs. nozzle pressure ratio for AR=5

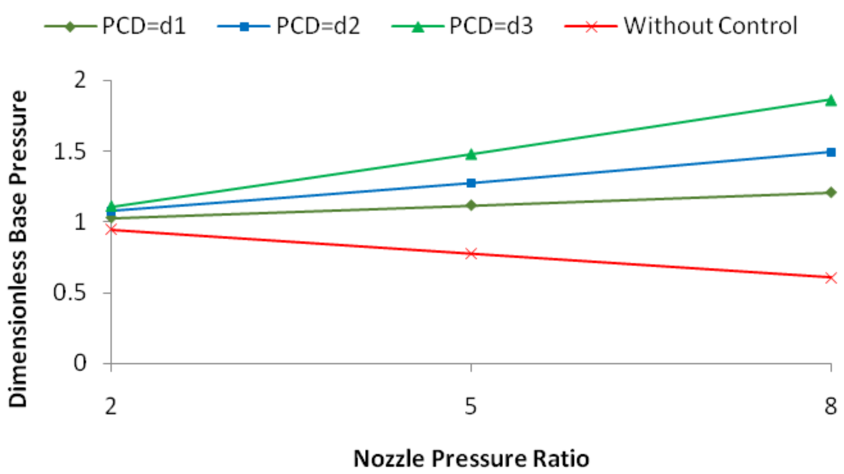

Figure 10. P_b/P_a Vs. nozzle pressure ratio for AR=8

When the area ratio becomes 8, the reattachment length gets increases, and hence the base region is again increased. From figure 10, it is observed that, for area ratio 8, the base pressure is less than atmospheric pressure for all the values of nozzle pressure ratios without control jets. In this case, for all nozzle pressure ratios, the control jets are very useful to increase base pressure. From the above graph, it can also be seen that for area ratio 8, the control jets are more effective at pitch circle diameter d_3 followed d_2 and then d_1.

Further analysis is done for different air blowing pressure ratios to optimize blowing pressure. The air blowing pressure should be optimum to save energy, and one can select an optimum value by observing the following results. In this analysis, the blowing pressure ratios considered are 2, 3, 4, 5, 6, 7, and 8. The results of this analysis are shown with the help of the following graphs.

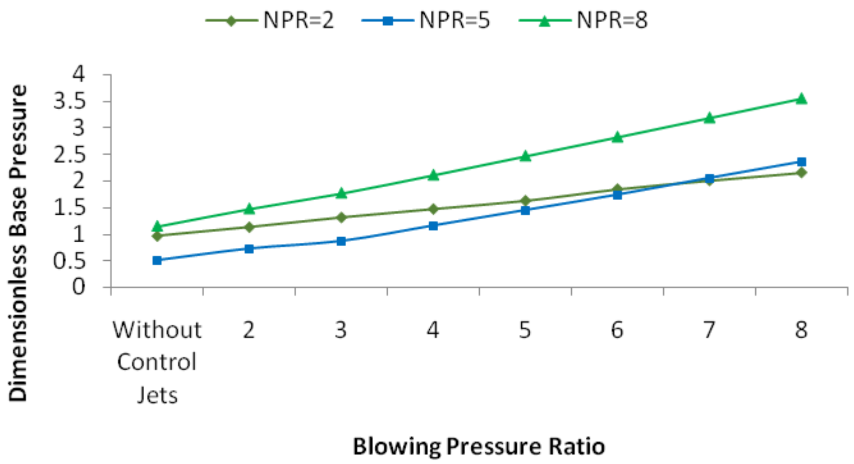

Figure 11. P_b/P_a Vs. blowing pressure ratio for AR=2

Figure 11 is plotted for the ratio of base pressure to atmospheric pressure versus blowing pressure ratio for Area ratio 2. From figure 11, it is observed that, for area ratio 2, the base pressure is less than atmospheric pressure for nozzle pressure ratios 2 and 5, without control jets. Our objective is to optimize the blowing pressure ratio. For nozzle pressure ratio 2 and 5, the minimum blowing pressure ratio should be 1.5 and 3.5, respectively.

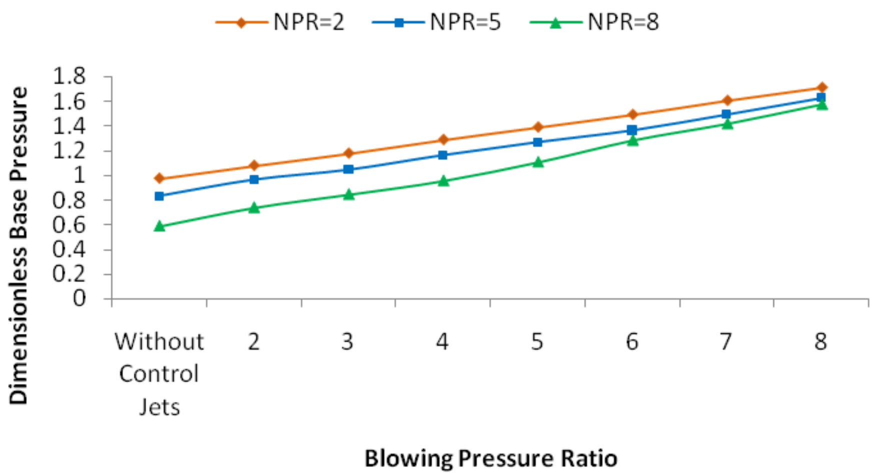

Figure 12. P_b/P_a Vs. blowing pressure ratio for AR = 5

Figure 12 is plotted for the ratio of base pressure to atmospheric pressure versus blowing pressure ratio for Area ratio 5. From figure 12, it is observed that, for area ratio 5, the base pressure is less than atmospheric pressure for all the values nozzle pressure ratios 2, 5, and 8 without control jets. For nozzle pressure ratio 2, 5, and 8, the minimum blowing pressure ratio should be 1.5, 2.5, and 4.5, respectively.

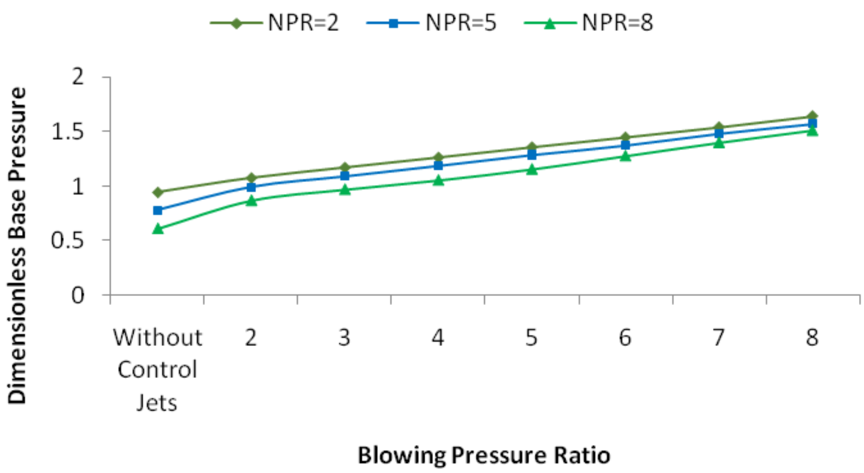

Figure 13. P_b/P_a Vs. blowing pressure ratio for AR=8

Figure 13 is plotted for the ratio of base pressure to atmospheric pressure versus blowing pressure ratio for Area ratio 8. From figure 13, it is observed that, for area ratio 8, the base pressure is less than atmospheric pressure for all the values nozzle pressure ratios 2, 5, and 8 without control jets. For nozzle pressure ratio two the minimum blowing pressure ratio should be 1.5, for nozzle pressure ratio 5, the minimum blowing pressure ratio should be 2.5, and for nozzle pressure ratio 8, the minimum blowing pressure ratio should be 3.5.

CONCLUSIONS

From results, it is concluded that the base pressure is strongly influenced by nozzle pressure ratio, area ratio, and control jets location. As the area ratio increases, the reattachment length increases, and hence the base region increases. As nozzle pressure ratio increases, the nozzle becomes under-expanded, and for under expanded nozzle, the control jets are more effective at area ratio 5 and 8. The control jets are very effective in controlling base pressure. As the area ratio increases, the effectiveness of control jets increases.

For area ratio two at nozzle pressure ratio 8, there is no need of control jets as the base pressure is already more than atmospheric pressure. However, when the nozzle pressure ratio is five, the base pressure is almost half of atmospheric pressure; in this case, the control jets play an essential role in increasing base pressure. For area ratio 2, the control jets are more effective at pitch circle diameter d_1 than d_2 and d_3.

For area ratio 5 and 8, the base pressure is less than atmospheric pressure for all the values of nozzle pressure ratios. In these cases, for all nozzle pressure ratios, the control jets are effective in increasing base pressure. For area ratio 5, the control jets have approximately the same effectiveness at pitch circle diameters d_1, d_2 than d_3 at NPR 2 and 5, but for NPR 8, the control jets are more effective at PCD d_1. For area ratio 8, the control jets are more effective at pitch circle diameter d_3 followed d_2 and then d_1.

From the results, it is observed that the blowing pressure ratio is a function of area ratio and nozzle pressure ratio. If the area ratio is increased, the base pressure is decreased in the base region of the enlarged duct, and hence, in this case, the control jets are more useful to increase base pressure. The optimum blowing pressure ratio for all the combination of area ratios and nozzle pressure ratios are as follows.

For area ratio 2, at nozzle pressure ratio 2 and 5, the minimum blowing pressure ratio should be 1.5 and 3.5, respectively. For area ratio 5, at nozzle pressure ratio 2, 5, and 8, the minimum blowing pressure ratios should be 1.5, 2.5, and 4.5, respectively. For area ratio 8, at nozzle pressure ratio 2, 5, and 8, the minimum blowing pressure ratio should be 1.5, 2.5, and 3.5, respectively.

NOMENCLATURE

CFD	Computational Fluid Dynamics
PCD	Pitch circle diameter *(d_1, d_2, and d_3)*
AR	Area ratio

NPR	Nozzle pressure ratio
BPR	Blowing pressure ratio
d_i	Nozzle inlet diameter
d_t	Nozzle throat diameter
d_e	Nozzle exit diameter
L_c	Nozzle convergent length
L_d	Nozzle divergent length
L	Enlarge duct length
D	Enlarge duct diameter
C	The difference of radii of enlarged duct and nozzle exit
T	Input temperature
T_0	Reference temperature
μ	Viscosity at input temperature T
μ_0	Reference viscosity at reference temperature T_0
T_s	Sutherland's constant (for air 120 K)

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