Effect of Control on the Duct Flow at High Mach Numbers

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Abstract. Once the stream is drained through a nozzle, this research explores the pressure in a circular duct. This research investigates when the control is triggered, the pressure in the tube, and flow development. At the base, the flow regulators as tiny jets are used at PCD of 0.013 m, and the orifice radius is 0.5 mm. The flow variables are Mach (M) and the NPR. The investigation was done for M = 2.1 & 2.8. The expansion level was from 3 to 11. The duct area ratio used is 6.25. The duct length varied from 10 to 1. For M = 2.1, the tested NPRs were at different expansion levels. When they are under the impact of under-expansion, flow oscillations are noticed. At NPR 3, an adverse pressure exists at Mach 2.1, and similar patterns are seen for higher NPRs. The flow's wavy nature is dying out with the decrease in pipe length, and pressure recovery is smooth. The control regulator has not influenced the flow adversely.

Keywords: Nozzle, Mach number, NPR, L/D, and supersonic flows.

1. Introduction

In the current situation, the use of launch vehicles and space rockets has risen significantly. But still, the challenge involved in the aerodynamics of these vehicles. The critical issue is excessive pressure linked with the front shock and sub-atmospheric pressure at the vehicle's corner base. Due to the shock waves, this wave barrier drags, and the bubble drag precedes a tremendous fuel quantity ingestion with large inconsistencies in the ducts flow. Therefore, considering the widespread implementation of flow, this analysis relates to the regulation of base flows.

While scrutinizing the information, it is observed that the principal emphasis was to regulate the base flow using passive means, where geometric improvements in the experimental configuration are needed, with a slight increase in device weight without losing performance parameters. There is a need for an alternative energy supply required to implement active control, which is a big problem and, in most situations, a difficulty. We use dynamic techniques to regulate the flow and, therefore,
evaluate the control mechanism's usefulness. As we use air from the experimental setup's primary storage chamber, the requirement for a supplementary source of energy is not needed. Passive control methods are used by several researchers to manipulate the flow, and the base pressure, only some of them associated with the current work, are discussed below.

In recent years, in a base region for NPRs from 1.27 to 1.69 and \( L = 10D \) to 4D in a subsonic flow regime. Passive control using dimples to synchronize flow in the recirculation region at the high-speed flow in a situation with a step [1]. For a CD nozzle with an abrupt change in the area and circling cylinder, they applied static cylinders [2] for different Mach numbers, NPR's, \( L / D_s \), and area ratios as passive control. Generally, the use of passive control would result in a rise in weight and a change in the configuration of the nozzle, so it was first realized in the early 2000s, Khan et al. [3] implemented an active microjet flow control in a nozzle with sudden expansion for supersonic flow controls. Later, the active control impact was enhanced by varying the flow rate. It is also found for noise control [4] to identify and augment departure control utilizing tiny jets [5]. After monitoring the flow from the active microjet control, it is also necessary to know whether the flow changes in the duct or not. Hence, recent findings have shown that several studies have been replicated with equivalent or variable Mach number and area ratios with the same NPR and \( L/D \) ratios [6], [7].

Our next research focused on the literature, which is based on the numerical investigation in which computational tools such as ANSYS Fluent, STAR CCM, and Opensource software were used to investigate the flow phenomena inside the duct by varying flow parameters and nozzle geometry parameters. In this study, turbulence modeling was the key concern for integrating problems such as compressible or incompressible flow fields. Most of the work was known to be compressible flow for the present form of the issues. They numerically investigated the flow fields when the microjet is present or absent with plots and contours observation. From the Fluent, more studies have been found in recent years in which some studies have been utilized with the pressure-based solver, and K-epsilon turbulent modeling was used [8]. Furthermore, Khan et al. [9] focused more on the analysis of area ratio using numerical method. For this investigation, the author's utilized contours flowed in each case of area ratio and optimized the recirculation zone when the flow is controlled or not controlled with microjet. Khan et al. [10] validated the experimental results with fluent results and further continued the fluent results with a change of parameters to investigate the microjet active control [11]. Furthermore, this type of studies using the turbulence modelling for incompressible flow range of splitter plate [12], [13], wedge [14] and non-circular cylinder [15] has been found. Apart from these studies, the design of experiments has also been utilized to investigate the flow fields and influence of microjet control with optimization techniques and analysis methods.

Following the literature study focused on experimental, numerical, optimization, and machine learning methods, no research has been done on current parameters and the duct flow. The present work is more on active control, and thus dynamic control rather than passive control has been the subject of research. More studies have nevertheless been performed in the last four decades with passive control. In the last decade, active control is used because it is a more effectively controlled method.

2. Problem Formulation

The base pressure on the blunt projectile base is associated with the upstream boundary layer's transition point's depth and position. The boundary layer's width right at the corner's leading-edge defines projectiles' pressure at the recirculation area for turbulent boundary layers. The fineness ratio
of missiles divided by the Reynolds number depends on one-fifth power to compare this outcome. Figure 1 shows the key features of the unexpectedly extended flow area to define the problem statement.

Figure 1. A flow area view of the abrupt expansion.

3. Experimental Work

Fig. 2 indicates the system utilized for the present analysis & tests, as discussed in Khan et al. [16-18]. The investigational technique used for the experiments consists of a storage tank where the air is stored at 15 bars from a 25 HP compressor.

The pressure transducer procured from National Instruments capable of measuring pressure from 0 to 300 psi was utilized. The base and the wall pressure for ten taps were used using the instrument. It has a frequency of 250 Hz and shows the median reading on the PC panel. It means that we do not lose any details about the flow because of the high sampling rate. Eight holes are drilled at the base, four of which were for power, and the others were for calculation. The distance between them was 5 mm for the initial ten pressure tapes, and the distance between the remaining taps is 10 mm after the ten wall tapes.
**Figure 2.** Two-dimensional view of the proposed method for experimentation

The flow separates at the nozzle's exit gets attached to the duct at 75 mm. The boundary layer will then expand from this stage of the reattachment, and the flow revival occurs. And once it exceeds the atmospheric pressure value, a smooth outride in the pressure is anticipated. The duct and the setup are seen in Figure 3.

![Figure 3. Pressure tapping’s attached to the duct.](image)

**4. Results and Discussion**

Findings for $A_2/A_1 = 6.25$ are given in Figs. 4 to 5, at Mach 2.1 and 2.8, NPR's, 3 to 11, and $L = 10D$ to 1D.

Figs. 4 gives the findings for Mach 2.1. This tendency appears to be due to the greater level of adverse pressure of the NPRs tested. It is found that the peak pressures at this Mach number remain closed to atmospheric pressure, which is right for this area ratio and Mach number. When inertia is low, the NPRs are with favorable pressure happens. The flow under the impact of positive pressure for all the NPR tested. But for this case, nozzles are flowing at an adverse pressure gradient. Hence, they accomplished higher pressure due to the compression of the flow. They are resulting in peak values of 15 % above the atmospheric condition. At $L = 10D$ & Mach 2.1, the regulator finds a minimal rise of the static pressure for the majority NPRs at higher NPRs, and the command efficacy is barely insignificant. At NPR, three jets face intense adverse pressure. This tendency remains at $M = 2.1$ for NPRs 3 to 7.

Fig. 4 (b) describes comparable pressure effects at $L = 8D$, as was detected in the earlier plot. It is noticed that the variation in pressure and enormity has decreased significantly owing to the consequence of diminished duct size and the greatest area accessible to the stream, and the flow has to turn out to be very smooth out as compared to the prior case. Figs. 4((c)-(d)) exemplifies the findings at $L = 6D$ & 5D. Owing to the extreme respite to the shear layer. Vacillations in the pressure are suppressed due to ambient pressure, and the highest-pressure value is a smaller amount compared to a greater length of the pipe $L = 10D$ and 8D. The peak wall pressure values marginally more than the free stream atmospheric pressure.

The fluctuations inflow is merely for NPR = 9 & 11. The flow has smoothed in the duct for the majority of NPR tested. When the control appears or absent, the pipe pressure is the same in $L = 6D$ and = 5D. This tendency persists up to $L = 4D$ and 3. It is observed that for NPRs 3, 5, and 7, the
pressure improvement is accomplished right from \( x/D = 0 \). This is owing to the too extreme level of overexpansion. For decreased L/Ds as \( L = 2D \) and 1D, it is apparent that duct size is insufficient for the flow to continue to connect to the duct.

![Graphs showing pressure improvement](image1.png)

(a) Mach No. = 2.1, L/D = 10

(b) Mach No. = 2.1, L/D = 8

(c) Mach No. = 2.1, L/D = 6

(d) Mach No. = 2.1, L/D = 5

(e) Mach No. = 2.1, L/D = 4

(f) Mach No. = 2.1, L/D = 3
Figs. 5 represents the outcomes for Mach 2.8. The findings show that the effects at Mach 2.8 are distinctly related to the earlier plots for smaller inertia levels. The jets continued to be over expanded. Anticipated to the massive degree of adverse pressure, the commencing tenets of pressure are fewer than the pipe length's ambient pressure. For Lower NPR's, it is by a factor of 0.9 and 0.8, respectively. Additionally, it gets broadened for the greater NPR with a decline in the length. Since the jets facing adverse pressure, the normalized pressure ratios persisted at 20 % fewer. This ratio was 1.2 at the smaller Mach for a like span of the pipe size. When the flow departs from the nozzle and enters the pipe, pressure revival occurs with no oscillations.

They achieve more excellent pressure at the nozzle's exit. The crest magnitudes are fewer than the backpressure as the substantial pressure revival has gotten at the opening stage itself. Consequently, a further bounce in the pressure is not noticed. The pressure regaining follows with 20 % of the duct length from the nozzle exit, which indicates that due to the increased area, the oscillations decline, and pressure recovery is smooth. At L = 10D, the control does not negatively alter all the NPRs, and the control usefulness is minimal. The tendency observed at NPR 3 at low Mach persists at M = 2.8 for all NPR.

Fig. 5 (b) renders pressure findings at L = 8D, as noticed from the figure, excluding the pressure variation that has diminished significantly and stayed in conjunction with 20 % of the tube. Figs. 5 ((c)-(d)) characterize pressure outcomes at L = 6D & 5D owing to the decline in the length of the pipe. There are no oscillations in the duct flow. Due to backpressure, the enormous pressure is lower than those for a larger tube size, particularly in L = 5D. The stream has smoothed in the duct, and pressure matches in the presence and absence of a regulator. This tendency persists up to L = 4D., For smaller pipe sizes like L = 3D, 2D, and 1D, findings show that pipe size is inadequate for the stream to persist connected to the pipe.

Once again, it restates that the decrease in the and hence, the noise suppression with control is possible for both at under and overexpanded nozzle flow and the regulator does not impact the duct's pressure adversely.
5. Conclusion

As flow control in the wall and the ducts flow field, the present study sets out the small jet's efficacy. The measured NPRs are such that all two Mach 2.1 and 2.8 requirements are met by the jets. When the nozzles are under expansion, variations in the flow field are observed, and this phenomenon lasts along the pipe. The flow faces negative pressure, and with flow regulators, the oscillations have reduced because merely the Mach waves appear. Finally, we note from the findings above that the flow regulator has no disadvantageous bearing on the wall pressure is noticed. The microjets may be used as a base pressure device without impacting the duct field adversely.

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