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# Influence of microjets on flow development for diameter ratio of 1.6 for correctly expanded nozzles

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ABSTRACT

This paper aims to study the microjet's efficacy as a management tool for the duct's flow field. The nozzle was correctly expanded for a diameter ratio of 1.6 (i.e., area ratio = 2.56). The Mach numbers considered were from 1.25 to 2. The investigation shows that the development and recovery of the duct flow are smooth at lower Mach numbers. At Mach 1.48, jet noise was reduced considerably when the control is initiated. For higher Mach numbers of the study, namely Mach 1.6, 1.8, and 2.0, the flow's oscillatory nature was noticed. This phenomenon reiterates that the nozzles flow is wave-dominated. For most of the flow, the flowing nature remains unaltered due to control. The flow remained connected with the duct for duct length twice the nozzle exit diameter.

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## 1. Introduction

High-speed flow analysis has implemented the criteria for collecting aerodynamic data by introducing both active and passive control techniques, including base and wall pressures for an extensive range of Mach numbers, Reynolds number, and modulation of these forces. Control and manipulation of the base and wall flow field warrant an ongoing research effort since this field of base flow plays a significant role in deciding projectiles and rockets' flight potential. The lesser pressure on the vehicle's rear contributes to these vehicles' overall drag between 35% and 50% [1]. The study's scope includes the design of nozzles, flux field interactions, shock wave-limiting speeds, base drag, and advanced concepts. Performance is highly reliant on the expansion nozzle's aerodynamic configuration, and the key parameters are the step height and the diameter-length ratio [2]. The evidence indicates the reliance of the variables to regulate the base flow drag. One such variable is the wall pressure on the fluid flow, which affects the flow efficiency. The growing need for higher performance in rocket nozzles encourages higher-performance nozzles with a wide area ratio. The issue of separation of flow and the impact of wall pressure come into play.

Both active and passive approaches can minimize flow separation. Passive techniques include increasing the length of the nozzle or using splitters or ribs. However, passive strategies are only useful in a restricted set of conditions and introduce unintended results. Another level of description to control the base drag is active control methods. It involves the use of microjets or techniques for the regulation of the flow separation phenomenon. Dynamic control methods often operate in a wide variety of operating conditions. Research of the flow structure and development of shock waves contributing to the base pressure change factor of the flow field used in assessing changes in the wall pressure and the area ratio of changes in the nozzle [3–7].

The numerical analysis on nozzle flow for the Nozzle Pressure Ratio (NPR) in the range from 2 to 8 was carried out by Pathan et al. [8] and Khan et al. [9]. The area ratios taken for the study were 2, 4, 6, 8 and 10. The investigations reveal that the lower area ratio is not acceptable for higher NPR. In contrast, a higher area ratio gives more room to expand compressed air and would have a minimum drag base. The base drag is highly determined by the area ratio to a specific limit. The effect of the microjet control on the different NPR and L/D (length to diameter) ratios was very well studied and reported that the base drag coefficient decreases with the usage of microjets together with no loss of wall pressure.

Aabid and Khan [10] investigated the duct wall's static pressure and growth using microjet control. Microjets were used at the base

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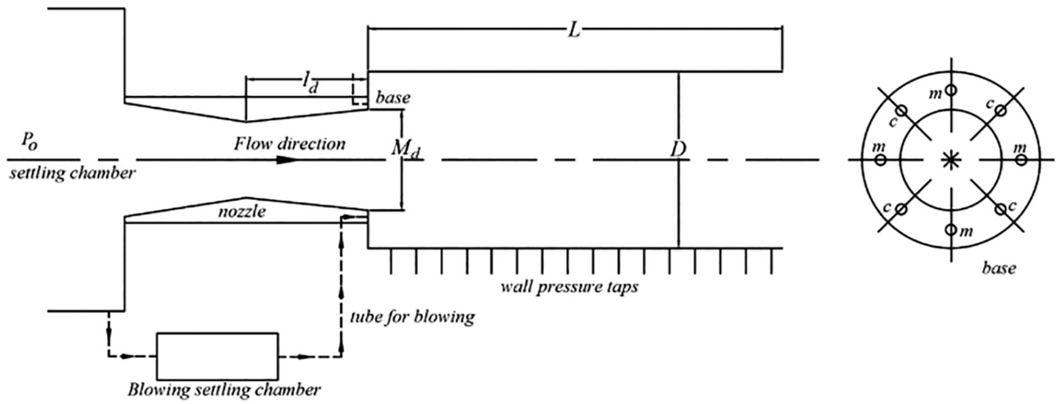


**Fig. 1.** Schematic of the Nozzle and Duct.

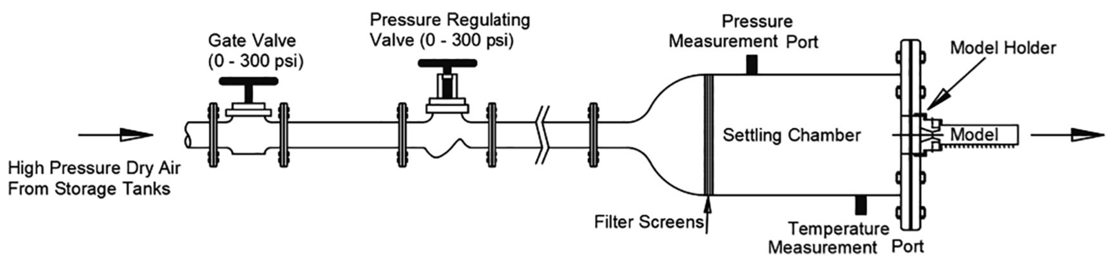


**Fig. 2.** Schematic of the Highspeed Jet Facility [19,20].

with PCR of 6.5 mm. The L/D ratio and NPR of the investigation were from 1to 10 and from 11 to 3. They conclude as the tube's length decreases, the inflow of vibration is lost, and a smooth pressure rise in the duct is observed. The experimental investigation of Bashir et al. [2] on the sudden expansion of axisymmetric passage of wall pressure control reports that microjet use positively impacts the flow at specific Mach numbers. 50% to 60% increase in wall pressure is found at L/D = 10 and fluctuating wall pressure in the case of correctly expanded flows. The Finite Element (FE) approach was used by the researchers to explore the efficacy of microjets of Convergence-Divergent nozzle. The findings have shown that the microjet control effect does not negatively influence the duct's flow field [11–14].

Based on the literature, in the present study, wall pressure is studied at supersonic Mach numbers at different L/D ratios in a suddenly expanded circular duct. The data is recorded at correct expansion NPR for all supersonic Mach numbers. Microjets is used as an active control technique to measure controlled jet pressure variations.

## 2. Experimental procedure

### 2.1. Experimental model and jet facility

Fig. 1 shows the schematic of the CD nozzle attached to a suddenly expanded circular duct. The settling chamber is supplied with compressed air from the storage tank through a pressure regulating valve (PRV) at 150 psi pressure. Once the flow reaches equilibrium in the setting space, it expands into the suddenly enlarged round tube by the round nozzle. By adjusting PRV, the required stagnation pressure is attained in the settling chamber [15]. Fig. 2 represents a view of the setup used in the current research. Experiments are carried out in the open jet facility of high-speed aerodynamics laboratory, Bearys Institute of Technology, Mangaluru, India. A CD nozzle affixed to the settling chamber displays the configuration to create the nozzle's inlet pressure when the nozzle is associated with the duct. In order to minimize the flow disruptions induced by the control valve, a mixing length is imposed between the valve and the settling chamber [16,17]. A sixteen-channel pressure transducer able to accumulate 0–15 bar of pressure is used to record the pressure. It traces 350 data points in a second and records the average data [18].

### 2.2. Uncertainty analysis

For the general procedure of uncertainty analysis, the readers are referred to the articles [21,22]. A sample calculation for uncertainty in the wall pressure is presented for NPR5, Mach 1.8 and area ratio 2.56. Atmospheric pressure = 737 mm of Hg = 29.02 in. of Hg. At NPR 5 stagnation pressure in the settling chamber and in the control, chamber are 116.06 in. of Hg (gauge) and 114 in. of Hg (gauge). Wall pressure = −24.88 in. of Hg (gauge). Assuming one inch as the maximum possible error in the measurement of stagnation pressure in settling chamber, control chamber and wall pressure. In equation (1) three groups of terms on the right-hand side are

From equation 3.6 [21,22], the uncertainty involved in $P_w$ is derived as

$$u_{p_w} = \pm\left[\left(\frac{P_0}{P_w}\frac{\partial P_w}{\partial P_0}u_{p_0}\right)^2 + \left(\frac{P_c}{P_w}\frac{\partial P_w}{\partial P_c}u_{p_c}\right)^2 + \left(\frac{P_a}{P_w}\frac{\partial P_w}{\partial P_a}u_{p_a}\right)^2\right]^{1/2} \tag{1}$$

Using equation (1),

$$\frac{P_0}{P_w}\frac{\partial P_w}{\partial P_0}u_{p_0} = \left(\frac{14508}{4.136}\right)(0.036)(0.00689) = 0.0087$$

$$\frac{P_c}{P_w}\frac{\partial P_w}{\partial P_c}u_{p_c} = \left(\frac{143.02}{4.136}\right)(0.0651)(0.006992) = 0.0157$$

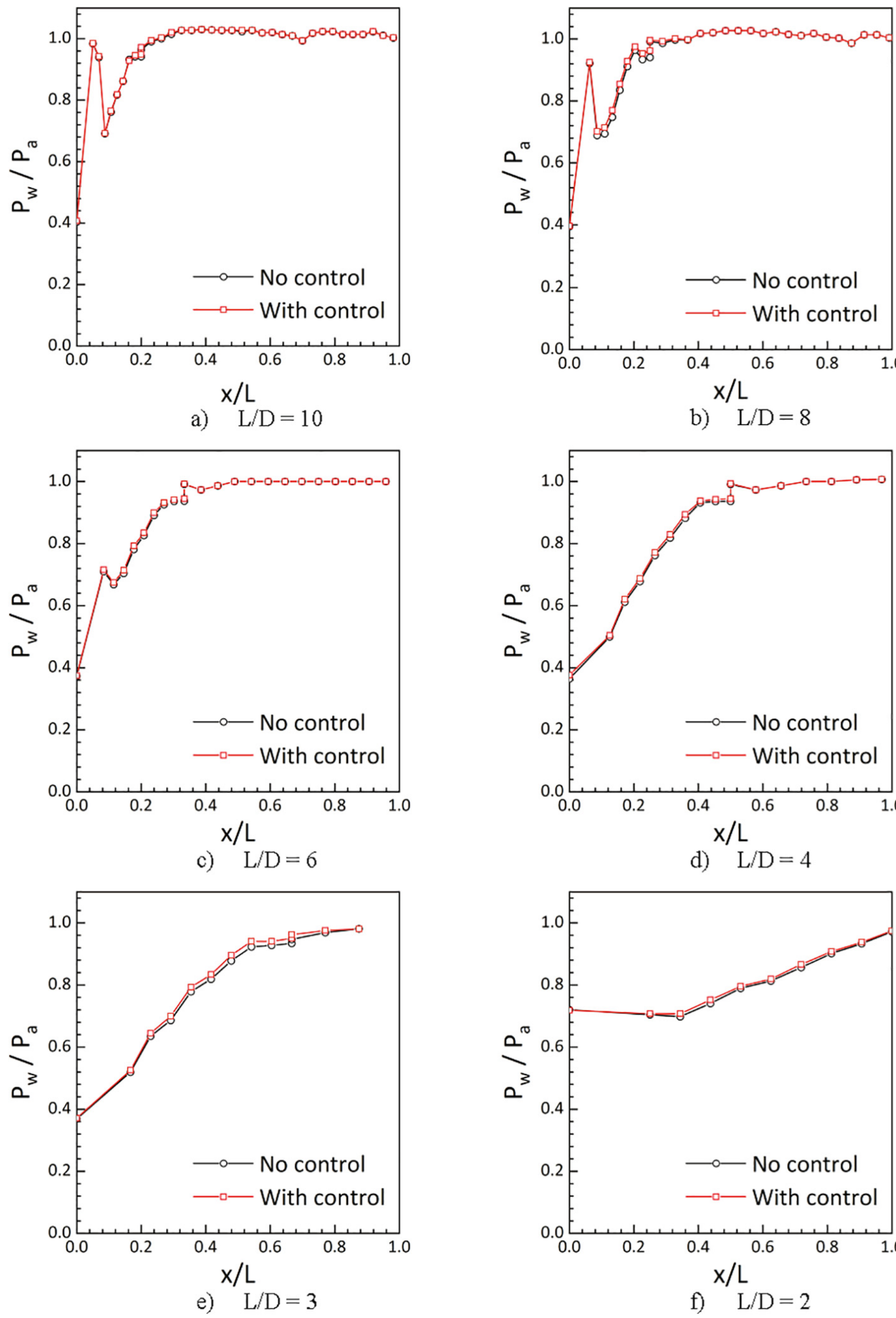


**Fig. 3.** Flow development in the duct at Mach number 1.25, and for correctly expanded NPR 2.59 at different L/D ratios.

$$\frac{P_a}{P_w}\frac{\partial P_w}{\partial P_a}u_{p_a} = \left(\frac{29.020}{4.1136}\right)(0.0717)(0.0035) = 0.0017$$

$$u_{p_w} = \pm\left[(0.0087)^2 + (0.0157)^2 + (0.0017)^2\right]^{1/2} \tag{2}$$

$$u_{p_w} = \pm 1.803\% \tag{3}$$

It is therefore evident that the findings obtained in the uncertainty range of ±1803%.

## 3. Results and discussion

One of the substantial problems the scholars face while doing a study with the sudden expansion is that the duct's flow field often becomes oscillating. The boundary layer dealings with waves in the duct usually turn oscillatory. The justification for selecting this inertia level was to assess the tiny jets' effectiveness at low, medium, and high supersonic Mach numbers. Therefore, it becomes obligatory for a researcher to work on sudden expansion problems to monitor the dilated duct's wall pressure distributions. The duct's pressure was measured to account for this adverse effect for all combinations of the present experimental investigations.

Fig. 3((a) to (f)) show the kind of the stream of duct for Mach M = 1.25 for duct lengths L = 10D, 8D, 6D, 4D, 3D, and 2D. The flow field for L/D = 10 and 8 are almost the same. At x/L = 0, base pressure values are considered as both have the same magnitude. Initially, it begins with a normalized value of 0.4, and due to the shock wave's presence, there is a swift soar in the pressure values. Further, there is a decline in the duct pressure downstream owing

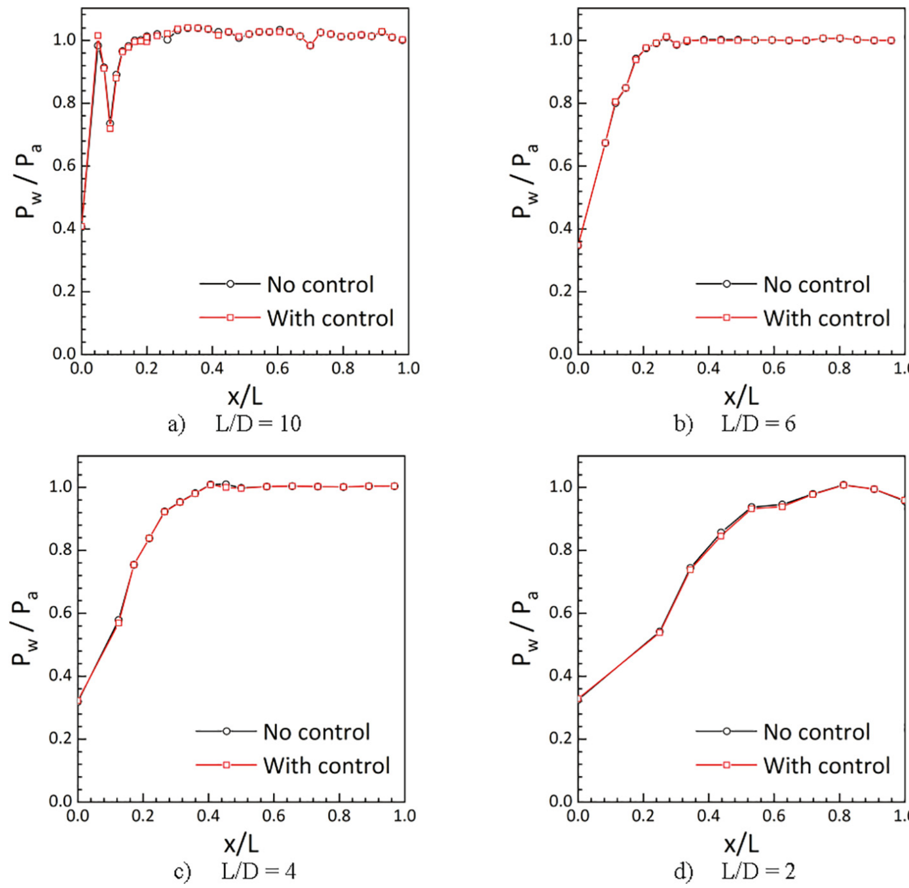


**Fig. 4.** Flow Development in the Duct at Mach number 1.3, and for correctly expanded NPR 2.77 at different L/D ratios.

to the expansion wave's presence. From the reattachment point onwards, there is a smooth pressure recovery. This trend's motivation may be the wave's impact at the jet departure, that transforms the flow missing from the base zone, thus undermining the maelstrom located in the separated area.

The oscillations in the wall pressure are decreased significantly; pressure recovery is fast, as seen in Fig. 3((c) to (e)) for duct length L = 6D, 4D, and 3D. This may be due to the smaller duct length; the backpressure also influences the flow field. However, for duct length, L = 2D, Fig. 3(f) suggests that the duct size is inadequately intended for the stream to keep attached to the pipe. Due to the small duct, the flow assumes the extreme value of around 75% of the ambient pressure value. It is also seen that further downstream of the duct up to 30% of the duct length, the wall pressure remains unchanged. Away From the reattachment point, there is a progressive rise in pressure until it attains the ambient pressure value.

Findings for inertia level M = 1.3 are displayed in Fig. 4((a) to (d)). Fig. 4 (a) for L/D 10 shows a marginal increase in the magnitude due to an increase in Mach number. Once the flow enters the duct, the jump in wall pressure is more than what it was seen at the lower Mach number. Later in the downstream, it follows a similar pattern. Similar results are seen for L = 6D and 4D in Fig. 4((b) to (c)). For L = 2D duct length, the wall pressure pattern is marginally modified due to the ambient influence, as seen from Fig. 4(d).

For inertia level of M = 1.48 are demonstrated in Fig. 5((a) to (f)) for different duct lengths. Anderson and Williams [23]. It is fascinating to see to it from these outcomes that though for most of the instances demonstrate like performance as that for the earlier Mach numbers, indicating no undesirable impact of the duct flow control. Nevertheless, here is a few sequences of factors affecting the flow field very firmly to presume much lesser value contrasted to without control cases, as shown in Fig. 5((a) to (b)). The similar behaviour of the suddenly expanded supersonic base flows was observed by Anderson and Williams [23]. Fig. 5 ((a) and (b)) show that trend of the flow in the duct is analogous, as was seen earlier for with and without control cases. But at Mach M = 1.48, it is witnessed that once tiny jets are used, there is a significant disparity in the stream. The flow management effects in a decrease in pressure. All these instances displayed a significantly-decreased sound level compared to no control. A tangible description for this enthralling occurrence demands further detailed analysis of these factors. For the lasting duct length, L = 6D to 3D, the tendency remains similar, as seen for earlier lower Mach numbers in Fig. 5((c) to (f)).

Fig. 6 shows the kind of stream in the duct at Mach 1.6 for distinct duct sections. By Way Of the gradual growth in the inertia level, there is a change in the flow pattern. The flow has become oscillating. For duct length, L = 10D, 8D, and 4D (Fig. 6((a), (b), (d))), it is more prominent. Apart from flow becoming oscillatory, the control results in a reduction in pressure resulting in lower noise levels. This trend was more pronounced at Mach M = 1.48. The flow field is very complex once it is departing the nozzle. The flow is apportioned into the main jet and separated shear layer. The separated shear layer get reattached with the duct. In separation and reattachment, excessive interaction of the separated shear layer with the duct occur.

Moreover, the shock wave interaction with the duct wall also takes place. Along with the divided streamline, the shock is formed. All these activities make the stream development in the duct very complicated. Since the pipe is of brass metal, it is impractical to

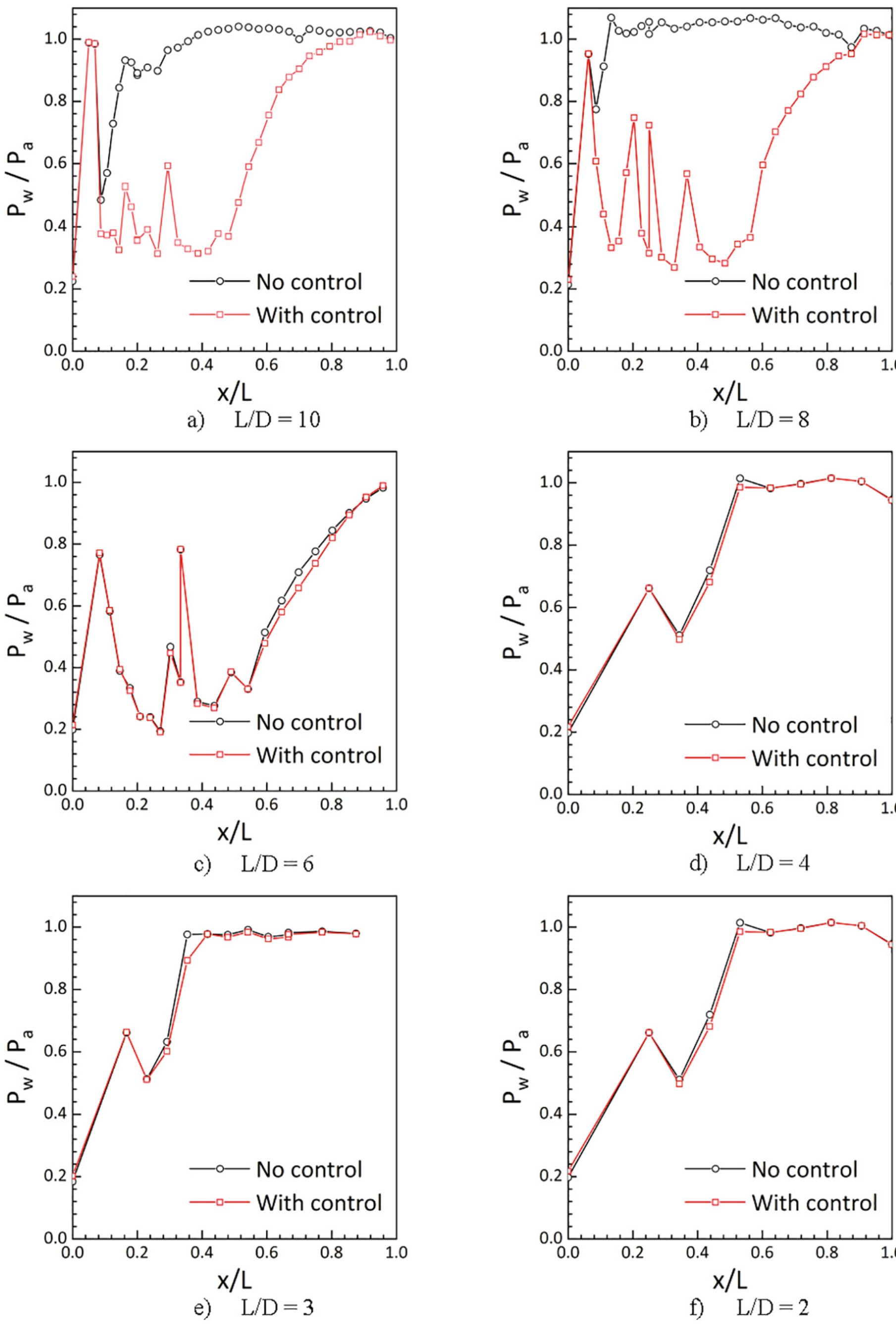


**Fig. 5.** Flow Development in the Duct at Mach number 1.48, and for correctly expanded NPR 3.27 at different L/D ratios.

envisage the flow. Based on the wall pressure pattern, we can infer the flow field's progress and sort of the stream. When the pipe is small L = 4D to 2D, the stream is still stuck to the pipe. However, the oscillations are very low, and the flow recovery is smooth due to atmospheric pressure for short duct length.

Results for pressure indicating the influence of dynamic control in the Way of tiny jets Mach 1.8 are presented in Fig. 7 ((a) to (f)). For enlarged duct lengths from L = 10D to 2D, the trends are on similar lines. A sudden increase in the pressure at the duct length of 8D is noticed. The pressure in the duct attains ambient conditions. Later, due to the further interaction and reflection of the shock waves, the flow field's oscillations are observed. The excessive oscillations at these Mach numbers from 1.6 to 2. 0 were expected as the jets at these Mach numbers are screech prone. In the downstream control results in noise suppression. The shear layer remained attached even for duct length L = 2D.

The results for Mach 2.0 for different duct lengths are shown in Fig. 8 ((a) to (f)). For all the duct lengths of the present study, the flow developed in the duct continues oscillating. There is a sudden jump in the pressure, becoming identical to the free stream pressure for the length L = 8D and 6D of the duct. The pressure ratio depends on the shock wave strength and its interaction with the flow pattern within the reattachment length. For this study, the diameter ratio is 1.6. The reattachment length depends on the duct's diameter ratio with the nozzle exit, the nozzle exit Mach (M), and NPR. The wavy flow pattern at high supersonic Mach numbers in the duct may be due to the factors listed above. Further, we would like to emphasize that it is a general perception

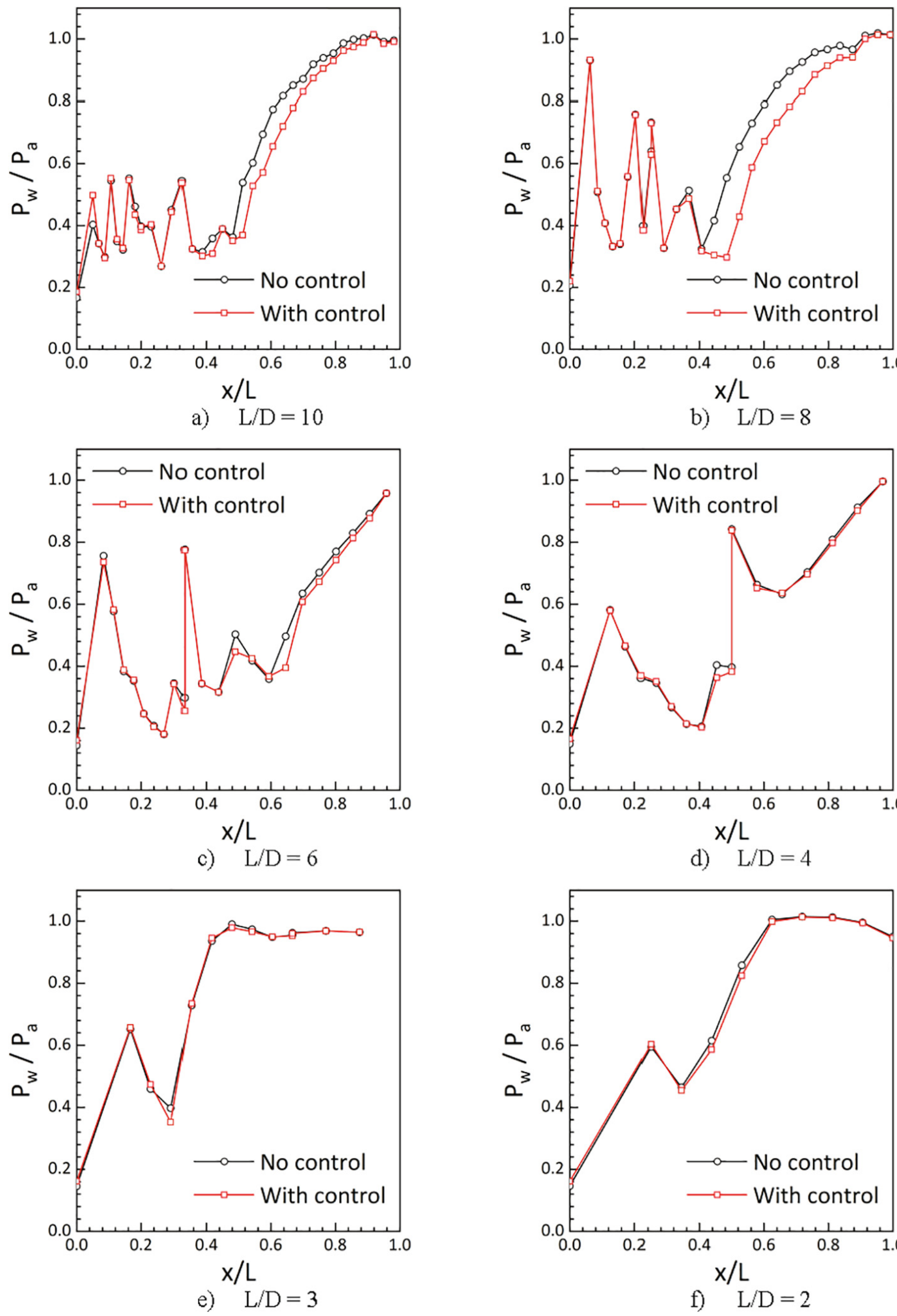


**Fig. 6.** Flow Development in the Duct at Mach number 1.6, and for correctly expanded NPR 4.25 at different L/D ratios.

that when the nozzles are perfectly expanded, the flow field is free from the shock waves. We can say the flow field from the correctly expanded nozzles is wavy due to the shock waves' presence because of the above discussions.

## 4. Conclusion

- The stream is connected to the duct, even at duct length L = 2D. For inertia levels, the flow development is smooth.
- The results show that at Mach 1.48, once the regulation management is employed, it results in a decrease of pressure appreciably, and the jets were quiet.
- At significantly massive inertia levels from M = 1.6 to 2.0, the flow's oscillatory nature are noticed as these Mach numbers are screech prone.
- The reattachment length is dependent on the step height, inertia intensity leaving the nozzle, and the expansion level.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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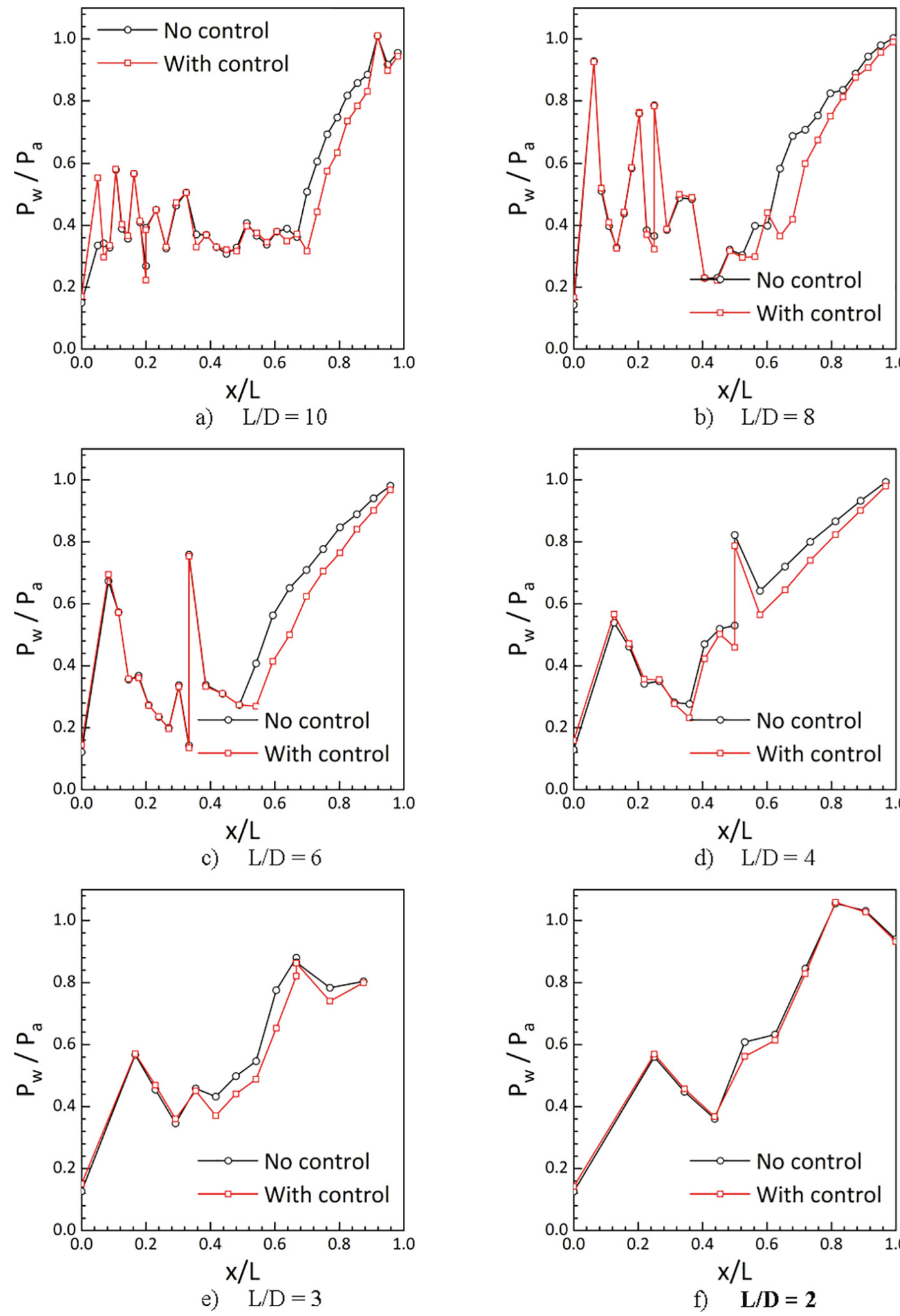


**Fig. 7.** Flow Development in the Duct at Mach number 1.8, and for correctly expanded NPR 5.75 at different L/D ratios.

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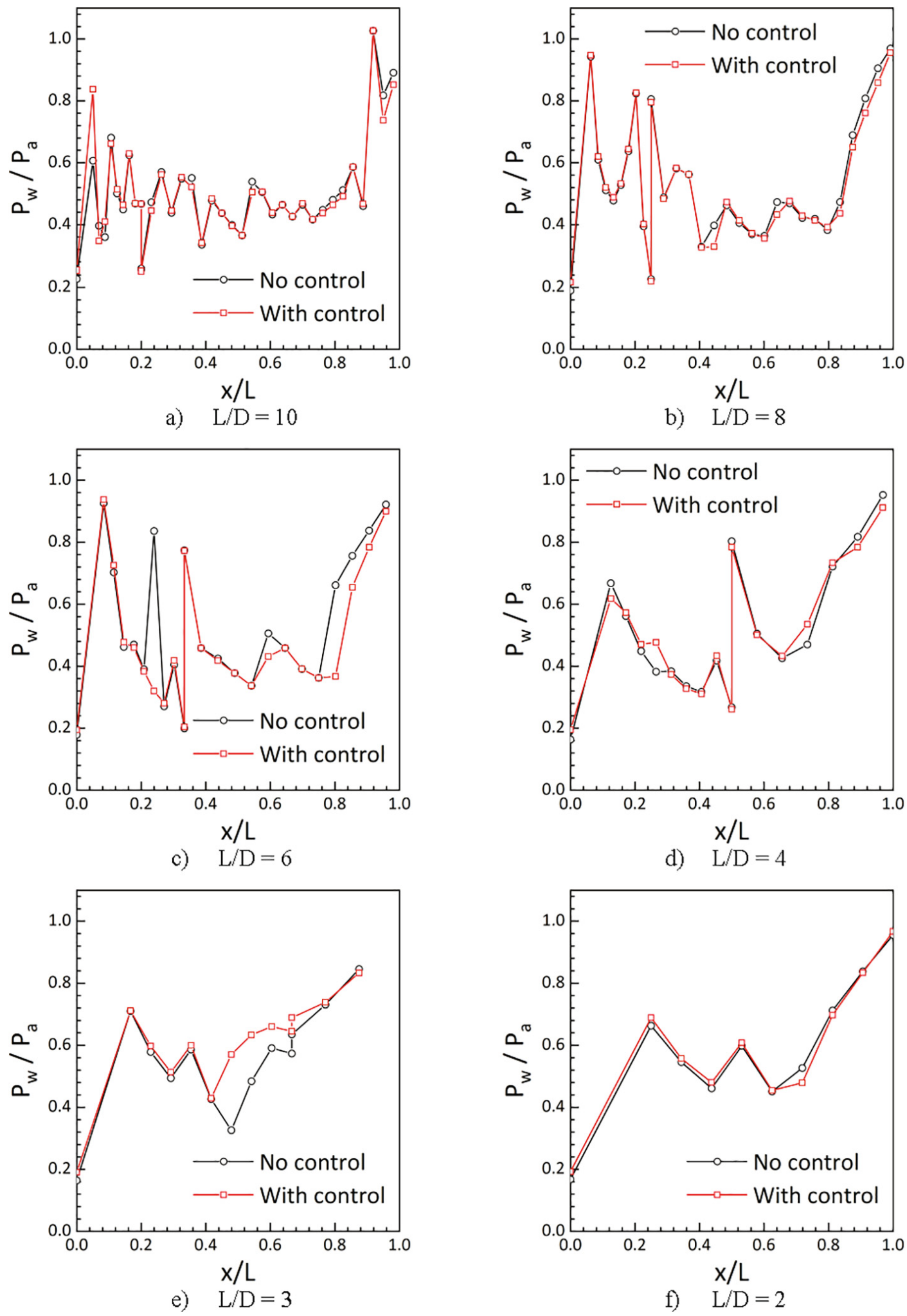


**Fig. 8.** Variation of wall pressure at Mach number 2.0, and for correctly expanded NPR 7.83 at different L/D ratios.


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