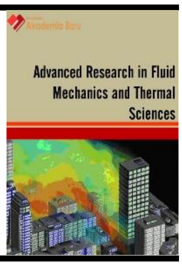
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Wall Pressure Measurements Beneath the Supersonic Jets in an Abruptly Augmented Nozzle

Open Access

Musavir Bashir[1,*], Sher Afghan Khan[2], Zakir Ilahi Chaudhary[3], Vilas Shinde[3]

[1] School of Aerospace Engineering, Universiti Sains Malaysia (USM), Penang, Malaysia
[2] International Islamic University Malaysia (IIUM) at Department of Mechanical Engineering, Malaysia
[3] Department of Mechanical Engineering Datta Meghe College of Engineering Airoli, Navi Mumbai, India

ARTICLE INFO

Article history:
Received 15 August 2019
Received in revised form 3 December 2019
Accepted 9 December 2019
Available online 4 March 2020

ABSTRACT

The ballistic research has introduced the requirements for obtaining aerodynamic data including base and wall pressures over a very wide range of Mach number, Reynolds number and manipulation of these forces by applying both active and passive control strategies. The manipulation of base and wall pressure plays a significant role in bluff body aerodynamics and control of aerodynamic forces is essential in reduction of drag and improving overall performance of such bodies. In this study, experimental investigation was conducted in sudden expansion axi-symmetric passage for controlling wall pressure. Micro jets constituting of four micro-holes around base and symmetric to nozzle axis are used as active control to manipulate the wall pressure. Wall pressure distribution is depicted for Mach number 1.25 and 1.3 respectively. Length-to-diameter (L/D) ratios of current investigation range from 10 to 5 with area ratios of 2.56. It is found that wall pressure is highly impacted by the microjet flow control at certain Mach numbers and geometrical parameters like the area ratio and L/D ratio also play a significant role in flow control and 50 % to 60% increase in the wall pressure is found at L/D = 10. It is also shown that that the nozzle pressure ratio (NPR) also influences the wall pressure. However, wall pressure distribution of the ducts is found fluctuating in nature in case of correctly expanded flows and remains ineffective even with microjet control.

Keywords:
Base pressure; wall pressure; flow control; nozzle pressure ratio; microjets

1. Introduction

Control of the base flow field and manipulation of the base pressure is worthy of a sustained research effort because the base flow field plays a considerable role in determining the flight capabilities of projectiles and missiles. Indeed, it has been shown that the lower pressure on the aft section of the body can contribute between 35–50% of the total drag for these vehicles [1]. For example, the base drag for the Space Shuttle was determined to be roughly half of the net orbiter drag during reentry [2]. Specifically, efforts toward the experimental control of base flows, and with other flows that contain similar flow features, is essential because many important flow parameters

[*] *Corresponding author.*
E-mail address: sakhan06@gmail.com (Sher Afghan Khan)

are still frequently predicted inaccurately with typical computational methods [3,4]. Supersonic boundary-layer control and the use of secondary flow for deflecting a supersonic jet have received considerable attention in the past for converging-diverging nozzles [5]. Execution of the aircraft nozzle relies upon the design of the divergent section, which guarantees that the course of the escape gases is specifically in reverse, as any sideways effects would not add to push [6]. Gas expands through a CD nozzle from subsonic to supersonic conditions, the stream under goes many types of distinct processes that increments the kinetic energy involving stream division, unsteadiness, stream blending, Shock Induced Boundary Layer partition and Mach shock Diamonds [2,5]. Few of them may prompt pressure loss; consequently, decrease the general push produced by the nozzle. Moreover, when the stream of the nozzle is either Over-expanded or Under-expanded, the loss in push because of Mach diamonds makes the nozzle less productive [7,8].

Previous researches have demonstrated that flow processes happening inside (shocks and stream divisions) and outside (Mach shock Diamonds) to the nozzle still withhold numerous execution disadvantages which stay unsolved [5,9]. To achieve its practical potential, the outline of a fume's nozzle fills two fundamental needs. To begin with, it regulates power plant exit pressure to achieve perfect design conditions, which is gained through variations in area of nozzle. The other purpose is conversion of PE to KE by quickening the fumes gas, which fulfilled by productive expansion of the gases to the surrounding pressure. Increase in Nozzle Pressure Ratio leads to the generation of a Normal shock (shock opposite to the axis of the stream) soon after the stream passes the throat of the nozzle (chocked nozzle) and will move downstream of the nozzle, the compressive impact will bring about an imbedded shock wave that is powerful and bended [10]. Mach patterns of shock with a Mach circle at the triple point in the convergence of the Oblique shock waves, referred to as under-expansion are as found in Figure 1 [5]. The stream attributes related with an unbalanced geometry setup under supersonic conditions has been less advantageous in past; consequently, leads emphasis onto this examination. The geometry varieties made at the different area of the nozzle may decrease inner attributes of the nozzle stream, boundary layer division, shock initiated partition and reverse flow, detachment bubbles when exhaust gas is extended to supersonic conditions [4].

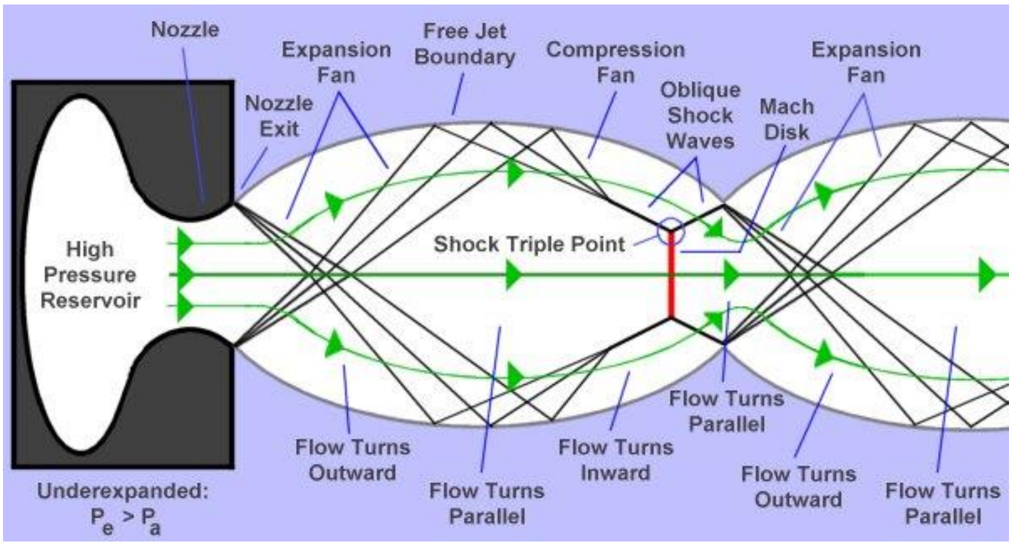


Fig. 1. Wave structures that create shock diamonds in an under-expanded flow [5]

Therefore, experimental research furthering understanding of base flows and their control is of significant practical importance to both the experimental and computational-fluid-dynamics community as well as to defense and commercial interests. The current study is principally motived with expansion of air jets into ducts with micro-jet technique. NPR, nozzle exit Mach number, and duct L/D ratio were treated as independent parameters. With control on for base flows, the impact of these controls on the wall pressure field in the duct becomes primary factor which means it is vital to ensure that the wall pressure field is not under adverse impact (i.e. made oscillatory) by the control. Following the same, the pressure distribution of the wall in the duct was assessed. Experiments were conducted for nozzle pressure ratios (NPR) 3, 5, 7, 9, 11 and for specific levels of expansion (i.e. Pe/Pa = 1-0, 1.5, 0.556 and 0.277). These levels of expansion were chosen to evaluate the efficiency of active control in the form of micro jets under correct, under and over expanded conditions for area ratio 6.25. The L/D ratio was varied from 10 to 1. Three convergent-divergent nozzles with Mach numbers 1.87, 2.2, and 2.58 were tested. Each nozzle had exit diameter of 10 mm.

2. Literature Review

Rathakrishnan [11] studied the impact of ribs on a suddenly extended axi-symmetric streams laying accentuation on the base pressure diminishment and the channel pressure field. Annular ribs with perspective proportion 3:1 was observed to be the ideal and they don't acquaint any motions with the wall pressure field of the channel, in the meantime the expansion in pressure loss contrasted with plain was likewise under six for every penny. Notwithstanding for the case with passive control the conduit L/D in the range 3 to 5 encounters the base pressure, as on account of plain channels. He presumed that there is an edge of the control rib AR which is fundamental for getting most extreme suction at the base alongside least pressure loss and non-oscillatory stream advancement in the enlarged duct.

Tests were conducted at different expansion level to assess the efficacy of the flow manipulator [10]. From the outcome of the test it was observed that there is significant reduction in the suction at the base with the dynamic flow manipulator without affecting the flow in the enlarged duct. Further, it was reckoning that the pressure at the nozzle lip dictates the flow in the presence and absence of the control mechanism. Experimental and numerical simulations for different NPRS, fixed area ratios in the range from 2 to 8, Mach number, at fixed value of L/D = 5 were carried and their results from the numerical simulations were in good agreement with the experimental results [12,13]. Experimentally investigation for passive control of the base pressure from rectangular nozzle exhausted in to the square duct of area ratio 9 was carried [14,15]. In their study they used static cylinder, rotating cylinder clockwise as well as the anti-clockwise to regulate the base flow and the square duct field at Mach 2. Results indicate that the static cylinder is effective when it is placed in recirculation zone provided the jets are correctly expanded or under expanded.

A delayed detached eddy simulation (DDES) of an over-expanded nozzle flow with shock-induced separation was carried out and found that the unsteady Mach disk is characterized by an intense vortex shedding activity and the interaction of these vortices with the second shock cell is a key factor in the sustainment of an aeroacoustics feedback loop within the nozzle [16]. To analyze the laminar flow in a sudden augmented pipe subjected to a uniform suction speed, numerical simulations has been carried out for this investigation [17]. Different finite element methods have been employed to solve the viscous effects of the flow and then the results are compared with the available results in the literature. It was concluded that the vortices generated near the step wall dwindles along the length for progressive values of blowing speed applied at the walls. Additionally, to date, separation control using microjets had primarily been examined in canonical flows such as a modified backward facing ramp [18] and for aircraft-related applications for two dimensional (at least geometrically) airfoils [4,19].

The above literature uncovers that although a bulk of literature available on this challenge of sudden expansion, vast writings of them comprise of work study without control. In fact, of the available literature on research of base flows with control, most of them use only passive control by means of grooves, cavities and ribs. Thus, it can be deduced that just a handful of studies report base flow examination and study with active control.

Hence, more insight view at the performance of active controlled base flows, specifically in the supersonic range will be of high value because of their significance in application in many problems of applied gas dynamics like, missiles and launch vehicles diminishment of base drag, base heating control etc. To achieve this goal, the current project examines the same with micro jets, also, effect of locations of micro jets.

3. Methodology

High Speed Aerodynamics Laboratory (HSAL) of Mangalore Institute of Technology, Karnataka housed the tests in its experimental facility as depicted in Figure 2 and 3. It displays Nozzle exit perimeter comprises of eight holes out of which four (marked c) were used to blow and rest (marked m) were employed to estimate base pressure (Pb). Blowing controls base pressure via control holes with help of pressure from the blowing chamber by engaging a tube joining the chamber and the control holes (c) along with pressurized taps set up on the duct wall to estimate wall pressure distribution. With intermediate gap as 4 mm nine holes were punched initially, and rest are done with a gap of 8 mm each. Mach numbers 1.25 and 1.3 are used to perform laboratory tests with NPR range as 3, 5, 7, 9, and 11 for both.

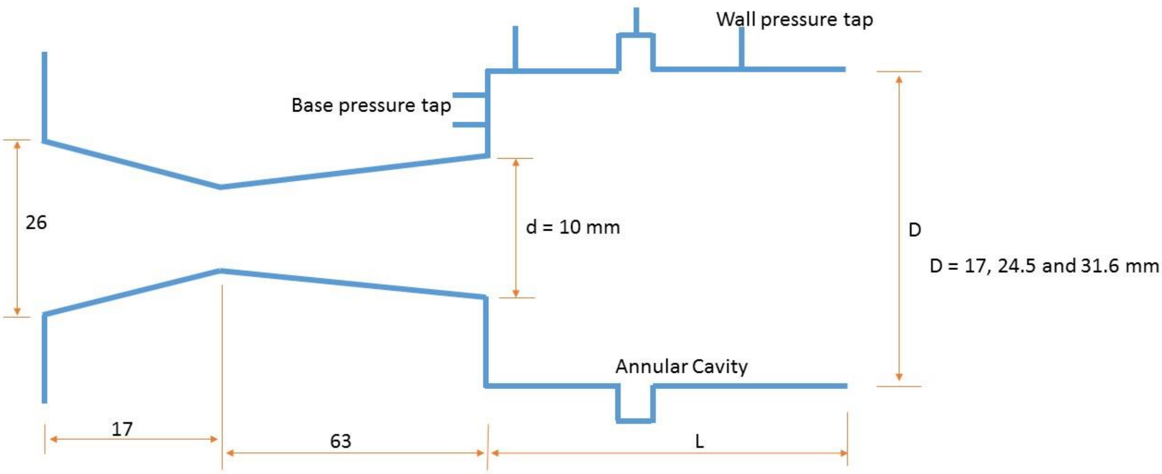


Fig. 2. Schematic of experimental model

Total pressure and base pressure values of settling chamber were assessed with help of 9010 modeled PSI pressure transducer (interfaced with a PC386). Specifications of this PSI are it consists of 16 channels with a range of pressures (0-300 psi). Sampling is done with 250 specimens for every second and shows the measured reading. Maker provided software was utilized to interlink PC with the transducer. User-friendly programming obtains information and demonstrates the pressure readings from all the 16 directs all the while in a window sort show on the PC screen. The product can be utilized to pick the units of pressure from a rundown of accessible units, play out a re-zero/full calibration, and so on.

Fig. 3. Experimental Setup depicting microjet controls and different area ratio nozzles

The transducer likewise has choice to pick the quantity of tests to be averaged, by methods for plunge switch settings. It could be worked in temperatures extending from -20^0 C to +60^0 C and 95% humidity. Device Mercury manometer was employed for the estimation of wall pressure which will compile data of both total and wall static pressures over the enlarged duct wall length. Here, NPR is ratio of total pressure to back pressure i.e. P_{stag}/P_{back}. Each measured pressure data was non-dimensionalized by isolating them with the surrounding climatic pressure (i.e. the back pressure).

Parameters also under investigation of the present examination are the jet Mach number (M), L/D ratio, A cross-section/A nozzle exit and the smaller scale jet blow pressure proportion. In the present investigation, the range proportions utilized is 2.56 and the blow pressure proportion is same as the NPR of those respective runs. The essential target of this examination is to think about the attainability of microjet blowing as a control component for controlling the base pressure.

4. Results

The measured data consists of the base pressure Pb, wall static pressure Pw distribution along the length of the enlarged duct and the nozzle pressure ratio (NPR) defined as the ratio of stagnation pressure Pstag to the back pressure Pback. All the measured pressures were non-dimensionalzed by dividing them with the ambient atmospheric pressure (i.e. the back pressure).

Other parameters of the present study are the jet Mach number (M), the area ratio (enlarged duct cross sectional area/nozzle exit area), length to diameter ratio of the enlarged duct (L/D) and the micro-jet blow pressure ratio. In the present study, the area ratios used is 2.56 and the blow pressure ratio is same as the NPR of the respective runs. The primary objective of this investigation is to study the feasibility of microjet blowing as a control mechanism for restraining the base pressure.

4.1 Wall Pressure Results

4.1.1 Wall pressure distribution for Mach number 1.25

The wall static pressure distribution along the enlarged duct length for Mach number 1.25 is presented in Figure 4(a) to 4(h). Outcomes in most cases suggest that the pressure field in both situations remains same. Which will in turn guarantee the wall pressure field doesn't come under active control adversely forcing it to oscillate violently. It is a huge advantage since, the major problem faced while using a control on base pressure is that the control will augment the oscillatory nature of the wall pressure field.

Results for L/D = 10 are presented in Figure 4(a) to (b). From figures, it is seen that at NPR = 11, 9, 7, and 5 the entire flow field in the duct is full of waves, the few shock wave is so powerful that the wall pressure is equal to the atmospheric pressure for NPR 7 and 5 whereas, for NPRs 11, and 9 initially it is equal to ambient pressure later it gets enhanced 45 and 20 percent and then through the next shock the wall pressure assumes equal to the value of the atmospheric pressure. At NPR = 3 there is oblique shock which results in steep rise in pressure and later flow gets expanded and again getting compressed then it becomes smooth. Since the flow is highly under expanded the initial values of the wall pressure at x/D = 0 are 0.8, 0.7, 0.58, 0.4, and 0.38 for NPRs 11, 9, 7, 5, and 3 respectively, the reason for the variations in the initial values is the change in the level of under expansion. Flow field with and without control remains the same.

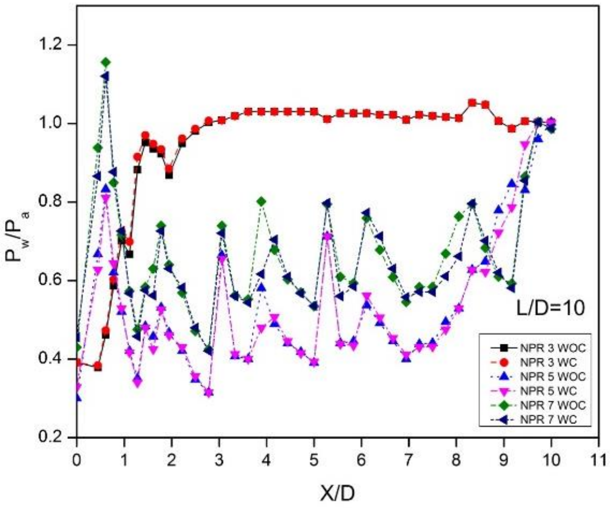
Figure 4(c) to (d) depict the experimental outcome of the investigations for duct length of 8D. As observed above for the case of L/D = 10, the wall pressure flow field is associated with the compression and expansion waves for NPRs 11, 9, 7, and 5 and for NPR 3 no such trend is seen. Further, due to decreased L/D, the initial jump in the wall pressure has gone up by 20 % and 40 % for NPRs11, 9 and 7. Some fluctuations in wall pressure with and without controls are observed for higher NPRs 11, 9, 7, and 5 towards the end of the duct due to back pressure effect.

Figure 4(e) to (f) show the outcome of the investigation for L/D = 6 it is seen that for the same NPRs, for NPRs 11, 9 and 7 there is a sudden jump in the initial wall pressure and it has gone up by 85 %, 55 % and 20 % respectively for NPRs 11, 9 and 7, however, for NPRs 5 and 3 the trend is the same as discussed earlier. Another phenomenon observed is that number waves have reduced considerable due to the short duct length and flow is likely to become smooth with further reduction in duct length.

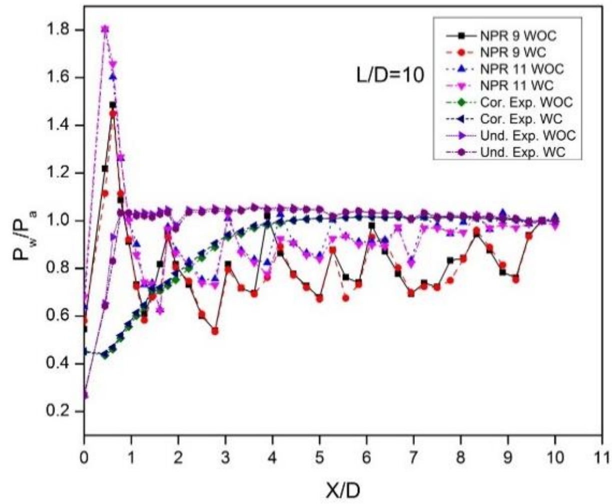
Results for NPRs 11, 9, 7, 5 and 3 for L/D = 5 are shown in Figure 4(g) to (h), they similar results as discussed earlier for NPRs 11, 9 and 7 for this L/D = 5 as well, but when we see the results for NPRs 11, 9, 7, and 5 there is marginal change in the terms of shock strength and number of waves due to the reduction in the duct length. Also, it is seen that the initial jump has further increased to the level of 80 %, 50 %, and 20 % for NPRs 11, 9 and 7. Rest of the behaviour remains the same.

In case of under-expanded jets, the results for L/D = 8 and 10 indicate peculiar phenomenon. It is seen that there is strong oblique shock wave present at x/L = 0, 0.15, 0.2, 0.3 and 0.5 for L/D = 8. For L/D = 10, the wall pressure has one strong shock and rest of the shocks are weak as compared to L/D = 8. The entire flow field is full of waves and flow remains identical with and without control which means when controls in the form of micro jets are employed, they do not disturb the flow field in the duct.

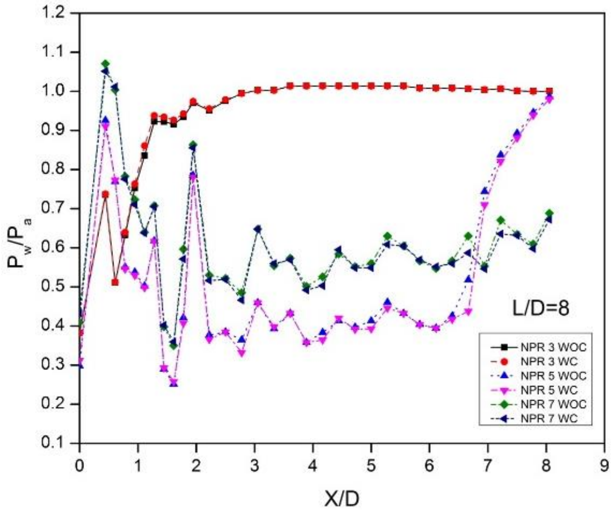
Results of wall pressure for L/D = 5 and 6 once again show that the flow field is identical with and without control and in both the cases the recovery of the wall pressure is not smooth rather it wavy in nature, and fluctuations in wall pressure field are observed. The main reason for this trend is due the jet being under expanded. Another observation is that the second jump in wall pressure has shifted back and there is third jump as well this could be due to the larger length of the duct. For M = 1.25, correct expansion occurs at NPR = 6.4. So, when we have low levels of under-expansion, i.e., at NPR = 9 and 11, for L/D = 10 then again, we obtain re-attachment point at about 70% of the length of the enlarged duct.


L/D=10
NPR 3 WOC
NPR 3 WC
NPR 5 WOC
NPR 5 WC
NPR 7 WOC
NPR 7 WC
P_w/P_a
X/D

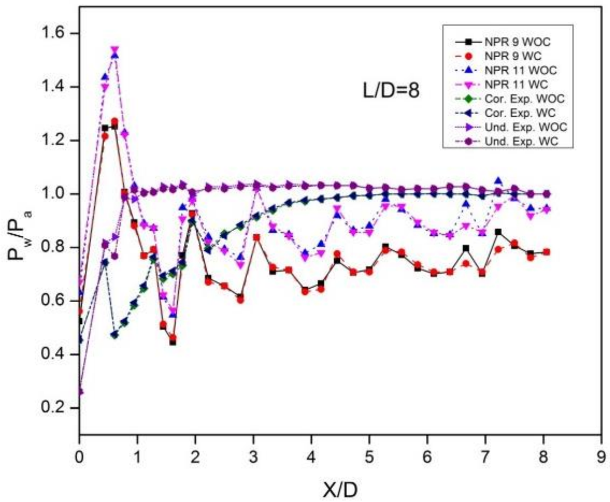
(a)


L/D=10
NPR 9 WOC
NPR 9 WC
NPR 11 WOC
NPR 11 WC
Cor. Exp. WOC
Cor. Exp. WC
Und. Exp. WOC
Und. Exp. WC
P_w/P_a
X/D

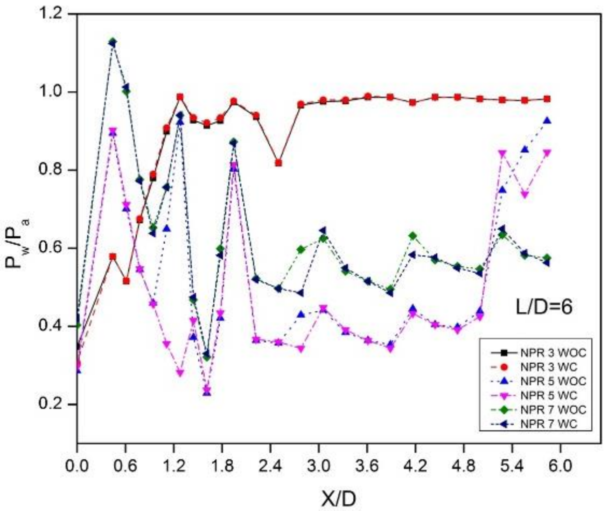
(b)


L/D=8
NPR 3 WOC
NPR 3 WC
NPR 5 WOC
NPR 5 WC
NPR 7 WOC
NPR 7 WC
P_w/P_a
X/D

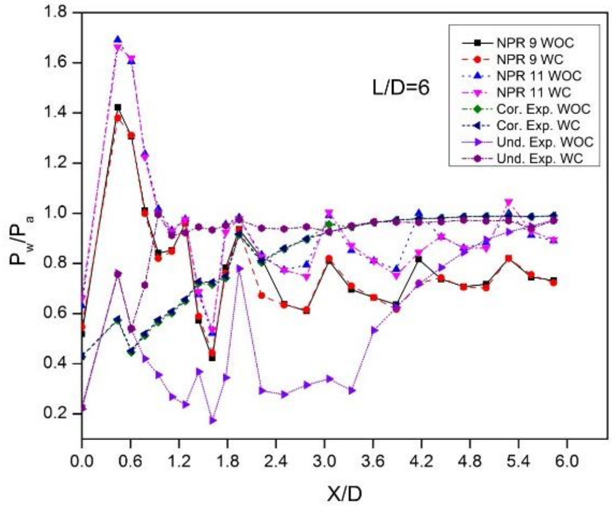
(c)


L/D=8
NPR 9 WOC
NPR 9 WC
NPR 11 WOC
NPR 11 WC
Cor. Exp. WOC
Cor. Exp. WC
Und. Exp. WOC
Und. Exp. WC
P_w/P_a
X/D

(d)


L/D=6
NPR 3 WOC
NPR 3 WC
NPR 5 WOC
NPR 5 WC
NPR 7 WOC
NPR 7 WC
P_w/P_a
X/D

(e)


L/D=6
NPR 9 WOC
NPR 9 WC
NPR 11 WOC
NPR 11 WC
Cor. Exp. WOC
Cor. Exp. WC
Und. Exp. WOC
Und. Exp. WC
P_w/P_a
X/D

(f)

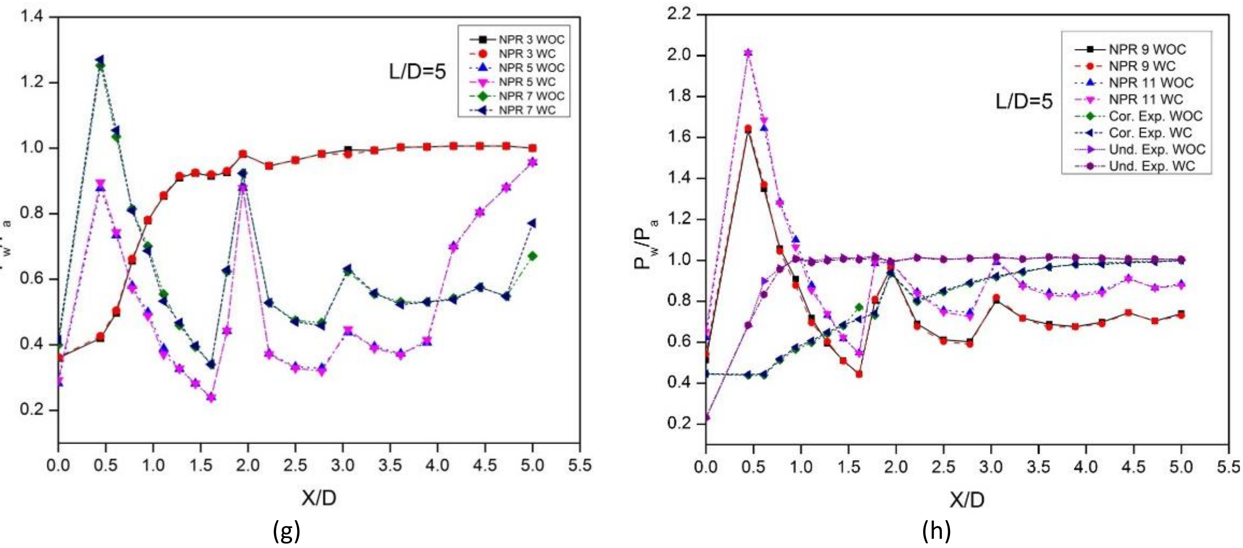


Fig. 4. Wall pressure results at Mach 1.25

4.1.2 Wall pressure distribution for Mach number 1.3

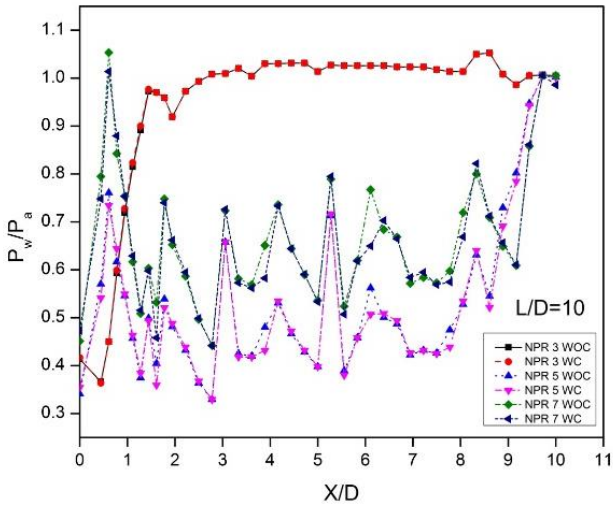
At Mach number 1.3, the results are depicted in Figure 5(a) to 5(h). Ideal required expansion requires an NPR of 10.7. At NPR's 9, 11 wall pressure fields were showcasing fluctuating nature. And, at NPR's 3, 5 and 7 it is recorded that wall pressure distribution is displaying finer variation. Micro jets do not impact wall pressure field much in many situations at given Mach number

At Mach number 1.3, we find that at higher values of L/Ds and NPRs (9 and 11) respectively fluctuation induced flow field is present, but these fluctuations reduce with L/D ratio decrement. Also, no noteworthy rise in reattachment length is visible for different NPR and L/D blend except L/D = 2 at NPR = 11. For this case we find an increase of 10% in reattachment length is secured by applying controls.

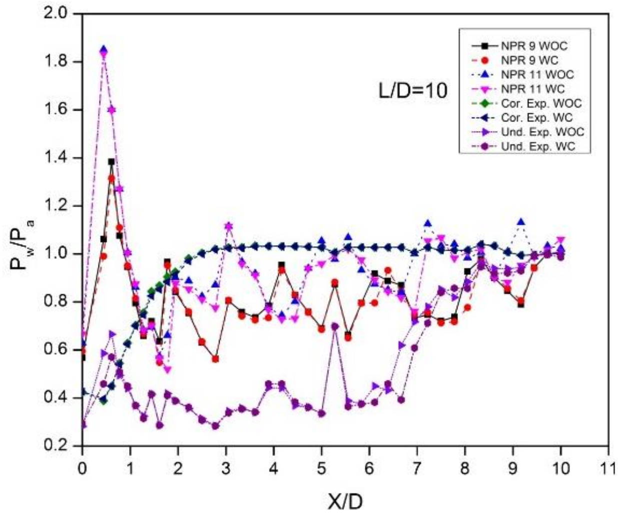
Similar results are seen in Figure 5(c) to (d) with the exception that in view of the shorter duct lengths namely L/D = 6 and 5, the flow field in the duct once again is spread over all along the length of the duct. In both the cases we observe six oblique shocks of variable strength and same number of the expansion waves and the very first oblique shock has got the same strength.

Wall pressure results for L/D = 10 to 5 for correctly expanded jets depict that at first wall pressure tap there is sudden increase in the pressure and this happens twice at x/D = 0 and 2 and then flow becomes smooth with marginal changes in the magnitude, When the control was employed it results in the similar behaviour till x/D = 3 and in the downstream micro jets are able to break the vortex and hence results in lower values of wall pressure, there are some shocks and later the recovery of the flow is smooth becoming almost equal to the back pressure. It was also observed during the tests that when micro jets are activated the noise produced by the jets was quiet and the noise produced is reduced considerably.

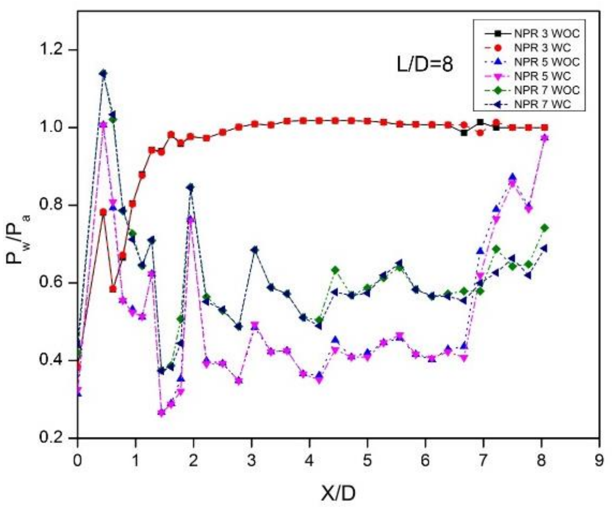
Wall pressure results for L/D = 10 to 5 for under expanded jets can be evaluated and it is seen that there are three strong and six weak oblique shocks which results in compressing the flow and which finally results in increase of the wall pressure in the duct, it is also seen that similar number of expansion waves are present there resulting in the expansion of flow leading to a low values of the wall pressure and this phenomena continue till the end of the pipe length and this was expected as the flow is under expanded and the will continue to expand till it attains the value of the ambient atmospheric pressure. However, when we observe the flow for L/D = 8 as shown in Figure 5(d) in this case there are four strong oblique shocks and the same number of expansion and this activity is limited to 40 % length of the duct and further in the downstream even though the flow still undergoes expansion and compression of moderate intensity to enable the pressure in the duct is equal to the back pressure value. This strange phenomenon for L/D = 8 seems to be due to the reduction in the duct length, and the back pressure will influence the flow in the duct the waves which were spread all along the length of the duct in case of L/D = 10 have been restricted to smaller length of the duct and this value is around 40 % of the total duct length.



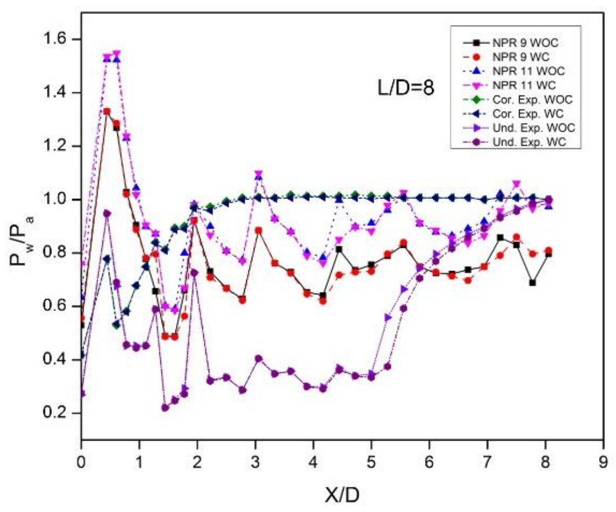
(a)



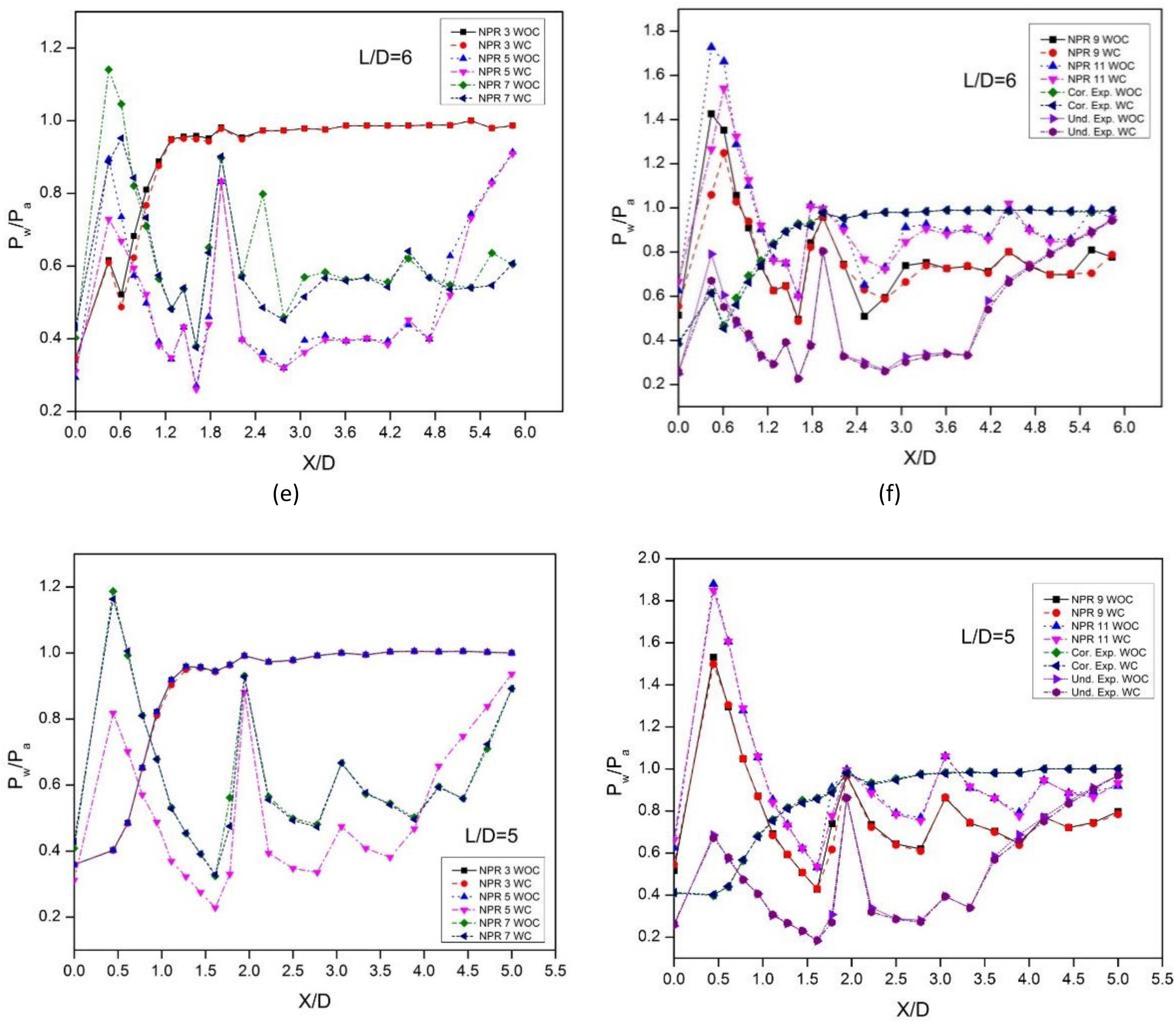
(b)



(c)



(d)



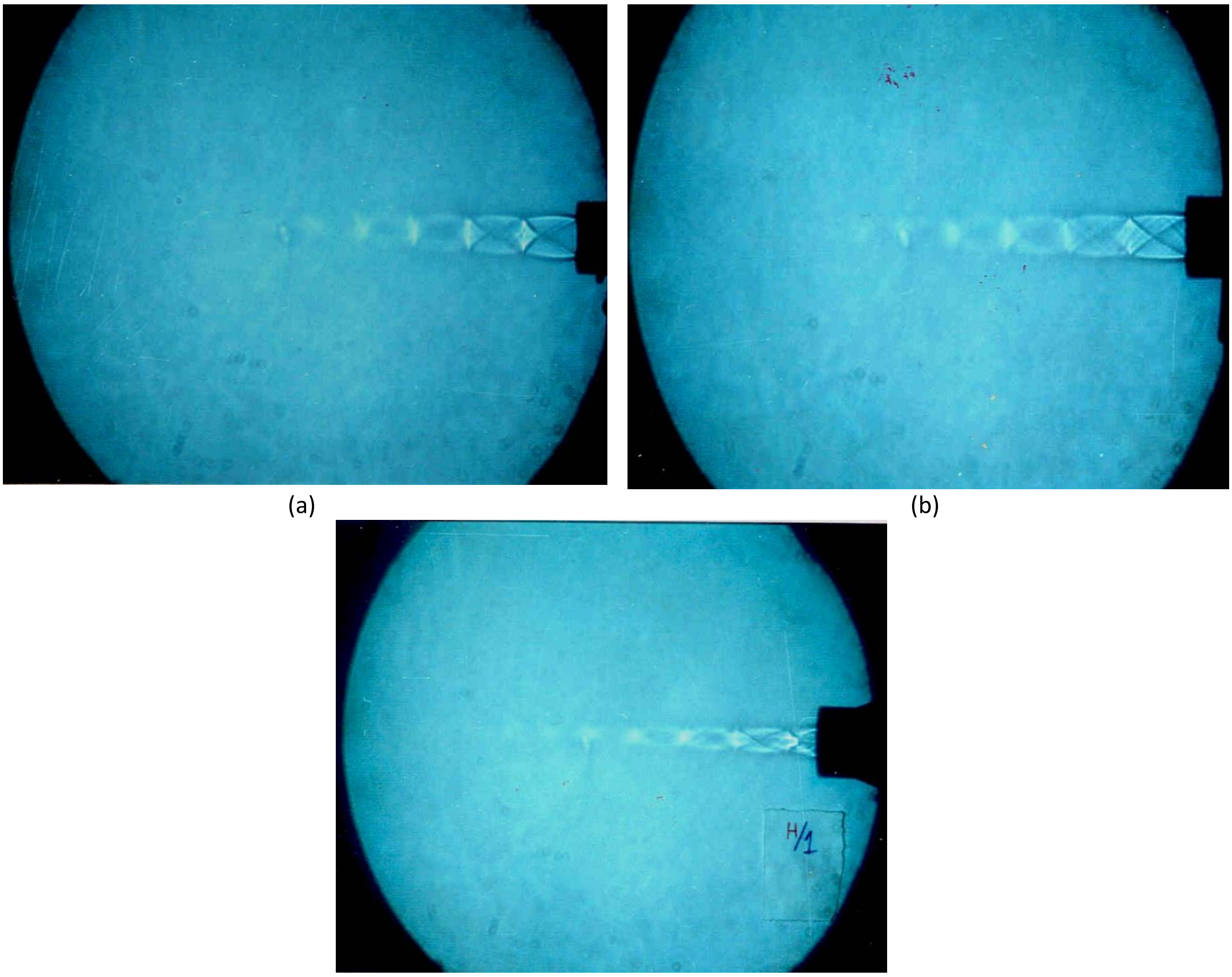
(e) (f)

(g) (h)

Fig. 5. Wall Pressure Results at Mach 1.3

4.2 Shadowgraphs at Different Nozzle Pressure Ratios

Figure 6 depicts the shock wave structures of the nozzle at NPR= 11, 9 and 7 respectively, as experimental shadowgraphs. Figure 6(a) and 6(b) shows flow fields of the nozzle at NPR=11 and 9 respectively. Higher nozzle pressure ratio shadowgraph images show a double-diamond pattern rather than the typical single diamond shock pattern. The distance between oblique shock waves in the shock trains increases with the NPR. It means that suddenly expanded flows are accompanied by shocks. As we observe that there are multiple lines in the shock trains of shadowgraph, which makes it interpretation more complex. Most of the times, these diamond structures are produced inside the nozzle, and then it appears at the exit of the nozzle. Similarly, Figure 6(c) depicts that at NPR=7, the pattern of diamond structure is strong at the lip and weakens as it extends away from the nozzle.



(a) (b)

(c)

Fig. 6. Shadowgraphs at Mach number at NPR 3, NPR 5 AND NPR 7 respectively

5. Conclusions

In this investigation, active control strategy using microjets was employed to manipulate the wall pressure of suddenly expanded nozzle. From the results, it is concluded that wall pressure is highly impacted by the geometrical parameters namely the area ratio of the passage, the L/D ratio of the broadening duct and nozzle exit Mach number. At higher L/D ratios of 10, the maximum jump in the wall pressure takes place within the reattachment length., which indicates that there is very strong shock at the nozzle exit, and in the downstream the shock is becoming weaker due to the process of reflection and recombination of waves. In this case, 50 % to 60% increase in the wall pressure is found. wall pressure distribution of the ducts is fluctuating in nature, but with presence of controls, this doesn't impact negatively micro jets. In case of correctly expanded flows, the wall pressure trends with and without control remain the same. At L/D = 3 appeared to be the limit for base vortex strength manipulation and L/D less than 3 proved to be insufficient for the flow to re-attach in most of the cases.

Acknowledgement
The authors declare no conflict of interest. No role of the funding from any sponsor was provided in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

[1] Viswanath, P. R. "Flow management techniques for base and afterbody drag reduction." *Progress in Aerospace Sciences* 32, no. 2-3 (1996): 79-129.

[2] Delery, J., and R. G. Lacau. "Prediction of base flows." *A0P'-A199 172* (1988): 34.

[3] Staats, Marcel, Carola Ebert, and Julien Weiss. "Experimental Investigations on Active Flow Control Applied to an Asymmetric Compressor Cascade." In *AIAA Aviation 2019 Forum*, p. 3494. 2019.

[4] Kreth, Phil, Farrukh Alvi, Vikas Kumar, and Rajan Kumar. "Microjet based active flow control on a fixed wing UAV." In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, p. 1260. 2010.

[5] Ekanayake, S. "Numerical simulation of a convergent divergent supersonic nozzle flow." Master Thesis, RMIT University (2013).

[6] Ivanov, I. E., and I. A. Kryukov. "Numerical study of ways to prevent side loads in an over–expanded rocket nozzles during the launch stage." *Acta Astronautica* 163 (2019): 196-201.

[7] Davis, Kate, Elizabeth Fortner, Michael Heard, Hannah McCallum, and Hunter Putzke. "Experimental and computational investigation of a dual-bell nozzle." In *53rd AIAA Aerospace Sciences Meeting*, p. 0377. 2015.

[8] Wu, Jie, and Tze How New. "An investigation on supersonic bevelled nozzle jets." *Aerospace Science and Technology* 63 (2017): 278-293.

[9] Balabel, A., A. M. Hegab, M. Nasr, and Samy M. El-Behery. "Assessment of turbulence modeling for gas flow in two-dimensional convergent–divergent rocket nozzle." *Applied Mathematical Modelling* 35, no. 7 (2011): 3408-3422.

[10] Khan, Sher Afghan, and Ethirajan Rathakrishnan. "Active control of suddenly expanded flows from overexpanded nozzles." *International Journal of Turbo and Jet Engines* 19, no. 1-2 (2002): 119-126.

[11] Rathakrishnan, E. "Effect of ribs on suddenly expanded flows." *AIAA journal* 39, no. 7 (2001): 1402-1404.

[12] Khan, S., Musavir Bashir, and M. Asadullah. "An investigation of base flow control by wall pressure analysis in a suddenly expansion nozzle." *Journal of Scientific Research and Development* 3, no. 5 (2016): 1-6.

[13] Bashir, Musavir, M. Ahmed Ali Baig, Ahmad Faris Ismail, and S. A. Khan. "Control of Suddenly Expanded Flows from Correctly Expanded and under Expanded Nozzles at Supersonic Mach number for Area Ratio 2.56." *International Organization of Scientific Research-Journal of Mechanical and Civil Engineering (IOSRJMCE)*: 76-82.

[14] Asadullah, Mohammed, Sher Afghan Khan, Waqar Asrar, and E. Sulaeman. "Active control of base pressure with counter clockwise rotating cylinder at Mach 2." In *2017 4th IEEE International Conference on Engineering Technologies and Applied Sciences (ICETAS)*, pp. 1-6. IEEE, 2017.

[15] Chaudhary, Zakir Ilahi, Vilas B. Shinde, Musavir Bashir, and Sher Afghan Khan. "Experimental Investigation on the Effectiveness of Active Control Mechanism on Base Pressure at Low Supersonic Mach Numbers." In *Innovative Design and Development Practices in Aerospace and Automotive Engineering*, pp. 197-209. Springer, Singapore, 2017.

[16] Martelli, E., L. Saccoccio, P. P. Ciottoli, C. E. Tinney, W. J. Baars, and M. Bernardini. "Flow dynamics and wall-pressure signature in high-Reynolds number overexpanded nozzle with free shock separation." *arXiv preprint arXiv:1906.08500* (2019).

[17] Layek, G. C., C. Midya, and S. Mukhopadhyay. "Effects of suction and blowing on flow separation in a symmetric sudden expanded channel." *Nonlinear Anal Model* 13 (2008): 451-465.

[18] Kumar, Vikas, and Farrukh S. Alvi. "Toward understanding and optimizing separation control using microjets." *AIAA journal* 47, no. 11 (2009): 2544-2557.

[19] Liu, Yanming, Hong Zhang, and Pingchao Liu. "Flow control in supersonic flow field based on micro jets." *Advances in Mechanical Engineering* 11, no. 1 (2019): 1687814018821526.