Passive Control of Base Drag Employing Dimple in Subsonic Suddenly Expanded Flow

S. A. Khan, Mohammed Asadullah, and Jafar Sadhiq

***Abstract*— This paper presents an experimental and computational investigation to study the effectiveness of dimples to control the base pressure in Backward facing step (BFS) for various Nozzle pressure ratio (NPR) having Compressible flow to minimize the base drag. Two dimples of 3 mm diameter located at 1800 interval along pitch circle diameter of 23 mm in the base region was employed as passive controls. The test was conducted for NPR 1.27, 1.38, 1.52 and 1.69. The model is designed in such a way so as to provide four BFS with angle of incidence as 150 from which the flow suddenly expands to a square duct of 25 mm. The experimental investigation is carried out for different length of duct $4D \le L \le 10D$ to see the influence of geometric parameter on base pressure. From the present investigation, it was found that dimples as passive control is very effective at higher NPR and the wall pressure distribution too was quite stable at higher NPR. Also the geometric parameter was found to influence the base pressure for a particular NPR. Computational investigation using commercial CFD tool shows pressure and velocity distribution profile for both dimple and non-dimple control. Tests are carried out by using Navier-stokes equation, Turbulence model as SST, Reynolds number (Re) $=122.56\times10^{3}$. From this investigation it is clear that for a given nozzle pressure ratio one can find optimum L/D ratio which will result in maximum increase/decrease of base pressure and dimples can be effective passive controller for reducing base drag without disturbing the flow field.**

***Index Term*— Backward Facing Step, Base Pressure, Wall Pressure, Nozzle Pressure Ratio, Passive Control.**

I. INTRODUCTION

The backward-facing step (BFS) is one of the most fundamental configurations to study flow separation and following reattachment which occurs due to a sudden expansion in the flow passage. The existence of flow separation and reattachment plays an important role in many engineering applications, such as combustors, diffuser, electronic and turbine blade cooling as well as in external flows such as aircrafts [1]. For this reason, a number of studies on the flow separation and reattachment of the BFS geometry have been presented numerically and experimentally by many researchers in the past decades. Among these studies, the effect of Reynolds number, step height, aspect ratio has been reported for the 2D and 3D flows, which brought to insight for understanding the flow characteristics of the BFS configuration [2].

The flow behind the backward-facing step (BFS) is complex and involves various instability mechanisms. Some of the most common features behind the step recognized in the literature are illustrated in the Figure 1. Based on the important flow features studied by previous researchers in a planar BFS geometry, the flow wake can be distinguished into three main regions namely, the shear layer region, separation bubble or recirculation zone and the reattachment zone. The general characteristics of a BFS flow begins with an upstream boundary layer separating at the step edge due to the adverse pressure gradient that develops into a thin shear layer. As the flow progresses downstream, the shear layer grows in size with the amalgamation of the turbulent structures contained within. This region where the shear layer develops and grows is referred to as the shear layer region. The turbulent structures in the shear layer entrain irrotational fluid from the non-turbulent region outside the shear layer.

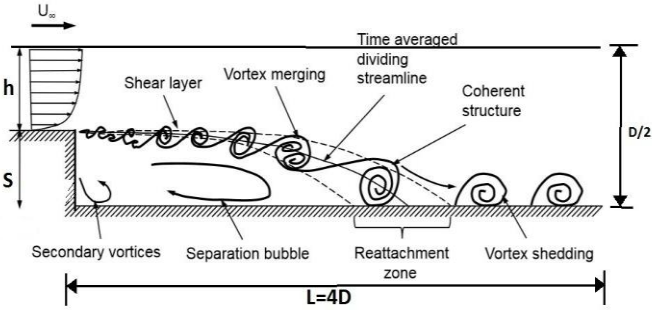

Fig. 1. Flow characteristics behind a BFS

The effectiveness of passive devices for axi-symmetric base drag reduction at Mach 2was studied by Viswanath and Patil [3]. The devices examined included primarily base cavities and ventilated cavities. Their results showed that the ventilated cavities offered significant base-drag reduction. They found 50 per cent increase in base pressure and 3 to5 per cent net drag reduction at supersonic Mach numbers for a body of revolution.

Ramamurthy [4] studied cavitation effects on flow past backward facing steps. He concluded cavities an effective passive control but could not explain about the nature and type of cavity.

Viswanath [5] reviewed the flow management techniques for base and after-body drag reduction of the problem of turbulent base flows and drag associated with it. This review presents the development that have taken place on the use of passive techniques or devices for axisymmetric base and net after-body

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drag reduction in the absence of jet flow at the base. In particular, the paper discusses the effectiveness of cavities, ventilated cavities, locked vortex after-bodies, multi-step after-bodies and after-bodies employing anon-axisymmetric boat-tailing concept for base and net drag reduction in different speed regimes. The broad features of the flow and the likely fluid-dynamical mechanism associated with the devices leading to base drag reduction were highlighted. Flight-test results assessing the effectiveness of some of the devices were compared with data from wind tunnels. This review indicates that base and net after-body drag reduction of considerable engineering significance in aerospace applications can be achieved by various passive devices even when the (UN-manipulated) base flow is not characterized by vortex shedding.

Biswas [6] has briefly explained about cavitation studies carried by following research scholars in his literature: Vigander and Appel studied cavitation along the surface of separation in two-dimensional sudden expansions and found that cavitation stabilizes the vortices formed against further breakup.

Tihon [7] in his paper has mentioned that the structure and stability of transitional backward-facing step flow is found to be sensitive to all the operation parameters studied in his work, i.e. (i) inlet flow rate, (ii) expansion ratio, and (iii) inlet flow forcing: The shape of longitudinal wall shear rate profile changes with an increase of inlet flow rate. Increasing expansion ratio makes the backward-facing flow structure more complex. The wall shear rate profile with steep longitudinal changes and thus with a tendency to produce secondary flow recirculation regions is induced.

Khan and Rathakrishnan [8] and Khan et al. [9-11] did experimental examination to assess the effectiveness of micro jets for over, under, and correct expansion to control the base pressure in suddenly expanded ducts at moderate and high supersonic speeds. The result thus produced showed that the maximum gain in the base pressure is 152 percent for Mach number 2.58. The result also indicated that the micro jets do not augment the wall pressure field. They showed that micro jets can function as an effective controller raising the base suction to almost zero level for some special cases. Further, it was concluded that the nozzle pressure ratio has a major role to play in fixing the base pressure with and without control.

II. NUMERICAL SET-UP:

The present study aims at two-dimensional numerical simulation of some benchmark problems using the in-house flow solution code AcuConsole and the commercial available code Altair HyperWorks and the results obtained using these codes are compared with available measurement and/or other computations. Three dimensional analysis is carried out using these codes as a tool.

Analysis of backward facing step is carried out by using Navier-stokes equation and turbulence model is chosen as SST model. SST model gives good results in sudden expansion regions. Convergence tolerance is set to 0.001 to get accurate solution which is carried for 30 time steps. Mesh size for ducts 4D is defined to be 0.01mm. Figure 2 shows the mesh and geometry setup. The residual ratio and solution ratios are also depicted in Figure 3 to Figure 6 to demonstrate that solution has reached to stability.

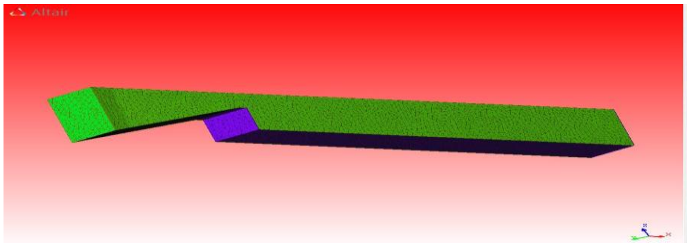

Fig. 2. Mesh design of BFS

- Residual ratio

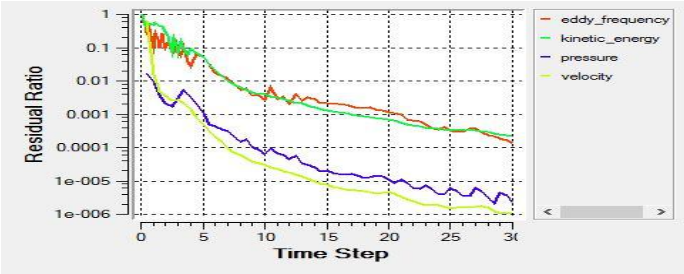

Fig. 3. Residual ratio for Duct L=4D without control

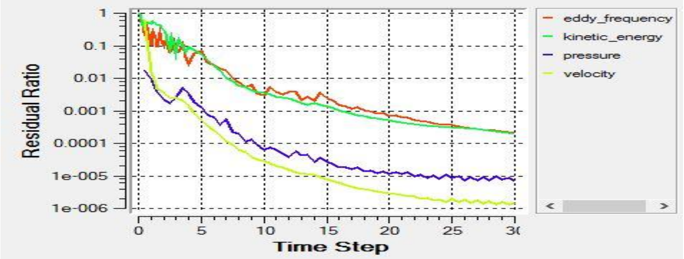

Fig. 4. Residual ratio for Duct L=4D with control

- *Solution ratio*

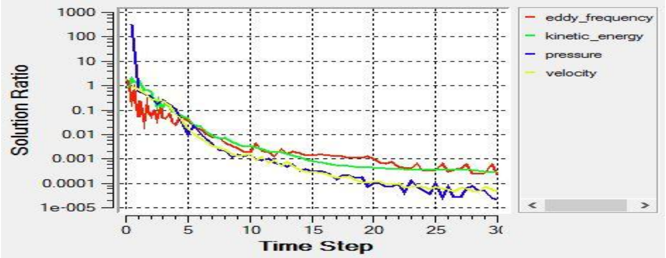

Fig. 5. Solution ratio for Duct L=4D without control

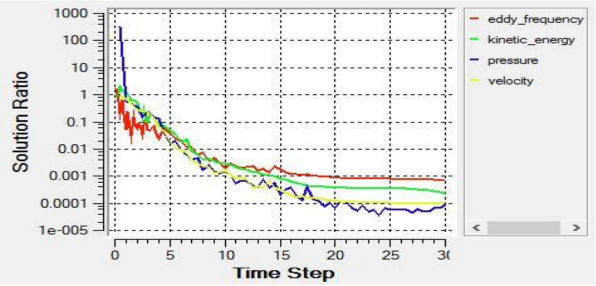

Fig. 6. Solution ratio for Duct L=4D with control

III. EXPERIMENTAL SETUP AND MODEL DESIGN

Figure 7 shows experimental setup used for present study. At the exit periphery of the nozzle there are four holes for measuring base pressure (Pb). Control of base pressure was achieved by using dimple. Wall pressure taps were provided on the duct to measure wall pressure distribution. First five holes were made at an interval of 5 mm each and remaining was made at an interval 10mm and 20mm each.

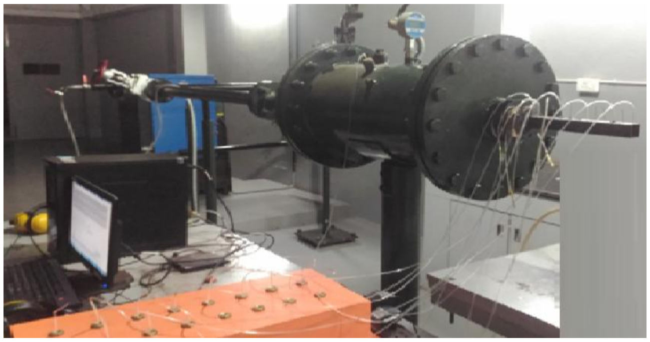

Fig. 7. Experimental setup of suddenly expanded nozzle

The model is designed by using solid edge as design tool. The Nozzle used in experiment is a square nozzle which can attain Mach=1. All the ducts are designed with same width and height which is 25×25mm the lengths of ducts are 4D, 6D, 8D and 10D. A plate having two dimples in its Pitch circle 11.5mm is placed between the nozzle and duct. Below figure shows the dimension of Nozzle, duct and Dimple plate as shown in Figure 8.

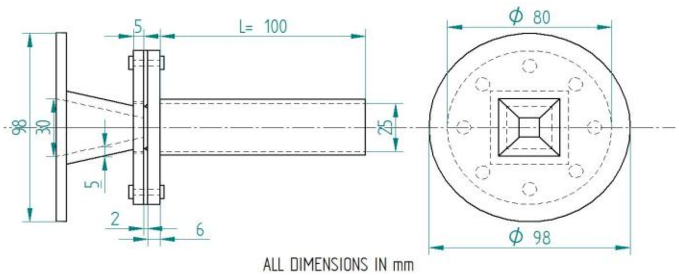

Fig. 8. Design and dimensions of nozzle and duct

IV. RESULTS AND DISCUSSION

This research focused on the efficiency of the base flow controls in form of dimple which is located at the pitch circle of the base region of sudden expansion axi-symmetric ducts to control base pressure. Base pressures have been non-dimensionalized using atmospheric pressure.

Figure 9 to 12 compares results of base pressures dependence on Mach number, area ratio and NPR (Range 3-11) with and without dimple control. NPR controls level of expansion and significantly influences the control effectiveness of dimple for a given Mach number. For Mach number regime 0.6 to 0.9, it, it is observed NPR is proportional to control effectiveness of increasing base pressure. The base pressure variation with NPR for L/D=4 at Mach numbers from 0.6 to 0.9 are shown in Table I and Figure 9

The trend of graph shows that, NPR strongly impacts the base pressure and also influences the control. For higher NPR the base pressure is low i.e high drag and control are very effective. For lower NPR the base pressure is high i.e low drag and control are not effective at all for L=4D.

TABLE I
Base pressure for Duct L=4D

L=4D A2/A1=6.25 Mach number=0.6,0.7,0.8,0.9		
NPR	**Pb/Pa without control**	**Pb/Pa with control**
1.27	1.004	0.997
1.38	0.9736	0.994
1.52	0.9544	0.967
1.69	0.9221	0.931

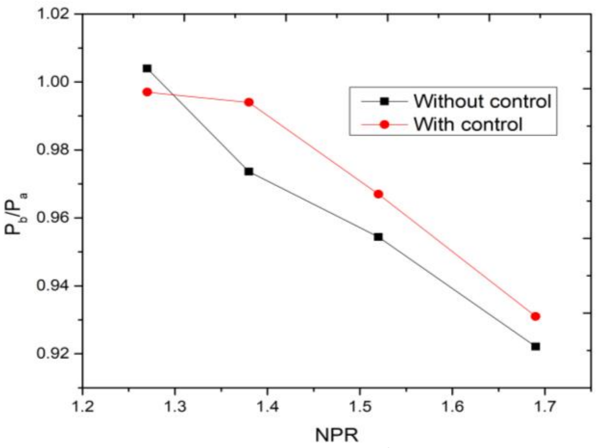

Fig. 9. Base pressure v/s NPR plot for Duct L=4D

The base pressure variation with NPR for L/D=4 at Mach numbers from 0.6 to 0.9 are shown in Table 4.1 and Graph 4.1

TABLE II
Base pressure for Duct L=6D

L=6D A2/A1=6.25 Mach number=0.6,0.7,0.8,0.9		
NPR	**Pb/Pa without control**	**Pb/Pa with control**
1.27	1.019	1.048
1.38	0.985	1.044
1.52	0.953	1.031
1.69	0.946	1.027

At L=6D the control is very effective from NPR 1.27 to 1.69

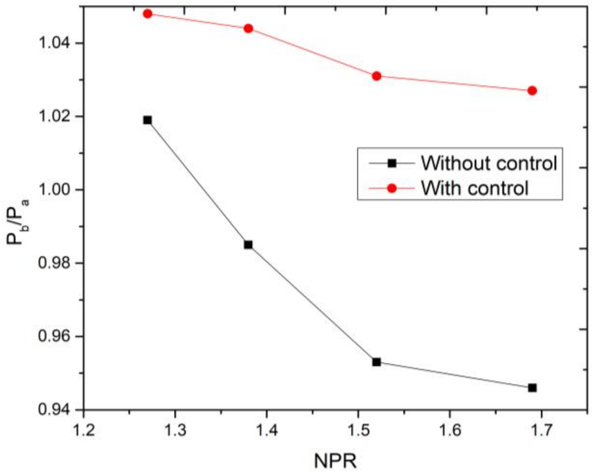

Fig. 10. Base pressure v/s NPR plot for Duct L=6D

TABLE III
Base pressure for Duct L=8D

L=8D A2/A1=6.25 Mach number=0.6,0.7,0.8,0.9		
NPR	**Pb/Pa without control**	**Pb/Pa with control**
1.27	0.999	1.05
1.38	0.989	1.048
1.52	0.9646	1.047
1.69	0.9333	1.042

For L=8D the control is very effective for all regimes of NPR

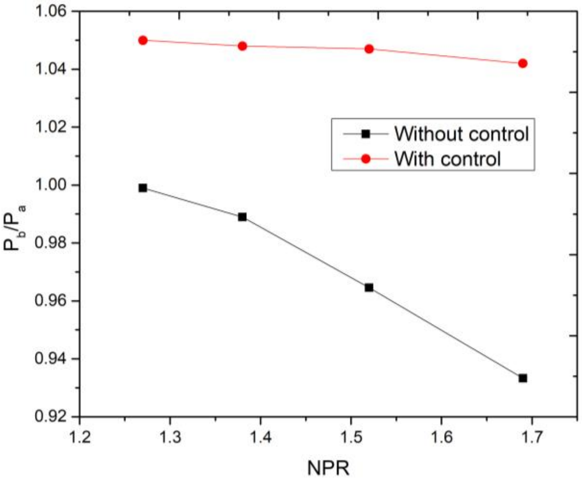

Fig. 11. Base pressure v/s NPR plot for Duct L=8D

For L=10D the dimple control is very positive for all NPR

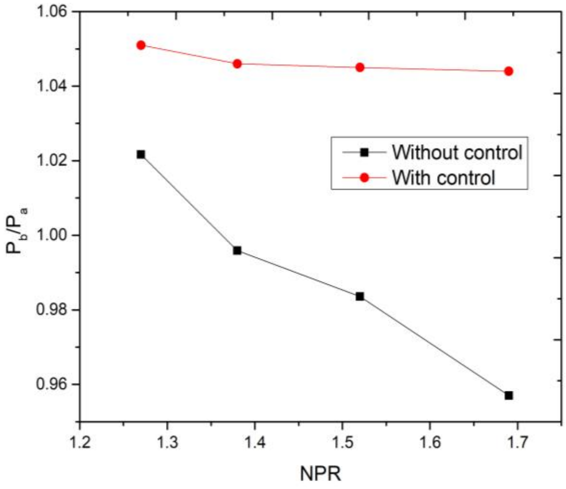

Fig. 12. Base pressure v/s NPR plot for Duct L=10D

Wall Pressure results

After sudden expansion behind backward facing step, the flow field might become oscillatory shown by wall pressure distribution in enlarged duct. So it becomes very important to see that our control is not enhancing these oscillations. It is seen in Figure 13 that for a duct of area ratio 6.25, L/D=4 and variable NPR the passive control near dead zone is bit oscillatory but then calms down until at exit due to end effects.

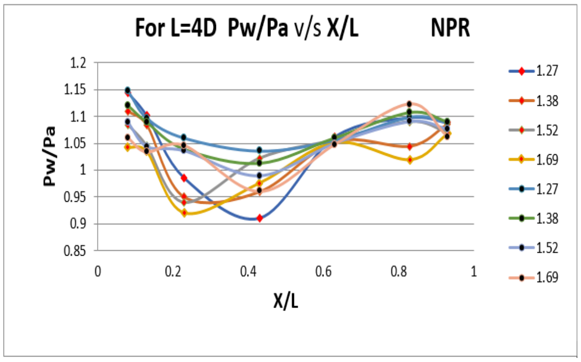

Fig. 13. Wall pressure v/s X/L plot for Duct L=4D

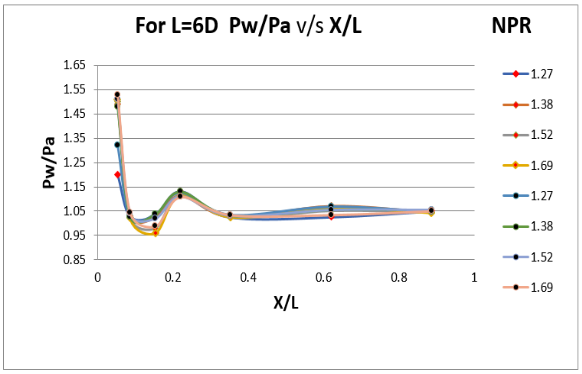

Fig. 14. Wall pressure v/s X/L plot for Duct L=6D

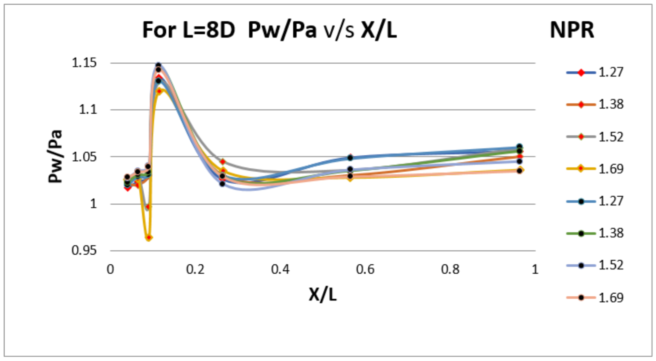

Fig. 15. Wall pressure v/s X/L plot for Duct L=8D

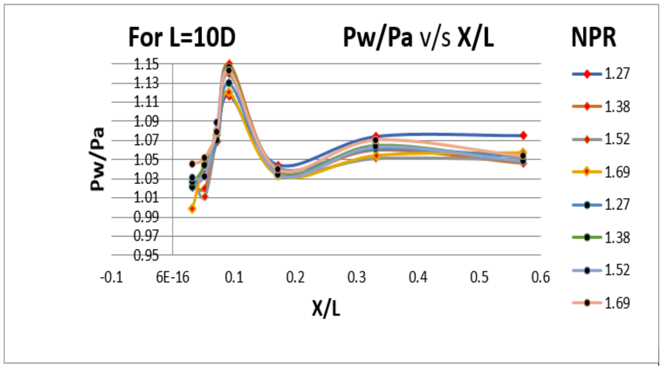

Fig. 16. Wall pressure v/s X/L plot for Duct L=10D

V. FLOW VISUALIZATION OF BACKWARD FACING STEP

The flow over a backward facing step is visualized for duct having length 4D the flow is found to be having effect near cavity by referring the pressure v/s distance graphs. Velocity is not much affected in these flow fields. Flow pattern for all different ducts does not very much. The effect of cavitation is studied for duct L=4D for Mach=0.8 and assumed that cavitation has effect for all the ducts. In following Figures from 17 to 24, the flow pattern of velocity magnitude and pressures are studied. The graph obtained from the CFD tool is judge whether the cavitation is having good or bad effect on downstream wall to reduce base drag.

- Velocity distribution

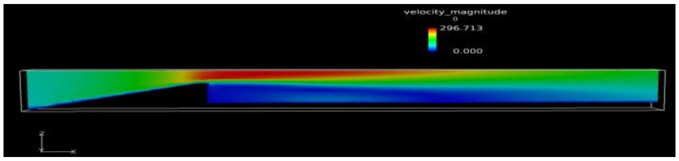

Fig. 17. Velocity magnitude profile for Duct L=4D without control (smooth profile)

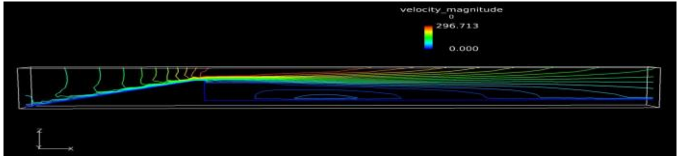

Fig. 18. Velocity magnitude profile for Duct L=4D without control (contour profile)

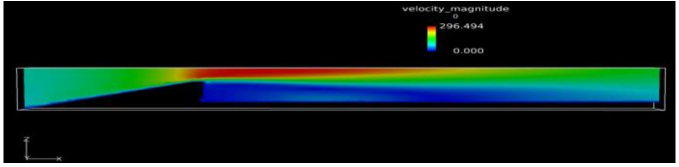

Fig. 19. Velocity magnitude profile for Duct L=4D with control (smooth profile)

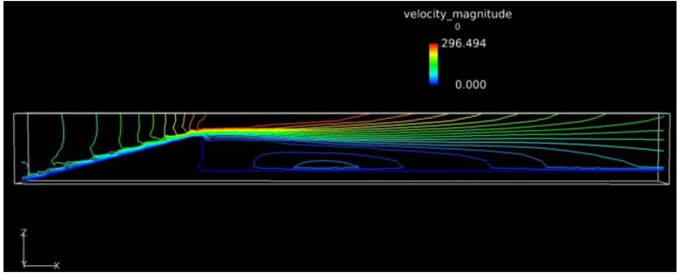

Fig. 20. Velocity magnitude profile for Duct L=4D with control (contour profile)

- Pressure distribution

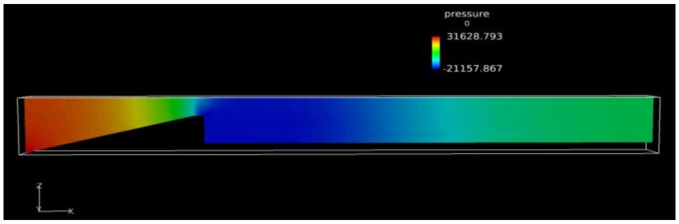

Fig. 21. Pressure profile for Duct L=4D without control (smooth profile)

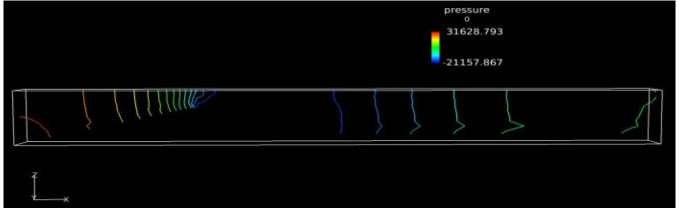

Fig. 22. Pressure profile for Duct L=4D without control (contour profile)

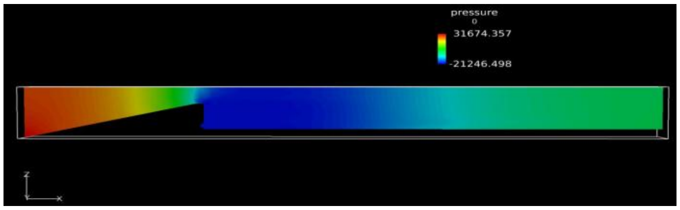

Fig. 23. Pressure profile for Duct L=4D with control (smooth profile)

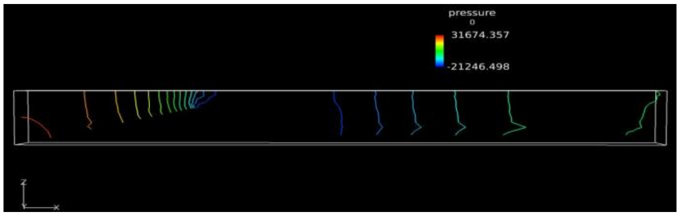

Fig. 24. Pressure profile for Duct L=4D with control (contour profile)

VI. CONCLUSION:

Compressible flow over a backward facing step was investigated experimentally, flow is visualized and studied for a wide range of NPR and L/D ratio for dimpled and non-dimpled conditions. The following conclusions can be drawn.

- From experimental results and flow visualization using CFD tool it can be seen that the dimple has a very good effect in reduction of base drag by controlling base pressure.
- For all L/D ratios 4D, 6D, 8D and 10D from experimental investigation we can observe that effect of dimple in controlling base pressure is positive in nature. As the length of the duct increases gradually, the control is getting very effective.
- From Pw/Pa v/s X/L graphs we can clearly say that the wall pressure is not getting affected by use of dimple. For 6D, 8D and 10D. The fluctuation in 4D duct wall pressure is unpredictable. From this it is clear that at low L/D ratio the wall pressure gets affected by using dimple.
- The base pressure is strongly influenced by geometric parameters such as L/D ratio. For a given Mach number and NPR one can identify the optimum enlargement length to diameter ratio which will result in maximum increase/decrease of base pressure.

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