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CONTROL OF SUDDENLY EXPANDED FLOW AT LOW L/D RATIO AND HIGH MACH NUMBERS

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ABSTRACT

In this paper results reported are the outcome of investigation carried to regulate the suddenly expanded flow through a converging-diverging nozzle at high supersonic Mach numbers and at lower length to diameter ratios. The geometrical and the flow variables assessed in this investigation are the diameter ratio, length to diameter (L/D) ratio, expansion level, and the Mach number. The step heights of the present case are 1.6, 1.8, 2.2 and 2.5. The tests were conducted for P_0/P_{atm} in the range of 3 to 11. The (L/D) ratio of the suddenly expanded duct of the test was from 10 to 1, however, the outcome are presented for L/D 4, 3, 2, and 1. The Mach numbers tested in the investigation are 1.9, 2.1, 2.4, and 2.8. The results show that the efficacy of the active control is considerable in regulating the base pressure. Further, it found that for Mach numbers 1.9 and 2.1 the control is very effective for NPRs 9 and 11 but, for NPRs 3, 5, and 7 the control efficiency is only marginal. At NPRs 7 and 9 for some cases peculiar trends are observed and the flow becomes oscillatory. It is seen that majority of the outcomes represent similar behaviour for duct length up to L = 3D, which means; that the back pressure has not negatively affected the flow field in the base region as well as in the duct. The lowest duct length needed for the flow to remain latched on with the duct is L/D = 3 in general for all the cases of the flow variables of the current investigation, however, for few combinations of the flow and geometrical parameters the flow remains attached even for L/D =2 as well as 1. With this it can be stated that the micro jets can be used as one of the methods for flow in the base area control without having any untoward effect in the flow field at the base region.

Keywords: L/D ratio, sudden expansion, base pressure, NPR, Mach no.

1. INTRODUCTION

The control of base pressure on nozzle base is a very important field of study and finds application in many areas. Some of the several applications are the rocket nozzle base pressure field, flow field at the base of the fuselage of the aircraft, and the blunt base of the projectiles. The base pressure for a rocket nozzle is reduced due to expansion fans sitting at the edge of the base. Thus the hot gases coming out of the nozzle tends to fill this area. This is undesirable since the high temperature of the gases is continuously felt at the base area. This experiment does not simulate the flow conditions on a rocket nozzle completely because the model is stationary. Still the results can give a very good idea on how to control the base pressure.

2. LITERATURE SURVEY

Rathakrishnan [1] studied the influence of ribs on the flow quality in suddenly expanded duct. He found that regulators as ribs results in the reduction of the base pressure up to a large extent, in comparison to that for without rib case. Annular ribs with L/D ratio 3:1 suit to be most appropriate combination for the given variables. Further, it is found that the ribs in the form of passive control do not cause any unsteadiness in the flow field of the suddenly expanded duct and any hike in pressure loss compared to without passive control at duct is < 6%. Khan and Rathakrishnan [2-6] conducted experiments to control the base pressure for Mach numbers 2.0 to 3.0. The studies were conducted at an over-expansion level of (P_e/P_a) =0.277. From their research they concluded that the base pressure attains the lowest value for the lowest area ratio namely 2.56 and the L = 6D for all the inertia levels of Mach numbers (2.0, 2.5 and 3.0). The active control seems to be to deliver encouraging outcome at M = 3.0 and A_2 = 2.56A_1. It was observed that the flow regulators enhance the pressure in the base region for these combinations of variables, amounting in an 83% reduction in base pressure. Ashfaq *et al*. [9] presented the outcome of the investigation to control the base pressure from a conical nozzle to discover the influence of NPR with sudden expansion at M = 1.0. From the investigation it was concluded that favourable pressure gradient need not give positive results every time. Zakir Ilahi Chaudhary *et al*. [11-13] from their test observed that the repercussion of Micro jets is very small in some cases in manipulating the pressure in the base area even under the influence of encouraging pressure variation at lower NPRs such as 3 and 5. Further they discussed that the micro jets affect the base pressure in positive as well as negative manner. The favourable and adverse nature of influence was found to be administered by the NPR and therefore the level of expansion. For lesser Mach numbers the base pressure tends to increase with the increase in NPR. The useful increase in base pressure is in the range of 10 to 40 per cent, which is very considerable. These outcomes will be handy for bodies moving at transonic Mach number, where the base drag is huge even a little reduction will give significant increase in the range and hence saving in the energy.

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3. EXPERIMENTAL SETUP

The setup of the present investigation is shown in the Figure-1. There are eight holes at the outer perimeter of the nozzle, four (marked m) are utilized for the pressure (P_b) recording at the base, four of which are (marked c) used for regulation of the pressure in the base area. The stagnation pressure in the regulation faucet is the same as that of Po_1 as the air is taken from the main faucet by connecting through a flexible tube.

To measure the pressure distribution in the enlarged duct, taps were positioned on the enlarged duct. Starting from the base region, initial nine holes were made at a small gap (as the major activity will take place within the reattachment length) and remaining holes were made at a larger interval. After scanning the literature it was revealed that, classic L/D as depicted in Figure-1 results in peak values of the pressure at the base as 3 to 6 in the absence of regulation. In the present study, the active controls are used; L/D ratios as high as 10 is to be tested and implemented.

Further, the setup was consisted of an axi-symmetric convergent-divergent nozzle without let diameter as D_1 connected by a cylindrical enlarged duct of higher diameter of diameter D_2, and the ratios of the diameter (i.e. D_2/D_1) are in the range from 1.6 to 2.5. In the present investigation the outlet diameter of the nozzle is kept 10 mm to compare our results with the existing data available in the literature.

The diameter ratios in this investigation were 1.6, 1.8, 2.2, and 2.5. Brass pipe was used to fabricate the suddenly expanded ducts. The experiments were conducted with the enlarged duct length L = 10D and once the investigation was over the duct length was machined to get the lower length of the duct. However, the results presented in this paper are for L/D = 4, 3, 2, and 1, however the investigations were done for L = 10D to 1D.

For recording the pressure in the control unit, the stationary pressure in the main storage chamber and the pressure recording at the base were performed bythe pressure transducer, PSI model 9010. This pressure transducer has 16 ports and pressure range is between 0-300 psi. It displays the reading after averaging 250 samples per second. To incorporate the pressure sensor with the desktop computer, software is provided by the manufacturer. The tool-bar driven code records data and show the observed pressure values of the 16 ports instantaneously on the desktop monitor.

The computer program is embedded with the facility to select the units of pressure in various units; before we start the test calibration of the transducer is done. The sensor is capable of selecting the amount of data for the mean values, by way of dipswitch settings. It can work effectively, up to 95 per cent dampness and in the temperatures range from -20°C and also +60° C.

4. RESULTS AND DISCUSSIONS

The observed data were Base pressure (P_b); static pressure (P_w) in the duct and expansion level during the course of tests. Later, all these observed values of the observed data were Base pressure (P_b); static pressure (P_w) in the duct and expansion level during the course of tests. Later, all these observed values of thepressures were made dimensionless by dividing them with the free stream pressure. In this investigation, the atmospheric pressure is taken as the back pressure.

From the literature, it is revealed that apart from the exit area available to the flow and expansion level,

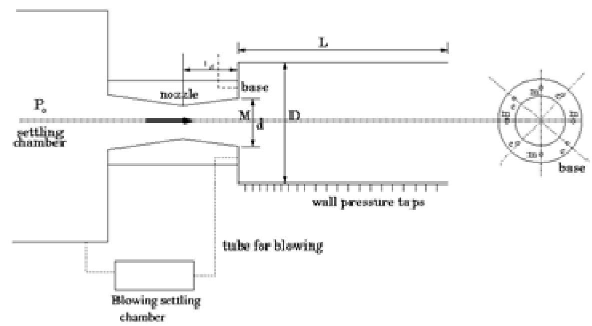

Figure-1. Experimental setup.

the Mach number at the outlet of nozzle has an active role to play on the numerical values of the base pressure. To evaluate the increment in base pressure values accomplished with active regulator in the form of tiny jets, the plots of the base pressure in the form of non-dimensional base pressure values with the non-dimensional step height of the suddenly expanded duct is used for presenting the results. The main reason for selecting step height is to see the effect of increase in the step height on the base pressure and the efficacy of the regulators as the active regulators in the form of tiny jets.

The feature of the effect of NPR for Mach numbers 1.9,2.1, 2.4, and 2.8 are presented in Figure-2((of relief, graphical representations of pressure at base with diameter ratio as a function of jet Mach number, L/D ratio, are depicted) in (a) to (j)), for L = 4D. The observed data for NPR 11 shown in Figure-2((i) to (j)) for the Mach number range 1.9 to 2.8, and these figures demonstrate the dependence of additional area on the base pressure. Jets are under expanded at Mach 1.9 and 2.1 at NPR 11, whereas for Mach numbers 2.4 and 2.8 jets are over expanded. Hence for under expanded jets, shear layer from the nozzle exit will go through the expansion fan. Under these conditions flow will have larger reattachment length consequent of additional relief will ultimately lead to lower pressure values for Mach 1.9 and 2.1.

Moreover, the control seems to be effective for these Mach numbers ending up with the higher value of base pressure in comparison to the without regulation case.

It is observed that for favourable pressure level the flow will expand till it attain free stream condition leading to decrement in pressure and at this point of time when flow regulators are activated it results in the larger values of pressure for the entire range of the variables of the present test.

Further, under the influence of adverse pressure gradient it leads to higher values of the base pressure with progressive increment in area. When we look at the data of

M = 2.8 increment the pressure in the base region is abrupt, and it could be due to the presence of powerful oblique shock as highest NPR tested is 11, hence with increment in inertia level, over expansion level will get enhanced.

For Mach 2.4 the base pressure remains unaltered till diameter ratio 2.2 and later there is abrupt increment in the magnitude of base pressure as shown in Figure-2(j). Results for NPR 9 are shown and Mach number range 1.9 to 2.8 are shown in Figures-2((g) to (h)). From figure it is seen that the base pressure marginally decreases with diameter ratio till 2.2 and later there is abrupt increment in the base pressure due to the net effect of expansion level and increment in area enjoyed by the flow at Mach 2.4, however, for Mach 2.8 there is continuous increase in the base pressure for all the diameter ratios and control reversal also takes place as shown in Figure-2(h). For NPR 9 at Mach 1.9 and 2.1 they represent similar results as it was seen for NPR 11 except for the highest diameter ratio 2.5 where there sudden reversal in the trend.

Base pressure results for NPRs 3, 5, 7 are given in Figures 2(b), (d), and (f)) for Mach 2.4, and 2.8. From the figure it is evident there is continuous increase in the base pressure with increase in diameter ratio as well as the Mach number except at Mach 2.4 and the diameter ratio 1.6 where the suction level is very high as shown in Figure- 2(f). For Mach 1.9 and 2.1 at NPRs 3, 5, and 7 it is seen that at NPR 7 for diameter in the range 1.6 to 2.2 there is marginal change in values and later shoots up, for NPR 5 the previous trend happens between diameter ratio 1.6 and 1.8 and sudden increase but for NPR 3 it keeps on increasing throughout. Figures 3((a) to (i)) shows the outcome of the test for L = 3D, they are the representative of the analogous of results as it was seen for L/D = 4, having all other parameters same except that the L/D has been decreased from 4 to 3 and this decreased L/D will have some influence of back pressure resulting in a boost in the base pressure as shown in Figures 3((a), (c), (e), (g), and (i)) for Mach 1.9 and 2.1. Similar results are seen in Figures 2((b), (d), and (f)) for NPRs 3, 5, and 7 for Mach 2.4 and 2.8. From above discussion, it is clearly understood that the regulation method is efficacious when the Pe/Pa is >1 and this phenomena will lead to decrease progressive decrease in the level favourable pressure ratio. Results for NPR 9 and 11are shown in Figs.3 ((h) and (j)), from the figure seen that the decreasing trend in base pressure continue till the diameter ratio 1.8 for both the NPRs and later there is abrupt increment in the magnitude of base pressure.

In case of lower duct length L = 2D, Pressure (Pb) are depicted in Figs. 4((a) to (j)) for NPR 3-11. Comprehensive nature is identical to that of L/D = 4 for M = 1.9, 2.1, 2.4 and 2.8 for the given level of expansion of the test range.

Nevertheless, the regulators efficacy and impact assumes its importance with the duct length as shown in Figures 4((i)-(j)). When the step height is low and the active regulator activated lead to high values in the base pressure. They conform to the results of Pe/Pa > 1.

From the figures it is found that the flow downstream is attached with wall for some combination of parameters even for L/D = 2, otherwise for most of the cases the flow is detached with the duct wall.

The test results for L/D = 1 are presented in Figures 5((a) to (j)) for NPRs 3 to 11. The overall nature of base pressure with increment in diameter ratio is the same to that for larger L/Ds for Mach number 1.9 and 2.1 for NPRs from 3 to 11 as seen in Figures 5((a), (c), (e), (g) and (i)). It is also seen the flow is attached with duct wall for NPR 5, 7, 9, and 11. Results for Mach 2.4 and 2.8 for NPRs 3, 5, 7, 9, and 11 and L/D = 1 are presented in Figures 5((b), (d), (f), (h), and (j)). It is evident from the figures that the flow is detached from the duct wall hence, the ratio of the base pressure with that ambient pressure is very close to unity which; is a clear indication that the flow is exposed to the atmosphere.

5. CONCLUSIONS

From this study the various conclusions drawn are as follows:

a) The results indicate that the efficacy of the regulators is minimal in regulating the pressure at base in the presence of adverse pressure gradient at lower NPRs namely 3, 5, and 7 as the flow exiting from the nozzle is over expanded. However, for higher values of the NPRs namely 9 and 11 the active control by micro jets lead to increase of base pressure values for all the diameter ratios of the present experimental studies.
b) At L/D =1 at Mach 2.4 and 2.8, for all the NPRs in the range 3 to 11 of the present study the results show different trend, flow is detached with the enlarged duct, and exposed to the free stream conditions and cannot draw any definite conclusions. However, for Mach 1.9 and 2.1 for the same L/D =1 and NPRs the flow remained attached up to NPR from 5 to 11, at NPR 3 the flow detached with the duct wall.
c) It is seen that majority of the cases show same trend for higher as well as the lower L/Ds, which means; that the free stream pressure has not negatively affected the flow field in the base region as well as in the duct specially for L/D = 4 and 3.
d) With this it can be stated that the micro jets can be an option for the researcher working in this area of base pressure flow control by micro jets to explore further as they do not impose any adverse impact in the flow field at the base region as well as in the enlarged duct.
e) Safely for Mach 2.4 and 2.8 the L/D = 3 seems to be duct length required in general for all the cases. However, for some combinations of parameters even at L/D = 1 and 2 the flow has shown that it is attached with the duct wall.

The results of this investigations lie in the uncertainty range of 2.6 % on the either side, also, the final outcome are reproducible in the range of 3 % on the either side.

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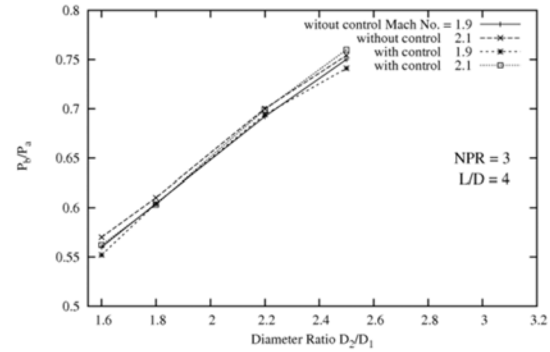

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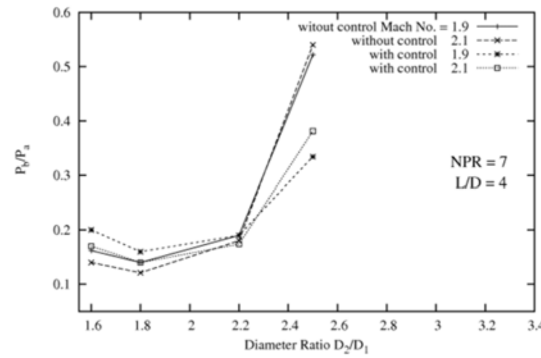

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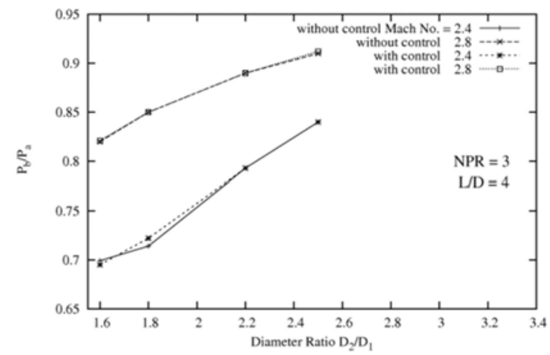

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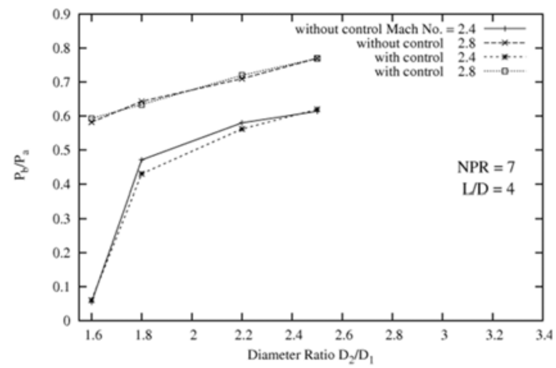

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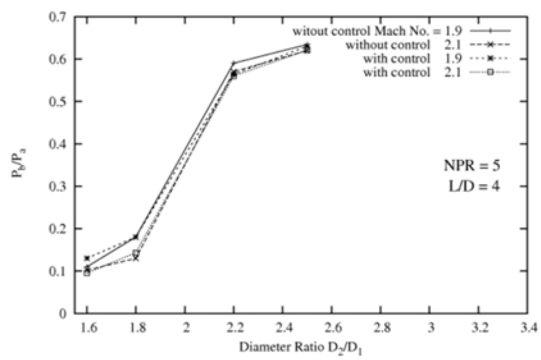

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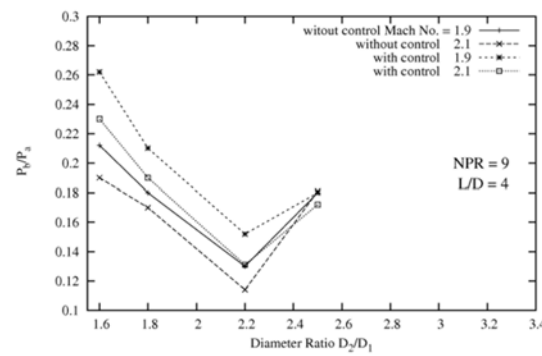

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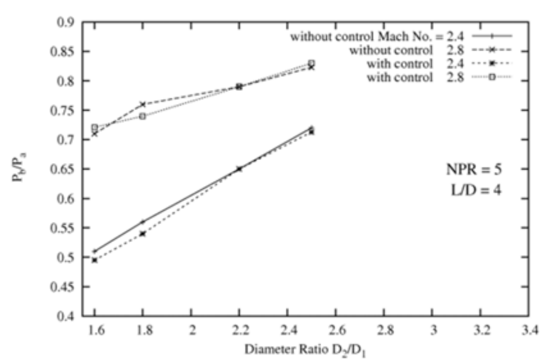

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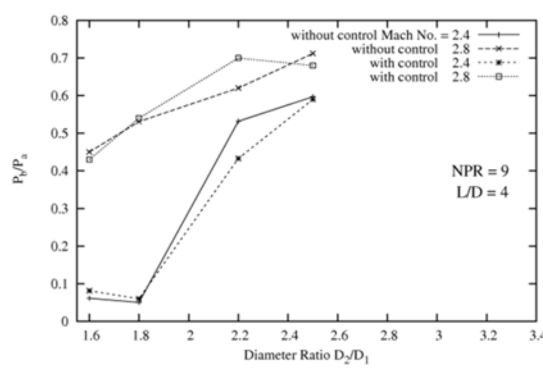

Figure-2(h)

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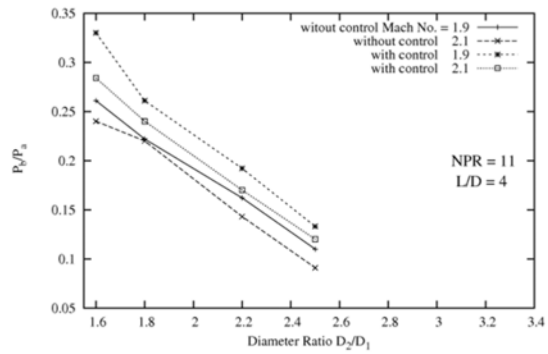

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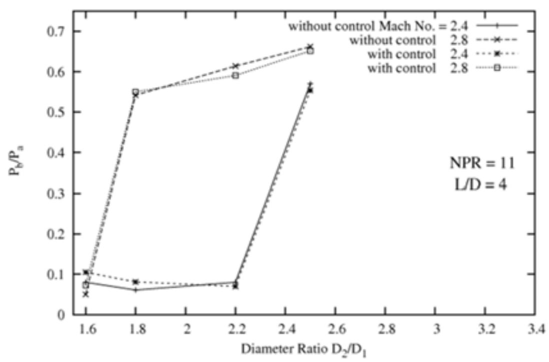
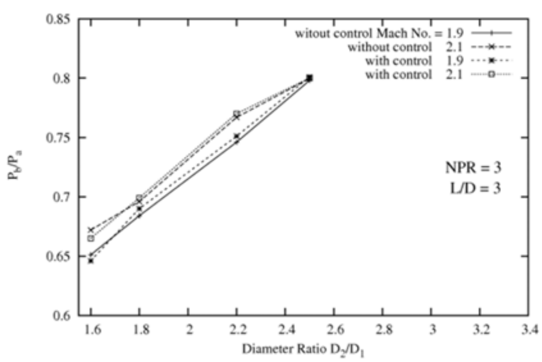


Figure-2(j)

Figure-2. Base pressure variation with diameter ratio for L/D = 4.



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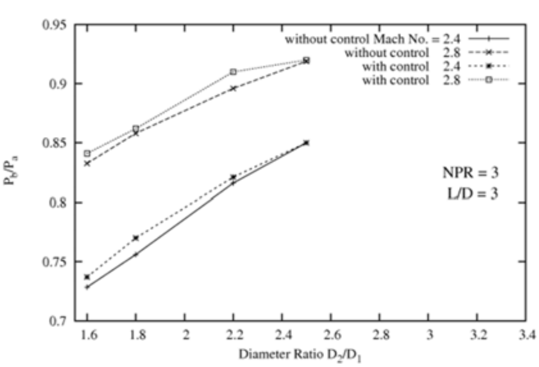

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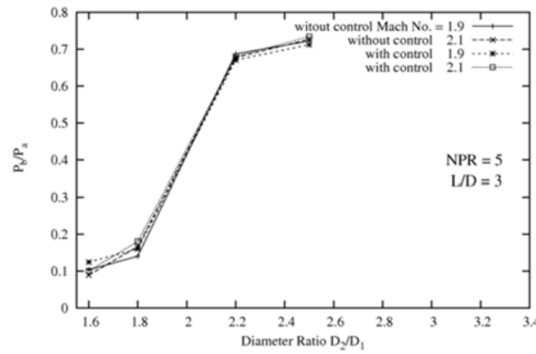

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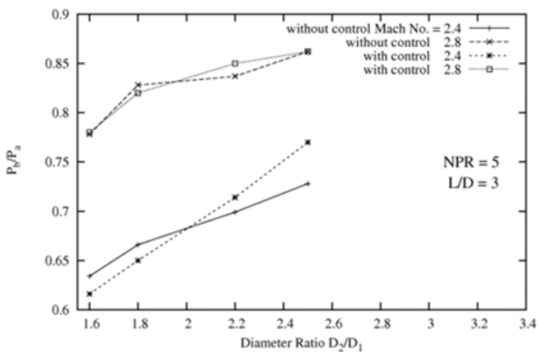

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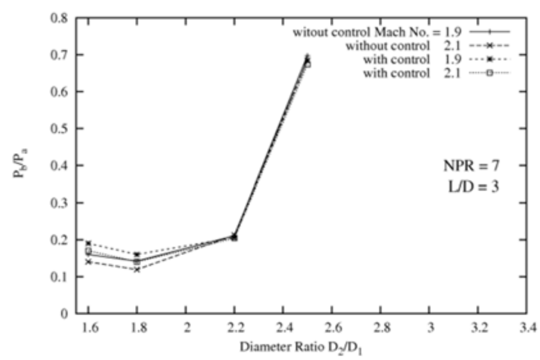

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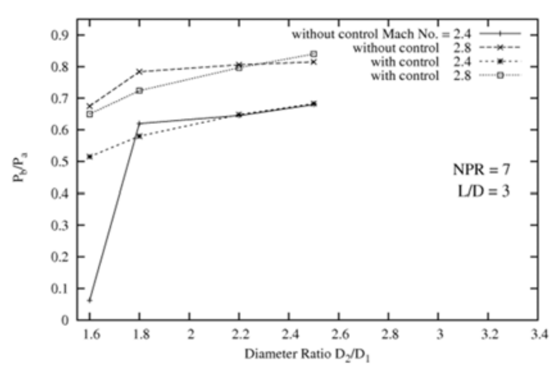

Figure-3(f)

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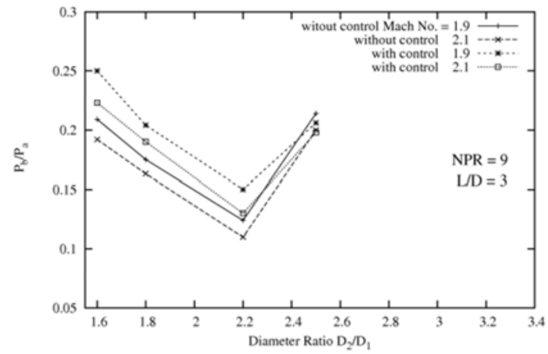

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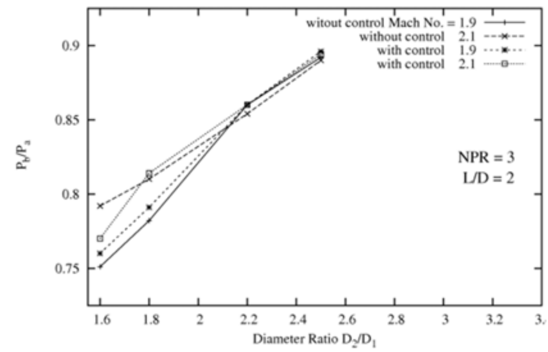

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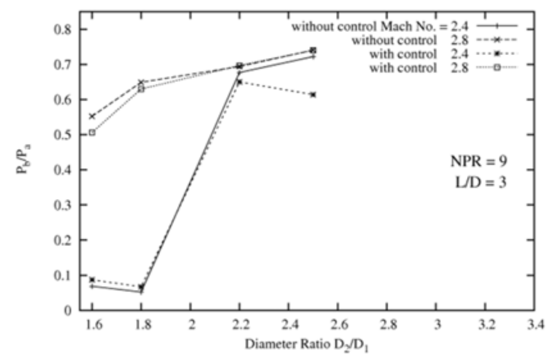

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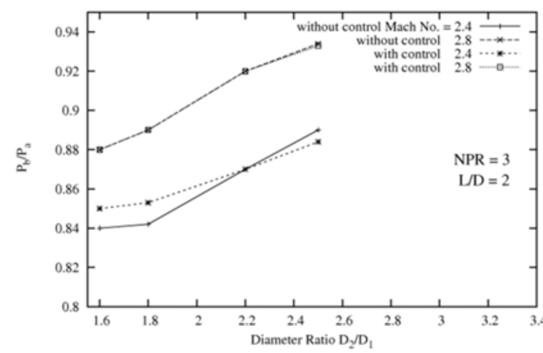

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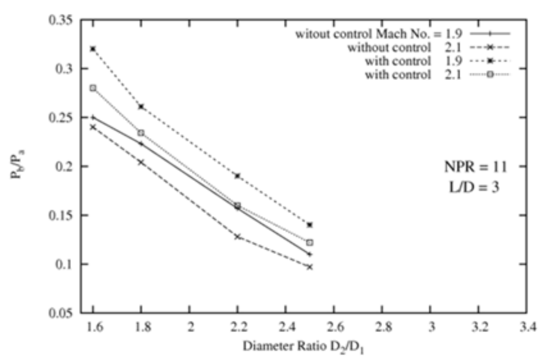

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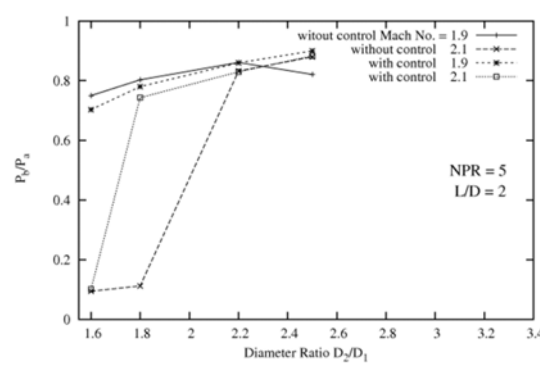

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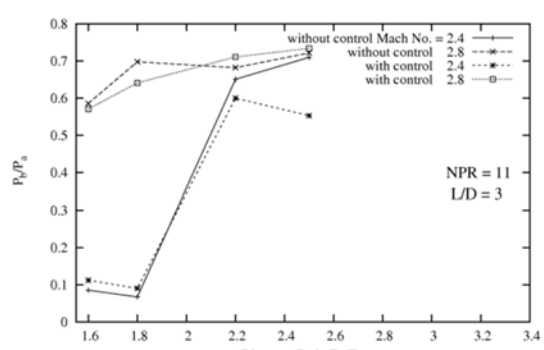

Figure-3(j)

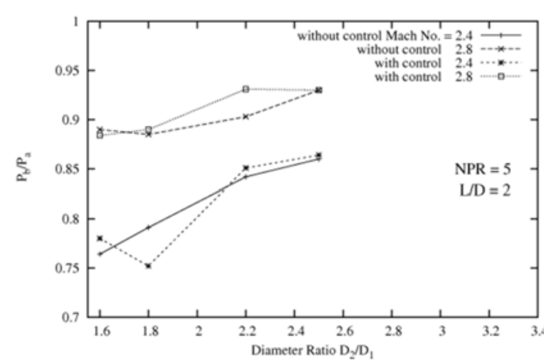

Figure-4(d)

Figure-3. Base pressure variation with diameter ratio for L/D = 3.

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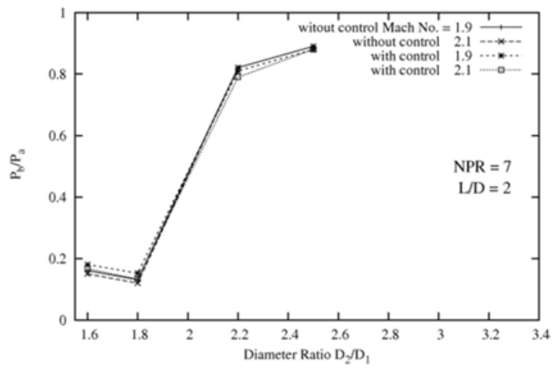

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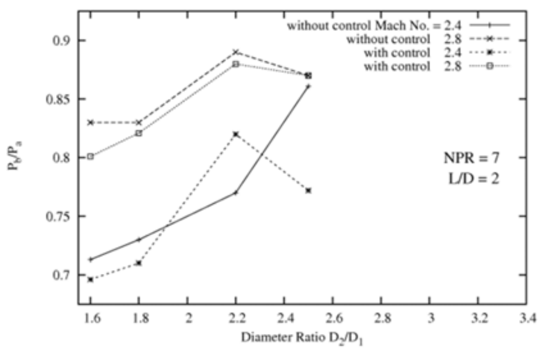

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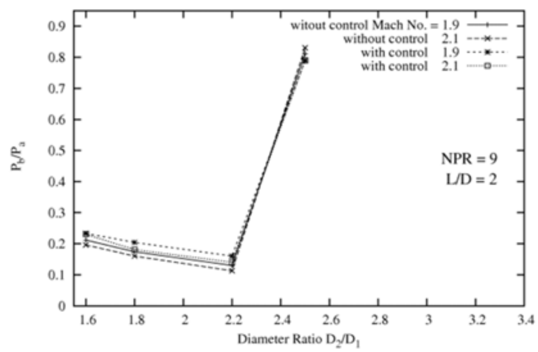

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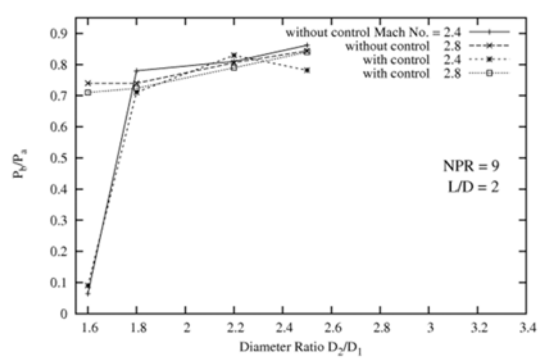

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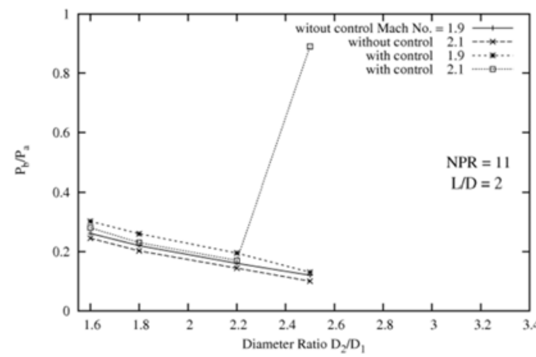

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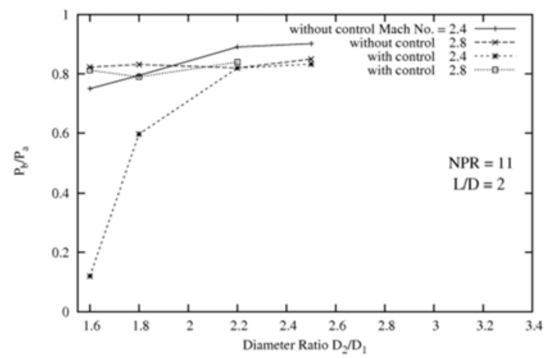
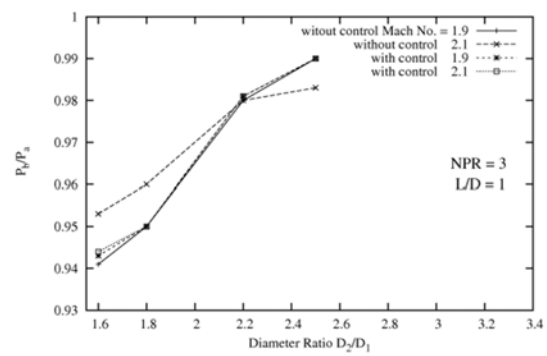


Figure-4(j)

Figure-4. Base pressure variation with diameter ratio for L/D = 2.



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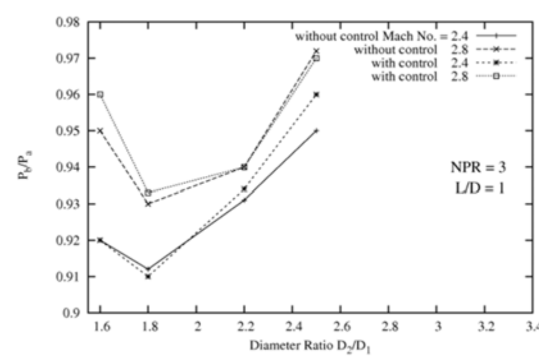

Figure-5(b)

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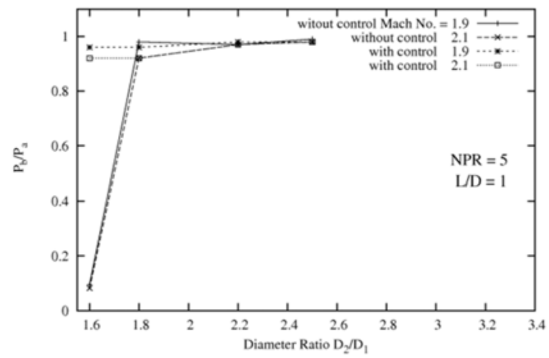


Figure-5(c)

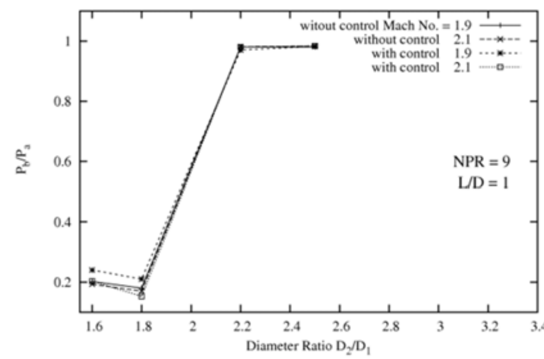


Figure-5(g)

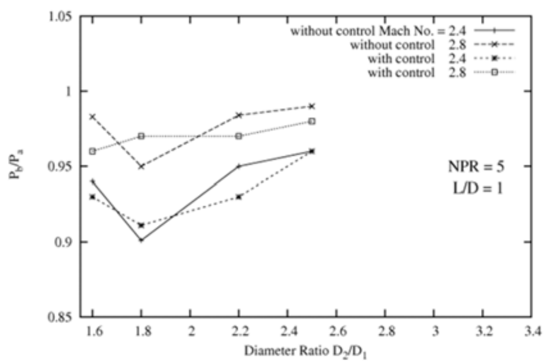


Figure-5(d)

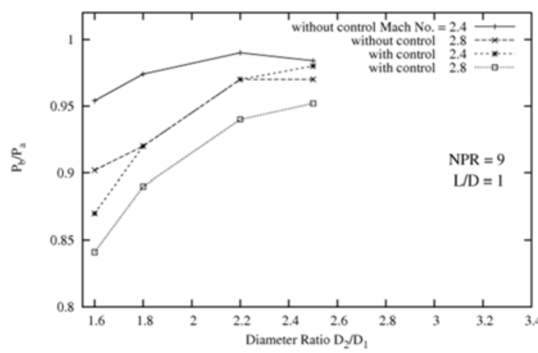
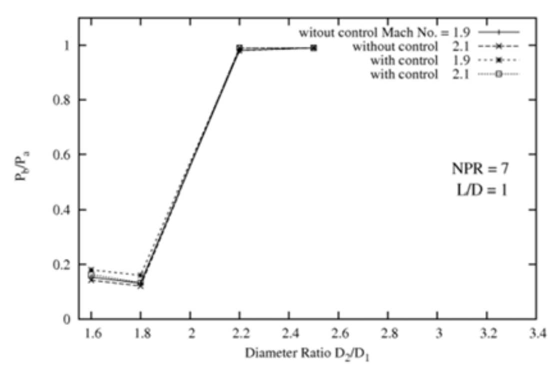


Figure-5(h)



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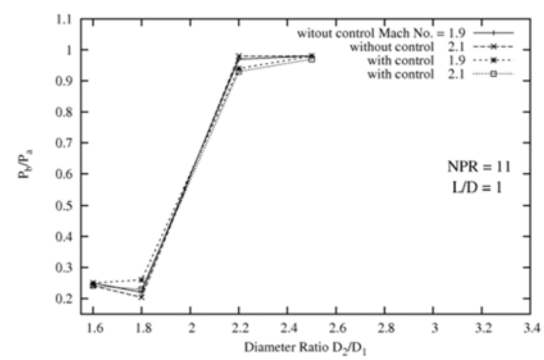

Figure-5(i)

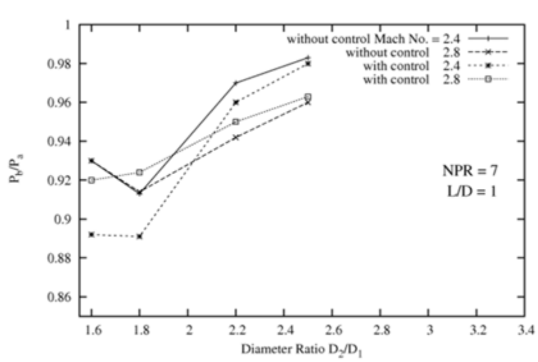

Figure-5(f)

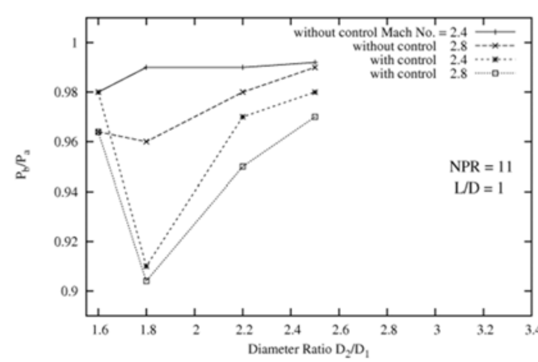

Figure-5(j)

Figure-5. Base pressure variation with diameter ratio for L/D = 1.

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