[5]Bar-Sever, A., "Separation Control on an Airfoil by Periodic Forcing," *AIAA Journal*, Vol. 27, No. 6, 1989, pp. 820, 821.

[6]Miau, J. J., and Chen, M. H., "Flow Structures Behind a Vertically Oscillating Fence Immersed in a Flat-Plate Turbulent Boundary Layer," *Experiments in Fluids*, Vol. 11, No. 2/3, 1991, pp. 118–124.

[7]Seifert, A., Eliahu, S., Greenblatt, D., and Wygnanski, I., "Use of Piezoelectric Actuators for Airfoil Separation Control," *AIAA Journal*, Vol. 36, No. 8, 1998, pp. 1535–1537.

[8]Greenblatt, D., Nishri, B., Darabi, A., and Wygnanski, I., "Some Factors Affecting Stall Control with Particular Emphasis on Dynamic Stall," AIAA Paper 99-3504, June 1999.

A. Plotkin
Associate Editor

Effect of Ribs on Suddenly Expanded Flows

E. Rathakrishnan*
Indian Institute of Technology, Kanpur 208 016, India

Nomenclature

D = duct diameter
L = duct length
P_a = ambient pressure
P_b = base pressure
P_t = total pressure at the center of enlarged duct exit
P_w = duct wall pressure
P_0 = settling chamber pressure
S = rib aspect ratio, defined as width/height of rib
X = axial distance along duct

Introduction

SUDDENLY expanded flowfields find application in many interesting problems of practical importance, such as combustors and combustion chambers, propulsion systems, parallel diffusers, and so on. The need for controlling such flowfields has motivated studies of these flows. Passive control mechanisms have always attracted scientists because they give the desired result without the need for separate mechanisms, as in the case of active control. There is a vast amount of information about suddenly expanded flow problems in the literature, describing the mechanisms governing the base flows.[1–17] One study that has direct relevance to the present study is that of Anasu and Rathakrishnan,[18] who studied the flow through a convergent axisymmetric duct with annular rectangular cavities at specified intervals. They concluded that the introduction of secondary circulation by cavities reduces the oscillatory nature of the flow in the enlarged duct, thereby enabling the flow to develop smoothly from the base pressure to the atmospheric pressure at which the expanded jet was discharged. Subsequently, Rathakrishnan et al.[19] extended the study to cover a range of aspect ratios and concluded that the cavity is of considerable effect in the enlarged duct and that the effect is more pronounced for longer ducts than for shorter ducts. However, these investigations were only for subsonic Mach numbers. Further, when passive controls in the form of a cavity are employed for flow control, there is a possibility of the cavity behaving like a closed cavity, thereby becoming ineffective as a control device. Therefore, it was felt that it may prove to be advantageous over cavities if the control is in the form of annular ribs. The idea of using projections instead of cavities as passive controls motivated the present study, wherein the secondary vortices generated by the projections were expected to yield a better wall pressure distribution. The goal of this work was to find the optimum geometry of ribs for the minimum possible base pressure, over a range of Mach numbers from low subsonic levels to sonic.

Received 21 October 1999; revision received 21 February 2001; accepted for publication 26 February 2001.

*Professor, Department of Aerospace Engineering. Member AIAA.

Experimental Setup

The experimental model consisted of a nozzle and an enlarged duct, as shown schematically in cross section in Fig. 1. The first diameter of duct length downstream of the nozzle exit consists of straight wall to keep the recirculating region near the base clean. After completing all of the measurements with one aspect ratio (width w/height h) of the ribs, the annular rib heights were machined to give the next desired aspect ratio. Three aspect ratios, 3:3, 3:2, and 3:1, were tested in the present study. The other parameters of the present investigation were the model area ratio, defined as the ratio of duct area to that of the nozzle exit, the length-to-diameter ratio of the enlarged duct, L/D, and the primary pressure ratio P_0/P_a. The model area ratio used was 6.25 in all cases. The L/D ratio was varied from 1 to 6 in steps of 1. The primary pressure ratios used were 1.141, 1.295, 1.550, 1.707, and 2.458, which corresponded to nozzle exit Mach numbers of 0.44, 0.62, 0.82, 0.91, and 1.0, respectively. Because these Mach numbers are calculated with isentropic relations, neglecting friction, the author feels that it is more appropriate to use the pressure ratio rather than the Mach number in the analysis. Hence, P_0/P_a is retained as a pertinent parameter. The measurements include the stagnation pressure of the settling chamber, the base pressure, and the wall pressure distribution along the length of the duct. To account for the pressure loss, the total pressure at the exit of the duct was also measured by positioning a total pressure probe at the center of the duct exit plane. All of the pressures were measured using mercury manometers, and the measurements were found to be repeatable to within ±3% and accurate to within ±5%.

Results and Discussion

All measured pressures have been nondimensionalized with the back pressure P_a. The lengths are nondimensionalized with the ductinner diameter D. Because the prime objectives in this study are to control the base pressure, to have smooth development of flow without oscillations in the duct, and to minimize the total pressure loss, the results are analyzed with these features in mind.

The base pressure variation with duct L/D for a pressure ratio of 2.458 for several passive control geometries is presented in Fig. 2. It is seen that the annular ribs with aspect ratio 3:1 result in base pressures that are appreciably lower than those for the expansion without passive control. Further, it is seen that with the 3:1 rib the minimum base pressure occurs for L/D around 4, and for a further increase of L/D the base pressure seems to be not influenced by L/D. For aspect ratios of 3:2 and 3:3, even though the base pressures, which are much lower than those obtained with the plain duct for L/D values less than 3, for higher values of L/D, the base pressure increases with increasing L/D, resulting in values much higher than those for the plain duct. From the results for pressure ratio 1.141 it is also found that the rib aspect ratio 3:1 results in minimum base pressure at L/D around 4.

The effect of the primary pressure ratio on the base pressure is shown for the passive control geometry with aspect geometry 3:1 in Fig. 3. The strong influence of the stagnation pressure on the base pressure is evident. The nature of the variation of base pressure with duct L/D for rib aspect ratio 3:1 is similar to that reported by Rathakrishnan et al.,[19] for passive control in the form of annular grooves, and by Rathakrishnan and Sreekanth,[10] for flow in pipes with sudden enlargement. The physical reason for the base pressure attaining a minimum for rib aspect ratio 3:1 may be the following: the shear layer that expands from the nozzle exit attaches to the enlarged duct wall downstream of the base. Depending on the reattachment length and the nozzle exit Mach number, the primary vortex that is formed at the base influences the base pressure. The strength of the primary vortex dictates the level of low pressure at the base region. Because of this low-pressure region, flow is induced from the wall region downstream of the reattachment point toward the base region. The extra mass that enters the base region is ejected to the main flow via shear layer entrainment, and this cycle continues. This ejection of mass was called "jet pump" action by Wick.[1] The flow of fluid into the base region reduces the primary vortex strength, thereby increasing the base pressure above the level it would attain if no fluid from the boundary layer downstream of the reattachment point entered the base region. That is, the ribs prevent the flow

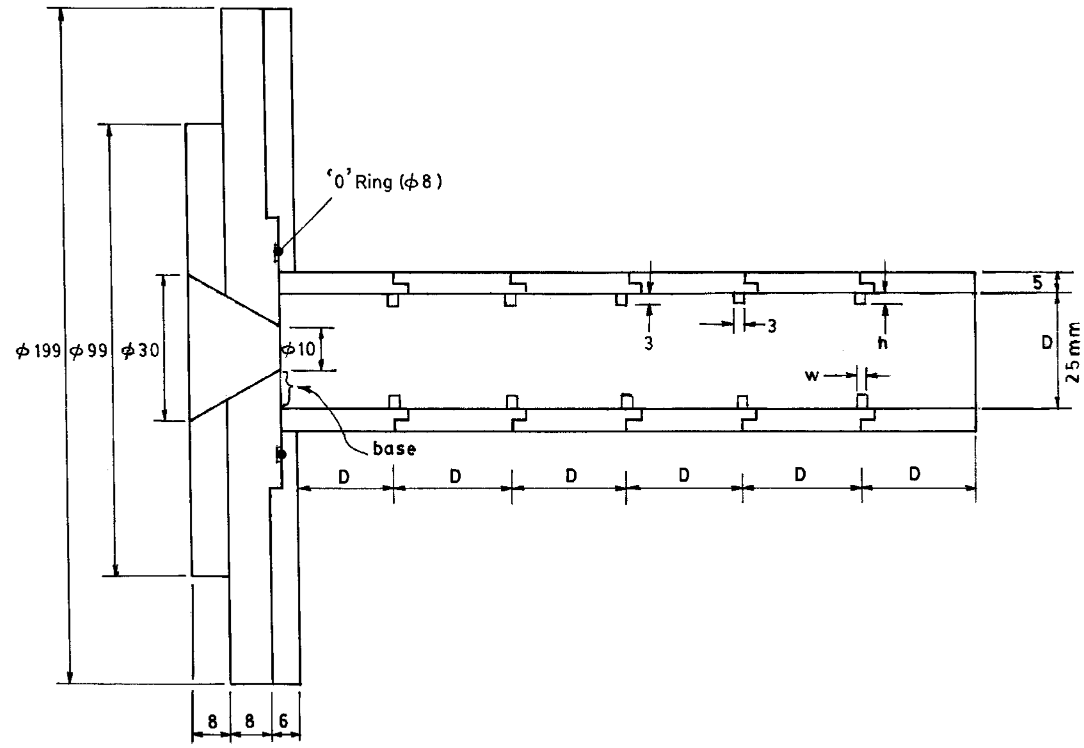

Fig. 1 Experimental model.

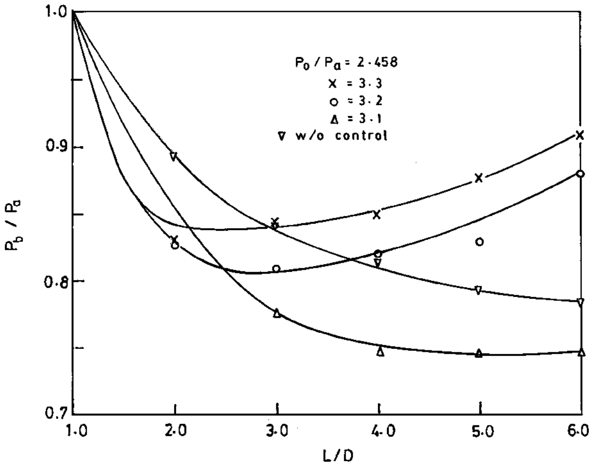

Fig. 2 Base pressure variation with duct *L*/*D*.

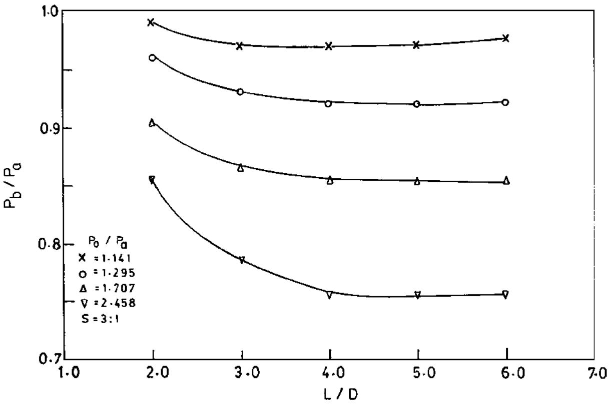

Fig. 3 Base pressure variation with duct *L*/*D*.

from the reattached boundary layer into the base region. This aspect of the flow process makes the passive control in the form of ribs effective. Therefore, the strength of the primary vortex is unaffected by the reverse flow, and this establishes a base pressure lower than the base pressure for a plain duct for similar conditions. However, when the rib height exceeds some limiting value, the rib itself might introduce a secondary vortex by behaving like a forward-facing step, or the rib may interact with the free shear layer from the nozzle exit. The primary vortex would be affected in either case. These kinds of disturbances due to passive control are capable of weakening the primary vortex and thereby increasing the base pressure. Such consequences are seen in the present study for rib aspect ratios 3:2 and 3:3. Therefore, for the parameters of the present study, it can be said that the rib aspect ratio 3:1 is the most effective in maximizing suction at the base region of a suddenly enlarged duct.

One of the problems associated with passive controls in sudden expansions is that the secondary vortices generated by the passive controls make the flow in the duct oscillatory. Therefore, it is a usual practice to analyze the suddenly expanded flows considering both the base pressure and the wall pressure distribution along the length of the duct. The variations of wall pressure along the length of the duct as a function of different flow and geometrical parameters were also investigated. It was found that the influence of the passive control aspect ratio on the pressure field of the duct is significant. However, the degree of influence increases with the increase of rib aspect ratio as well as with the stagnation pressure. The effect of the aspect ratio on the pressure field is only marginal in the vicinity of the base but it becomes significant as the distance increases from the base. However, at 80% of the duct length, the wall pressure becomes almost equal to the back pressure for all of the primary pressures of the present study for L/D equal to or greater than 3. For L/D less than 3, the expansion is such that the pressure at the end of the tube is slightly higher than the back pressure. This may be due to the fact that when L/D is less than 3, the flow does not have enough length to develop after reattachment. Therefore, the flow in the reattachment zone continues to have an effect even at the exit of the duct, thereby causing pressures that are slightly more than the ambient pressure.

The flow development in the duct showed a pattern indicating that the wall pressure reached nearly the atmospheric value, from its low value at the base, at a downstream location of about 80% of the duct length, for L/D more than 3. The point where the wall

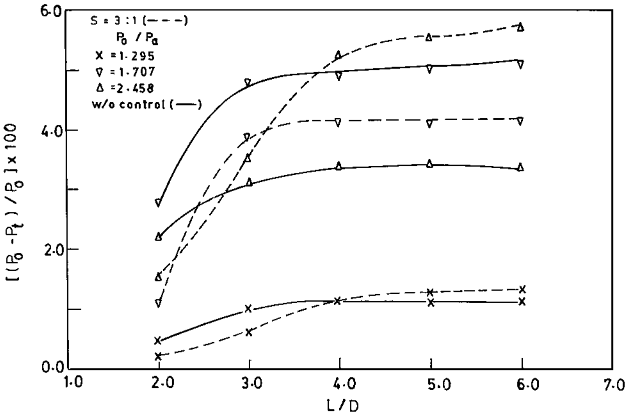

Fig. 4 Pressure loss vs duct *L/D*.

pressure reaches nearly atmospheric pressure is strongly influenced by the rib height. A decrease in the rib height makes this point shift downstream. Another important fact from these results is that, even though the rib aspect ratios 3:3 and 3:2 introduce mild oscillations to the pressure field in the enlarged duct, the aspect ratio 3:1 results in a considerable decrease in base pressure and does not introduce any appreciable oscillations in the pressure field.

The results of measured pressure loss are presented in Fig. 4 for the plain duct and duct with rib aspect ratio 3:1 for three values of primary pressure ratio. It is interesting to note that the increase in pressure loss due to the passive control is always less than 6% in the present range of parameters. The pressure loss results presented here suggest that the losses due to the introduction of the ribs are not great.

Conclusions

For suddenly expanded axisymmetric flows, passive controls in the form of annular ribs have been found to reduce the base pressure significantly, compared to a plain passage. Annular ribs with aspect ratio 3:1, compared to 3:2 and 3:3, prove to be efficient in reducing the base pressure. Further, ribs of aspect ratio 3:1 do not introduce any significant oscillations in the wall pressure field of the duct. At the same time, the increase in pressure loss compared to plain duct is less than 6%. Even for the case with passive control, ducts with L/D in the range 3–5 experience the minimum base pressure, as in the case of plain ducts. Rib aspect ratios 3:2 and 3:3 result in an increase of base pressure beyond $L/D = 3$, and they also introduce mild oscillations to the duct pressure field. This implies that there is a threshold of the control rib aspect ratio that is necessary for obtaining maximum suction at the base along with minimum pressure loss.

Acknowledgments

The author wishes to thank his students, Atul Mathur and Amit Goyal, for making the measurements of the work described, and K. Arun for his help in redrawing the figures.

References

[1]Wick, R. S., "The Effect of Boundary Layer on Sonic Flow Through an Abrupt Cross-Sectional Area Change," *Journal of the Aeronautical Sciences*, Vol. 20, Oct. 1953, pp. 675–682.

[2]Korst, H., "Comments on the Effects of Boundary Layer on Sonic Flow Through an Abrupt Cross-Sectional Area Change," *Journal of the Aeronautical Sciences*, Vol. 21, Aug. 1954, pp. 568, 569.

[3]Hall, W. B., and Orme, E. M., "Flow of a Compressible Fluid Through a Sudden Enlargement in a Pipe," *Proceedings of Mechanical Engineers*, Vol. 169, 1955, pp. 1007–1022.

[4]Sovran, G., *Fluid Mechanics of Internal Flow*, Elsevier, New York, 1967, pp. 1–26.

[5]Anderson, J. S., and Williams, T. J., "Base Pressure and Noise Produced by the Abrupt Expansion of Air in a Cylindrical Duct," *Journal of Mechanical Engineering Science*, Vol. 10, No. 3, 1968, pp. 262–268.

[6]Durst, F., Melling, A., and Whitelaw, J. H., "Low Reynolds Number Flow over a Plane Symmetric Sudden Expansion," *Journal of Fluid Mechanics*, Vol. 64, No. 6, Pt. 1, 1974, pp. 111–128.

[7]Cherdon, W., Durst, F., and Whitelaw, J. H., "Asymmetric Flows and Instabilities in Symmetric Ducts with Sudden Expansion," *Journal of Fluid Mechanics*, Vol. 84, Pt. 1, 1978, pp. 13–32.

[8]Brady, J. F., and Acrivos, A., "Closed Cavity Laminar Flows at Moderate Reynolds Number," *Journal of Fluid Mechanics*, Vol. 115, 1982, pp. 427–442.

[9]Yang, B. T., and Yu, M. H., "The Flow Field in a Suddenly Enlarged Combustion Chamber," *AIAA Journal*, Vol. 21, No. 1, 1983, pp. 92–97.

[10]Rathakrishnan, E., and Sreekanth, A. K., "Flow in Pipes with Sudden Enlargement," *Proceedings of the 14th International Symposium on Space Technology and Science*, Tokyo, 1984, pp. 491–496.

[11]Raghunathan, S., and Mabey, D. G., "Passive Shock-Wave/Boundary-Layer Control on a Wall-Mounted Model," *AIAA Journal*, Vol. 25, No. 2, 1987, pp. 275–278.

[12]Raghunathan, S., "Pressure Fluctuation Measurements with Passive Shock-Wave/Boundary-Layer Control," *AIAA Journal*, Vol. 25, No. 5, 1987, pp. 626–628.

[13]Raghunathan, S., "Effect of Porosity Strength on Passive Shock-Wave/Boundary-Layer Control," *AIAA Journal*, Vol. 25, No. 5, 1987, pp. 757, 758.

[14]Wilcox, J. F., Jr., "Passive Venting System for Modifying Cavity Flow Fields at Supersonic Speeds," *AIAA Journal*, Vol. 26, No. 3, 1988, pp. 374–376.

[15]Tanner, M., "Base Cavities at Angles of Incidence," *AIAA Journal*, Vol. 26, No. 3, 1988, pp. 376, 377.

[16]Viswanath, P. R., and Patil, S. R., "Effectiveness of Passive Devices for Axi-symmetric Base Drag Reduction at Mach 2," *Journal of Spacecraft and Rockets*, Vol. 27, No. 3, 1990, pp. 234–237.

[17]Kruiswyk, R.W., and Dutton, J. C., "Effect of Base Cavity on Subsonic Near-Wake Flow," *AIAA Journal*, Vol. 28, No. 11, 1990, pp. 1885–1893.

[18]Anasu, and Rathakrishnan, E., "Influence of Cavities on Flow Through Sudden Enlargements," *Proceedings of 14th Fluid Mechanics and Fluid Power Conference*, Srinagar, Kashmir, India, 1987, pp. 37–41.

[19]Rathakrishnan, E., Ramanaraju, O. V., and Padmanabhan, K., "Influence of Cavities on Suddenly Expanded Flow Field," *Mechanics Research Communications*, Vol. 16, No. 3, 1989, pp. 139–146.

J. C. Hermanson
Associate Editor

Functional Dependence of Flame Flicker on Gravitational Level

M. Y. Bahadori*
Science and Technology Development Corporation, Los Angeles, California 90049
L. Zhou†
Science Applications International Corporation, Torrance, California 90501
D. P. Stocker‡
NASA John H. Glenn Research Center at Lewis Field, Cleveland, Ohio 44135
and
U. Hegde§
National Center for Microgravity Research, Cleveland, Ohio 44135

Introduction

LAMINAR diffusion flames burning in quiescent oxidizing environments oscillate, or flicker, as a result of hydrodynamic instability, and the frequency of oscillation under normal-gravity condition is in the 10–18-Hz range.[1–3] However, for a wide range of gaseous fuels and Reynolds numbers, the flicker frequency is

Received 27 August 1999; revision received 5 March 2001; accepted for publication 7 March 2001.

*Senior Scientist, 11661 San Vicente Boulevard, Suite 600. Senior Member AIAA.

†Staff Scientist, 21151 Western Avenue.

‡Project Scientist, 21000 Brookpark Road, Mail Stop 77-5.

§Principal Researcher, 21000 Brookpark Road, Mail Stop 110-3. Associate Fellow AIAA.