

Static regulation of base drag: a review

Abstract

This review comprehensively examines the static regulation of base drag at high Mach numbers. A sudden growth in nozzle area causes flow separation and reattachment. This sudden increase splits the jet into a main jet and a separated region. When a cavity controls the flow, reattachment must occur within the cavity to influence the flow field. The findings confirm that the cavity helps only when the reattachment length is slightly larger than the cavity position. When the reattachment length is shorter than the cavity location or longer than the cavity placement, the cavity has no effect, and base pressure does not change with or without the cavity. Likewise, increasing the cavity aspect ratio may make the cavity effective. Cavity depth does not affect the cavity's control effectiveness.

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Introduction

The flow is supersonic if the Mach number exceeds unity. High-inertia flows are also recognized by shock waves that discontinuously modify flow properties and streamlines. Three drag components occur in supersonic flow: viscous drag, wave drag, and base drag. Base drag depends on flow and geometric parameters. Because of factors such as upstream effects from a corner in different Mach number flows at various Reynolds numbers, base drag is difficult to predict. Another variable affected by the separated zone about the base region is base pressure. As base pressure grows, base drag decreases; for complex phenomena such as sudden expansion flow fields involving separation, recirculation, and reattachment, expansion at the nozzle exit area reduces the pressure produced. Therefore, flow control methods such as dynamic and inactive control can manage the flow.

Literature review

Drag is the force that counters the propulsion of aerospace vehicles through the air. Every part of the aircraft generates drag. It forms from a solid body's interaction with a liquid. Without liquids, there is no opposing drag force. Velocity differences involving the entity and the fluid also create drag. There must be movement between the object and the liquid. There is no drag if there is no motion. Drag differs between subsonic and supersonic flow. In subsonic flow, drag consists of viscous drag and base drag, while flow at Mach numbers >1 adds wave drag (Figure 1).

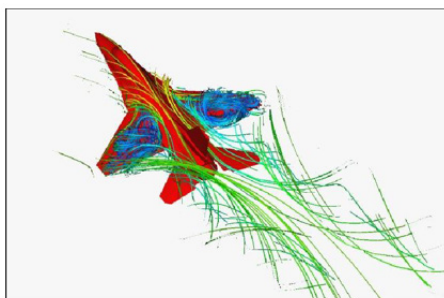


Figure 1 Flow field over a body moving at a supersonic speed.

Skin friction drag

Due to the fluid's contact with an object's surface, or called viscosity, skin friction drag is produced. Friction between either object or substance is similar. The degree of viscous drag depends on the properties of both the solid and the fluid, since it results from solid-fluid interaction. In conclusion, coarse surfaces have greater skin friction than efficient surfaces.

Base drag

Base drag is a component of drag prompted by the lower pressure originating behind a projectile's flat base. It persists because of boundary-layer effects. Base drag occurs on any elongated body where the flow separates from the rear side.

Wave drag

Shock waves form along the surface as an aircraft approaches the speed of sound. Shock effects create pressure changes and reduce net pressure. Shock wave development correlates with wave drag. Wave drag depends on the flow's inertia levels. Therefore, shock waves are air disruptions produced by high airflow speeds.

Literature review

In this section, we review the literature. Asadullah, M. et al.,¹ Conducted a study comparing the effect of single and multiple cavities on base flows. Khan, A. et al.,² conducted a comprehensive review on passive control of base Pressure. Mustafa et al.,³ Studied traditional and new flow-control techniques to enable high maneuverability and low structural weight for UAVs and MAVs, autonomous vehicles (George Dekoulis). Pandey et al.,⁴ conducted experiments on annular cavities for Base Flow Control. Cavity location plays an important role in base flow control. Cavity length plays an important role, whereas depth is insignificant in base flow control. Rathakrishnan et al.,⁵ studied the influence of cavities on a suddenly expanded flow field at sonic Mach numbers for three area ratios, namely 2, 4, and 10. Sethuraman et al.,⁶ reviewed base and wall pressure control using cavities and ribs in suddenly expanded flows.

Tanner,⁷ experimentally studied base cavities at various angles of incidence. Vijaya Raja et al.,⁸ experimentally investigated base pressure control with annular ribs. For lower heights, the ribs reduce base pressure, whereas 3 mm-high ribs increase base pressure considerably. Viswanath,⁹ wrote a comprehensive review of flow-management techniques for reducing base and afterbody drag. Khan et al.,¹⁰ numerically studied the effect of ribs in a suddenly expanded flow at a sonic Mach number. Khan et al.,¹¹ numerically simulated suddenly expanded flow from a converging nozzle at Mach 1.0. Khan et al.,¹² numerically determined the velocity distribution and base-pressure analysis of an under-expanded nozzle flow at Mach 1.0. Khan et al.,¹³ numerically and experimentally studied base-pressure control with semicircular ribs at the critical Mach number. The semicircular rib was less effective than the rectangular and triangular ribs.

Rehman et al.,¹⁴ experimentally studied and employed microjets to control base pressure for an area ratio of 4.84 at Mach numbers from 1.25 to 3. The results show that the control is effective up to Mach 2; at higher Mach numbers (2.5 and 3.0), the microjet-based dynamic control is ineffective because the nozzle flow remains over-expanded. Khan et al.,¹⁵ used passive control of base drag in compressible subsonic flow using multiple cavities. The results show it is effective only when the shear layer reattaches within the cavity length; otherwise, it is not effective. Khan et al.,¹⁶ studied the effect of nozzle expansion level on suddenly expanded flow for four area ratios (2.56, 3.24, 4.84, and 6.25) at Mach numbers from 1.25 to 3.0. Dynamic control using microjets is effective when the nozzle flow under a favorable pressure gradient. However, at Mach 2.5 and 3.0, the flow remains over-expanded, so the control is ineffective. Akhtar et al.,¹⁷ experimentally controlled CD nozzle flow using microjets at Mach 2.1. Microjet control effectively raised base pressure values without adversely affecting the duct flow field. Akhtar et al.,¹⁸ studied the effects of microjets on the flow field of a duct with sudden expansion. The results indicate that the flow pattern in the enlarged duct is not adversely affected, and the flow field with and without microjets remains identical. Akhtar et al.,¹⁹ conducted numerical simulations of a CD Nozzle and the Influence of duct length on the reattachment length.

In this review, we considered the rectangular cavity a static control mechanism for controlling base pressure and, hence, base drag. The reattachment length depends on the duct diameter, Mach number, and expansion level. As the duct diameter increases, the reattachment length increases progressively. However, when the shear layer passes through a converging-diverging nozzle, three possibilities exist. 1. The flow can be over-expanded if the pressure at the nozzle exit plane is less than the ambient pressure. Under these circumstances, the shear layer deflects toward the jet center, and the reattachment length increases. Hence, for a given duct length and Mach number, the reattachment length will increase when the jet is over-expanded. The dividing streamline may not fall into the cavity because the reattachment length increases.

Methodology

Base pressure control

Two methods regulate base pressure: Dynamic and static control. Dynamic control uses an external power source, such as blowing and suction, to manipulate the flow. Because it can be switched on or off as needed, active control is more useful than static control, but it requires extra energy and costs. Actuators are central to dynamic flow regulator implementation and have been a fragile association in advances in flow-control technique. Although static control needs

no external power source, it only changes duct geometry by adding splitter plates, ribs, cavities, boat tailing, etc. Passive control devices operate continuously, despite the need for, or the penalty of, execution.

Passive flow controller techniques

Passive flow regulator methods perfect flight vehicle performance by controlling boundary-layer flow features. This is because flow manipulation efficiently controls the interaction between separated flow and the viscous layer.

Cavity

Cavities can be categorized as dynamic, static, reactive, incessant, and uneven (Figure 2). The complexity of cavity flow makes it necessary to understand the flow inside and around it and its impact on base pressure, requiring multidisciplinary reasoning.¹ The principle is to generate a useful pressure slope by catching two counter-rotating vortices within static control. These caught vortices create an extra-low-pressure region over the suction surface, reducing drag. The cavities intensified the lift-to-drag ratio.

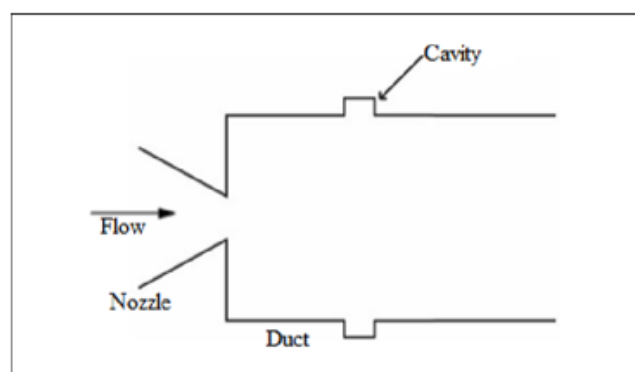


Figure 2 Flow field over a body moving at a supersonic speed.

Threaded spikes

The edge-through spike effectively controlled base pressure and, consequently, drag at the blunt base. This was thought to be due to increased friction from the spike's threads, which breaks large and small eddies into weaker, smaller eddies, raising base pressure even at critical inertia levels (Figure 3).

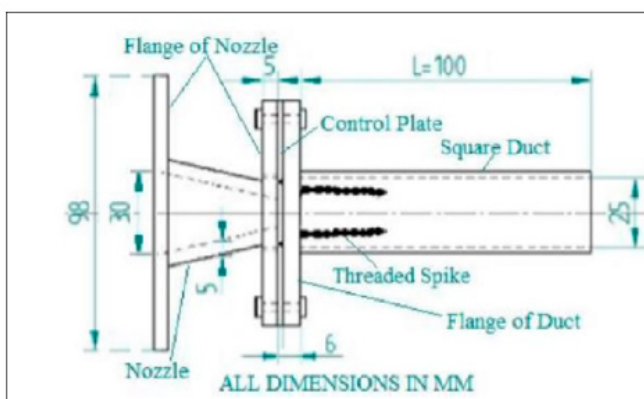


Figure 3 Experimental set-up of apparatus and beam used for analysis.¹

Grooves

Grooves create sizable distortions in the jet shape, leading to considerable mass inflow and sideways velocity. Grooves enhance

mixing between the jet fluid and the surrounding fluid. Groove length strongly influences the jet flow field. Grooved nozzles mix better than plain nozzles. Also, the shock cell formation in grooved nozzles appeared more fragile than in plain nozzles (Figure 4).

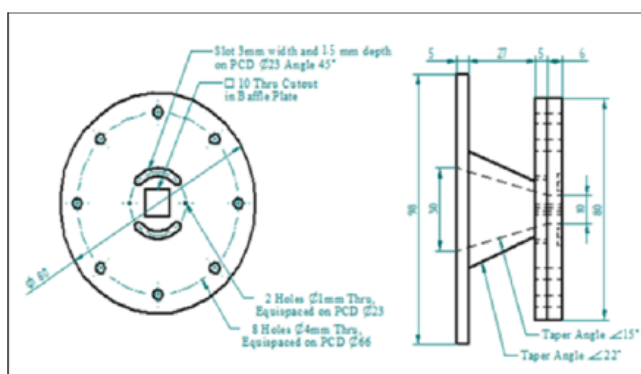


Figure 4 Passive control using square grooved nozzle.¹

Fluid flow at nozzle exit

Supersonic stream at the nozzle lip can be categorized into 3 conditions: over-expanded, ideally expanded, and under-expanded. Figure 5 shows the pressure propagation downstream of the nozzle. Although the pressure at (e) exceeds the backpressure, the flow in the diverging segment remains supersonic and expands to (f) at the nozzle lip, with no normal shock forming inside the nozzle, so the stream can be approximated as isentropic (Figure 6).

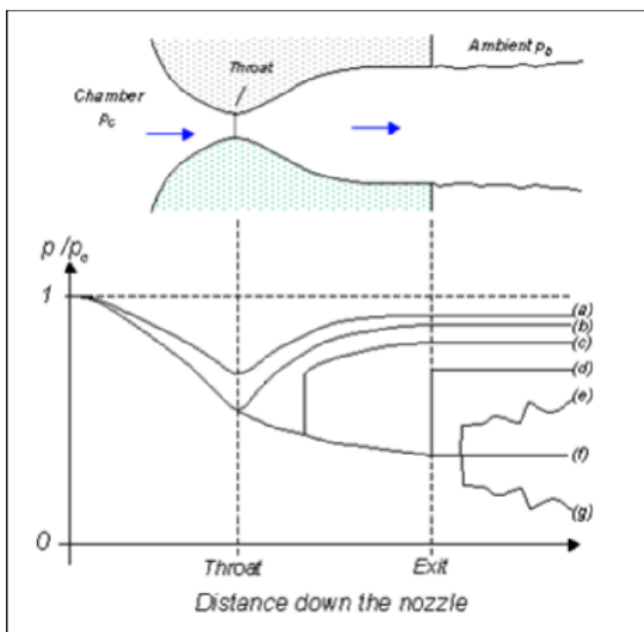


Figure 5 Pressure distribution along the nozzle.

Explanation

When a convergent-divergent (CD) nozzle enters a suddenly enlarged duct or larger pipe, the flow separates at the nozzle lip, creating a corner recirculation zone (base region) before reattaching to the pipe wall. The reattachment segment (L_r)—the space from the nozzle lip to the position where the dividing streamline hits the pipe wall—varies substantially depending on the NPR and the expansion state.

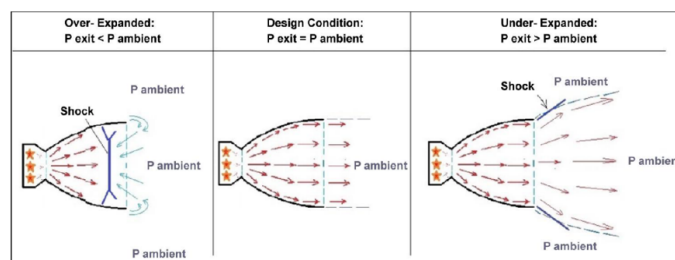


Figure 6 Nozzle flow pattern.

Summary of reattachment length variation

Nozzle Expansion State

Relative Exit Pressure (P_e) vs. Pipe Backpressure (P_b)

Exit Wave Structure

Reattachment Length (L_r)

Over-expanded ($P_e < P_b$)

Oblique Shock Waves Longest

Correctly expanded ($P_e = P_b$)

Wave-free / Mach Waves

Intermediate (Baseline)

Under-expanded ($P_e > P_b$)

Expansion Fan Shortest

Over-expanded condition ($P_e < P_b$)

Flow Physics: Because the pressure at the nozzle lip is less than the pipe pressure, the flow must compress. An oblique shock wave forms at the nozzle lip & angles inward toward the centerline.

Effect on reattachment: The oblique shock compresses the supersonic core jet, causing it to “pinch” or turn inward away from the pipe wall. This contraction delays the outward spreading of the blending shear layer, pushing the reattachment point further downstream. Consequently, the reattachment length is maximized.

Correctly expanded condition ($P_e = P_b$)

Flow physics: The exit pressure perfectly balances the back pressure inside the larger pipe. The flow exits smoothly without a major shock or expansion fan structure (ideally wave-free).

Effect on Reattachment: The shear layer grows naturally due to standard turbulent mixing at the boundary of the sudden expansion. The reattachment length serves as the nominal or design baseline length.

Under-expanded Condition ($P_e > P_b$)

Flow physics: Because the jet pressure at the exit is greater than the adjoining pipe pressure, the flow undergoes sudden external expansion—an expansion wave forms right at the nozzle lip.

Effect on reattachment: The expansion fan forces the supersonic jet plume to flare outward toward the larger pipe wall. Because the core flow bends directly toward the solid boundary, the dividing streamline intercepts the pipe wall much sooner. Increasing the nozzle pressure ratio (making it more under-expanded) further decreases this length, yielding the shortest reattachment length.

Figure 7 shows that the rapid-expansion flow pattern is intricate, with flow splitting, a circulatory zone, and later rejoining at the duct wall. The flow field is divided into two central regions: the flow recirculation region and the central flow area. The reattachment position is where the splitting streamline reaches the surface of the wall.

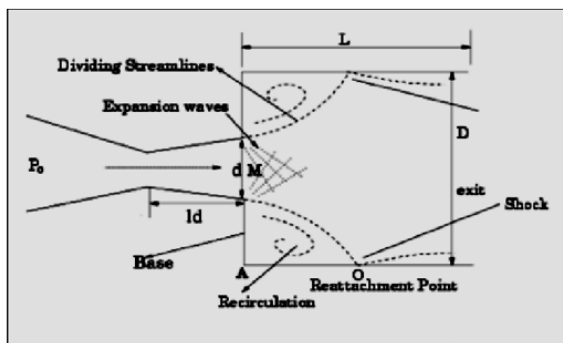


Figure 7 Sudden expansion flow field.¹

As shown in Figure 8, Pandey and Rathakrishnan,⁴ explained stream expansion in over- and under-expanded conditions. Mutual cases happen at supersonic Mach numbers. First, in under-expanded flow, an expansion wave forms at the CD nozzle lip. This will shorten the reattachment length because reattachment occurs earlier.

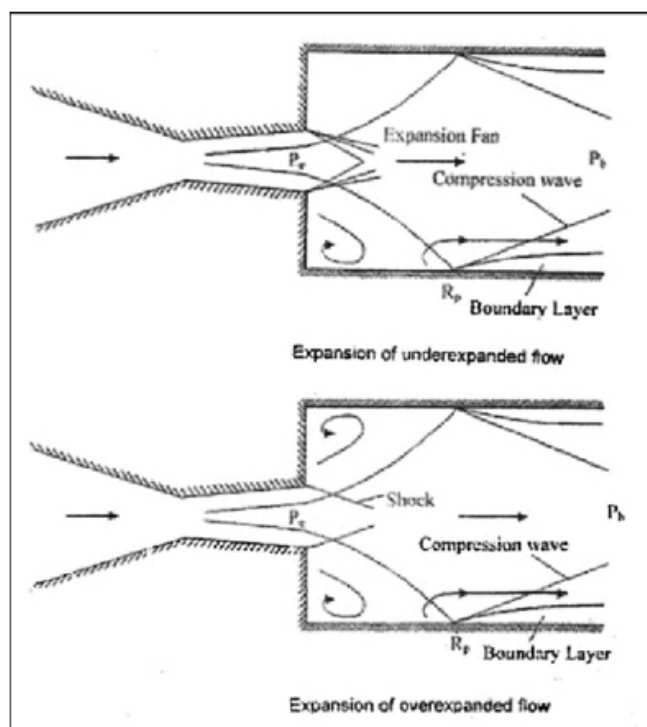


Figure 8 Sudden Expansion Flow Through CD Nozzle.⁴

Second, as the nozzle passes across the adverse pressure slope, an oblique shock wave forms at the nozzle lip. This will lengthen the reattachment length because the shock delays reattachment. In both cases, vortices form concerning the base and the reattachment location. These vortices will establish a suction force. The suction force changes with the reattachment distance. Hence, the smaller the reattachment size, the stronger the vortices. Sudden expansion has many applications. First, the sudden rise in the area can be used for flow over a blunt-edged projectile; it can also be used for cruise correction in the supersonic parallel diffuser. Third, it can be used in vernier rockets and the sern nozzle.

Base pressure variations with L/d ratio

To simplify, the developed model assumes steady, 1-D flow with no entropy change. Isentropic flow assumes zero heat transfer within the selected volume and negligible viscous losses, but it accounts for boundary layers, wakes, and shock waves. Critical conditions occur when the flow accelerates or decelerates isentropically until the Mach number changes from the free-stream Mach number to 1. At the throat, the flow reaches critical conditions when the Mach number equals 1 in the convergent portion because a normal shock wave forms owing to an impulsive variation in flow, where velocity declines and pressure increases, with the initial flow supersonic. For our design, we set the initial Mach number to 1.74, and the flow is reduced to 1. The figure below shows the velocity and pressure effects of a shock wave. Velocity and pressure are affected by shock waves. The shock wave terminates the supersonic flow; pressure increases after it. At the same time, velocity decreases, and the flow remains subsonic until the back pressure equals the exit-plane or ambient pressure. A supersonic section forms just downstream of the minimum-diameter section when the ambient pressure is lowered below the throat pressure. However, a shock wave might occur again in the diverging section, and the flow will return to subsonic. To prevent this, further reduce the back pressure until the shock wave moves farther down the diverging portion of the nozzle or to the exit (Figure 9) (Table 1).

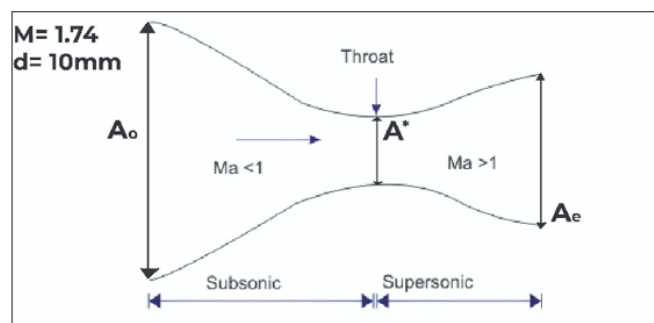


Figure 9 Convergent-Divergent nozzle showing the nozzle parameters.

Table 1 The effects of base pressure with variations of L/D and Area Ratio, Ar

Effects of base pressure					
$Ma = 1.74, ARS1 = 1, ARS2 = 2, de = 10 \text{ mm } d^* = 8.52 \text{ mm}, Ae / A^* = 1.37643$					
$Ar = 10$		$Ar = 6$		$Ar = 2.89$	
$L/D < 3$	$L/D > 3$	$L/D < 3$	$L/D > 3$	$L/D < 3$	$L/D > 3$
Base pressure decreases steeply.	Base pressure remains almost constant at all pressure ratios.	The base pressure depends strongly on the enlarged duct length.	Influences the base pressure noticeably at all nozzle pressure ratios.	Decreases the base pressure.	Increases the base pressure.

Figure 10 to Figure 12 show the base pressure ratio for three area ratios (10, 6, and 2.89) as a function of length-to-diameter ratio. For an area ratio of 10, the smallest duct needed to keep the flow attached to the duct wall appears to be $L/D = 3$ for both primary area ratios (2.1 and 2.93). The base pressure also assumes very high values and decreases continuously; however, this decrease stops once the duct is long enough for the flow to continue connected to the duct wall. Later, as the duct length increases further, the base pressure reaches a steady state and becomes independent of duct length. This area's ratio is the highest being tested. Cavity length and pressure-ratio variation do not influence the base pressure.

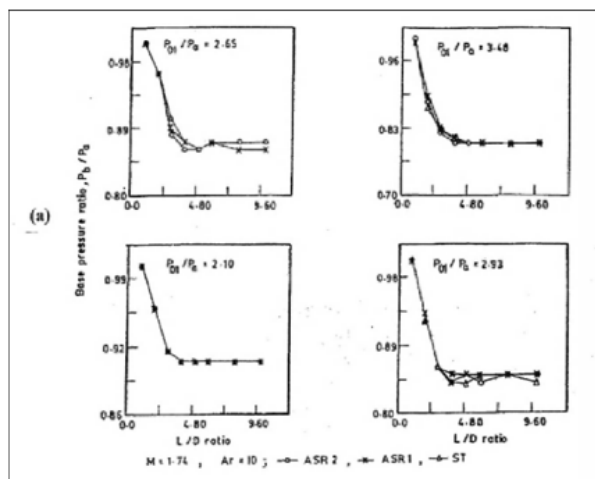
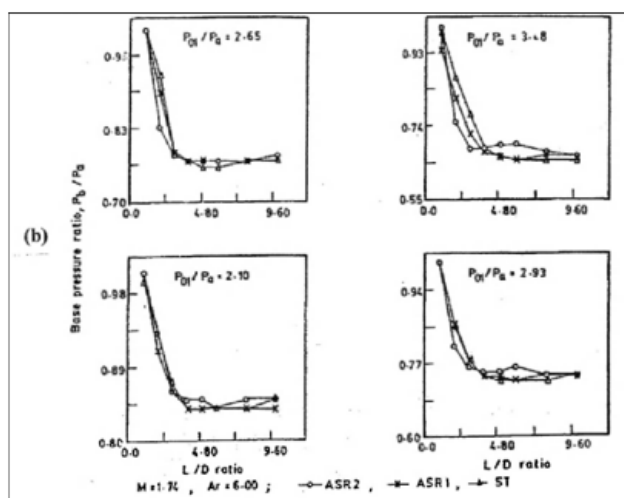
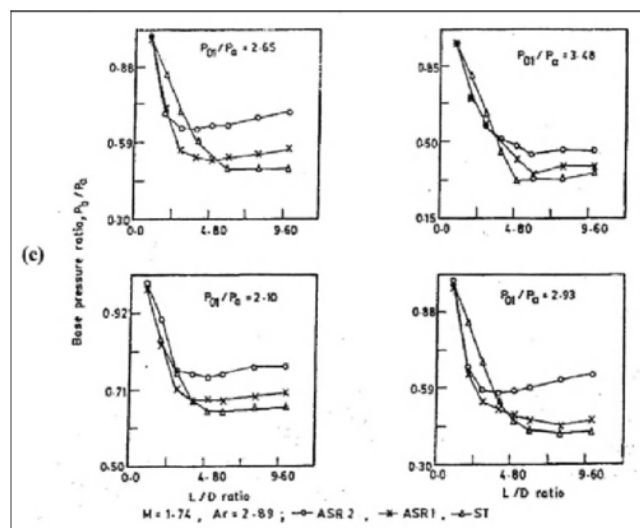
**Figure 10** Base pressure Vs. L/D ratio when $Ar = 10.00$.**Figure 11** Base pressure Vs. L/D ratio when $Ar = 6.00$.**Figure 12** Base pressure Vs. L/D ratio when $Ar = 2.89$.

Figure 11 displays the base pressure, which follows the trend in Figure 10. Here, the smallest L/D necessary to keep the flow connected was 3. The base pressure changed only slightly as the area ratio decreased from 10 to 6. Once the cavity length exceeds $ARS2$, it no longer affects the flow field and has a negligible effect on base pressure magnitude.

Similar results appear in Figure 12, since the wind tunnel could not operate at higher primary pressure ratios because a manometer measured the settling chamber pressure. The results are expected to differ significantly when the nozzles are operated in the ideally expanded and under-expanded cases. Unfortunately, the nozzles were operated at an extreme level of over-expansion. This may be one reason the cavities were not very effective.

Conclusion

Based on the above arguments, the ensuing conclusions are drawn: Base pressure depends strongly on inertia levels, NPR, flow relief, cavity placement, and the L/D ratio. Unlike sonic flow, where nozzle-lip pressure & the base pressure at the corner are the same, a CD nozzle allows three possible circumstances. The nozzle exit pressure can equal, be less than, or exceed the ambient pressure. Each case yields a different reattachment length and flow field. Accordingly, the base pressure magnitude varies, and thus the cavity control efficacy. Hence, the cavity may be ineffective in many cases; it works only when the flow enters the cavity, otherwise it is blind, and the flow stream does not sense its presence.

The reattachment distance also depends on the pipe diameter. For the lower enlarged ducts, the reattachment length can be as low as $L/D = 1$ for the smallest duct diameter. As the duct diameter increases, it may reach $L/D = 1.5$, 2, and 3.

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Conflict of interest

Author has no conflicts of interest.

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