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Active control of base flow and base drag at sonic and supersonic Mach numbers

Abstract

Base drag constitutes a major fraction of the total drag on aerospace vehicles at sonic and supersonic speeds, arising from the low-pressure, recirculating wake behind a blunt rear face. Reducing it yields large gains in range and payload, motivating the study of base flow control. This study reviews active methods—principally micro-jet injection and base bleed—and evaluates them against established passive techniques. The governing flow physics is examined through shear-layer separation, the dead-air recirculation zone, and the reattachment process that fixes base pressure, characterized via the base pressure coefficient. Drawing on experimental and computational studies of suddenly-expanded ducts and nozzles, the report assesses how active control raises base pressure relative to the uncontrolled baseline and identifies where each method is most effective.

Keywords: base flow, base pressure, active flow control, supersonic; sonic, micro-jet, base bleed, drag reduction

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Introduction

The problem of base drag

Every aerospace vehicle that operates at sonic or supersonic speed- a missile, a sounding rocket, an artillery projectile, or a launch vehicle- terminates in a blunt rear face, or base. This feature is a geometric necessity, since engines, nozzles, and payloads must be housed within the airframe, yet it carries a severe aerodynamic penalty. As the flow reaches the sharp shoulder of the base, it can no longer follow the abrupt rearward-facing step. The boundary layer separates, and a region of slow, recirculating fluid forms behind the body at a pressure well below that of the surrounding stream. The resulting pressure deficit, acting over the base area, produces a net rearward force known as base drag.

The magnitude of this penalty is the central motivation for the entire field of base flow control. For a slender body at supersonic speed, base drag is not a minor correction to the total drag budget; it can constitute a major fraction of the overall drag of the vehicle.[1] The practical consequences are direct and significant. For an artillery shell, a reduction in base drag translates immediately into increased range; for a missile, into greater effective reach and reduced propellant consumption; and for a launch vehicle, into an improved payload fraction. Because the base region is responsible for such a large share of the drag, a control technique that recovers even a portion of the lost base pressure can yield disproportionately large gains in vehicle performance. This favourable return on a relatively small intervention explains the sustained research effort devoted to manipulating base flow over the past several decades.[2]

Methods of base drag reduction fall into two broad categories. Passive techniques modify the geometry of the after body, through boat-tailing, base cavities, splitter plates, or ribs—and require no external power. Active techniques, by contrast, add energy or mass to the base region, for example, through base bleed or the injection of high-pressure micro-jets, and can be adjusted in response to flight conditions. The present review focuses on active methods of base flow control across the sonic and supersonic regimes and evaluates their effectiveness relative to the established passive baseline.

Theoretical physics of the base region

To understand why the base is a region of such low pressure, and how that pressure can be raised, the structure of the wake must be examined in detail. The near-wake of a blunt-based body can be divided into four interacting features: the separating shear layer, the recirculating dead-air region, the reattachment zone, and the recompression that closes the wake.

Flow separation at the base shoulder

As the external stream reaches the sharp corner of the base, the boundary layer that has developed along the body can no longer remain attached to the abruptly receding surface. It separates from the shoulder and rolls up into a free shear layer that divides the high-speed outer flow from the low-speed wake. In supersonic flow, the stream turns around the corner through an expansion process, accelerating and dropping in static pressure as it enters the wake. This sudden-expansion behaviour is precisely the phenomenon reproduced in the suddenly-expanded duct and nozzle experiments that form the experimental basis of much base flow research.[3]

The recirculating "dead-air" wake

Immediately downstream of the base, enclosed by the separated shear layer, lies a pocket of slow, recirculating fluid commonly described as the dead-air region. The fluid here circulates in a closed pattern and is largely isolated from the freestream, exchanging mass and momentum only through the turbulent shear layer that caps it. The pressure within this region is what is measured experimentally as the base pressure, and its variation with Mach number, nozzle pressure ratio, area ratio, and afterbody geometry constitutes the principal dependent variable in base flow studies.[4] The low momentum of the recirculating fluid is also what makes the region so receptive to control: a comparatively small addition of mass or energy can substantially alter the balance that sets its pressure.

Reattachment and recompression

Further downstream, the dividing streamline of the shear layer converges back toward the axis at the reattachment point, where the wake closes. Because the flow must realign with the axial direction, it undergoes a compression that, at supersonic speeds, manifests as a trailing recompression shock. The pressure rise associated with this reattachment is communicated upstream through the subsonic inner portion of the shear layer, and it is this back-propagated pressure that ultimately determines the level within the dead-air region. The base pressure is therefore not an independent quantity but the equilibrium outcome of the entire expansion–recirculation–reattachment sequence.

The low-pressure "sub-atmospheric" effect

The net result of this sequence is that the base sits at a pressure markedly below the ambient freestream static pressure. In effect, the wake behaves as a partial vacuum acting on the rear face of the vehicle and pulling it backward. The physical objective of every base flow control strategy can thus be stated in a single sentence: to raise the base pressure toward the freestream value, thereby shrinking the pressure deficit and the drag it produces.[2] Active control accomplishes this by energizing the shear layer or by feeding mass into the dead-air region, both of which displace the wake equilibrium toward a higher base pressure.

Key metrics and governing relations

Several non-dimensional quantities are used throughout the literature to quantify the base flow and the effectiveness of its control. They are collected here so that the parametric results presented in later sections can be interpreted consistently.

Base pressure coefficient: The central measure of the base flow is the base pressure, non-dimensionalized as the base pressure coefficient,

$$C_{pb} = (P_b - PDb/_{\infty}) / (½\, \rho_{\infty}\, V_{\infty}^2) = (P_b - P_{\infty}) / (½\, \gamma\, P_{\infty}\, M_{\infty}^2)\ (1)$$

$$C_{Db} = - C_{pb}\, (Db/D)^2\ (2)$$

Where P_b is the measured base pressure; p∞, ρ∞, V∞ and M∞ are the freestream static pressure, density, velocity, and Mach number, respectively; and γ is the ratio of specific heats. A more negative coefficient value indicates a greater pressure deficit and, hence, greater base drag, so the aim of control is to drive the coefficient toward zero. In experimental work, the result is often reported more simply as the base-pressure ratio P_b/P_{∞}, and the performance of a control method is expressed as the percentage increase in this ratio relative to the uncontrolled.[4]

Decomposition of total drag: The total drag of a body at supersonic speed is conventionally decomposed into three additive contributions,

$$D_{total} = D_{wave} + D_{friction} + D_{base}\ (3)$$

comprising the wave (pressure) drag generated by the shocks on the nose and forebody, the skin-friction drag arising from the viscous boundary layer along the surface, and the base drag associated with the low pressure on the rear face. Studies that resolve this breakdown for supersonic configurations confirm that, for blunt-based bodies, the base term is a dominant contributor to the total.[5] For this reason, the control effort is concentrated at the base rather than elsewhere on the airframe. Expressed in coefficient form, equation (2) becomes

$$C_D = C_{D,wave} + C_{D,friction} + C_{D,base}\ (4)$$

in which the base-drag coefficient is related directly to the base pressure coefficient and the ratio of base area A^b to reference area $A_{re}{}^f$ by

$$C_{D,base} = - C_{pb}\, (A_b / A_{ref})\ (5)$$

So that any increase in base pressure (a less negative Cp^b) feeds through directly into a reduction of the base-drag coefficient. Equation (4) makes explicit why even modest gains in base pressure are valuable: the contribution scales linearly with the area ratio, which for a blunt body is of order unity.

Governing operating parameters: In the suddenly expanded apparatus used to study active control, the state of the base flow is governed by a small set of nondimensional groups. The nozzle pressure ratio,

$$NPR = P_0/P_{\infty}\ (6)$$

Relating the stagnation pressure p_0 to the ambient pressure, determines whether the nozzle is over-, correctly, or under-expanded and therefore the sign of the pressure gradient that the base flow experiences. The area ratio A_2/A_1 of the enlarged duct to the nozzle exit, together with the length-to-diameter ratio L/D of the duct, fixes the geometry of the recirculation region, while the freestream Mach number M_{∞} sets the strength of the expansion at the shoulder.[3] The chapters that follow report base pressure as a function of these parameters, both for the uncontrolled baseline and under active control, and use the coefficient of equation (1) as the common basis for comparison.

Methodology

To understand how high-speed air separates behind rockets and projectiles, researchers use both laboratory experiments and computer simulations. This section explains the equipment used in labs, the critical dimensions of the test models, and the mathematical methods used in computer modeling.

The sudden expansion internal flow apparatus

Testing full-scale rockets or using large external wind tunnels is very difficult and expensive. External wind tunnels require a massive amount of high-pressure air. Also, the metal struts or stings used to hold the rocket model inside the tunnel disturb the air right behind the base, which ruins the data.[2]

To solve these problems, researchers use an internal flow system called a sudden expansion apparatus. Instead of blowing air around a model, they blow air into a pipe that suddenly widens. The way the air separates and creates a low-pressure zone at this sharp corner is physically identical to the flow separation that occurs behind a real missile base.[6]

This internal flow setup has several major advantages for laboratory research:

a) **Lower air consumption:** Because the air is contained inside a narrow pipe, the system needs much less compressed air than a massive open wind tunnel.

b) **No support interference:** There are no mounting brackets or stings inside the wake flow, so the recirculation zone forms naturally.

c) **Easy measurements:** Researchers can easily drill tiny holes into the solid metal walls to install pressure sensors right where the flow separates.

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Layout of the experimental equipment

A standard laboratory setup consists of a high-pressure air network, a stabilization tank, and the test pipe assembly:[2,6]

A. **Air storage and dryer:** High-pressure air from compressors passes through a dual-tower silica gel dryer. This step removes all moisture from the air, preventing water vapor from condensing and creating unwanted shock waves during the test.

B. **Primary settling chamber:** The dry air enters a large tank called a settling chamber. Inside this tank, the air slows to a complete stop. This creates a steady stagnation pressure (P0) and temperature before the air enters the nozzle.

C. **Primary nozzle:** The air accelerates out of the settling chamber through a nozzle. Researchers use a convergent nozzle to reach exactly sonic speed (M = 1.0), or convergent-divergent (De Laval) nozzles to reach supersonic speeds (M = 1.25 to 3.0). The exit diameter (d) of this nozzle is usually fixed at 10 mm.

D. **Suddenly expanded duct:** A larger metal tube (made of brass or stainless steel) is attached directly to the nozzle exit. This is where the flow suddenly expands.

E. **Active microjet controllers:** To control the base pressure, researchers drill four tiny holes (1 mm in diameter) into the flat vertical face of the expansion corner. These holes are spaced at 90-degree intervals around the main nozzle. They are arranged on a circle called the Pitch Circle Diameter (PCD), which is set to 1.3 times the nozzle exit diameter (1.3d).

F. **Secondary air supply:** These four microjets are connected to a separate, smaller settling chamber. This allows researchers to turn the microjet air on or off, and change its blowing pressure independently from the main nozzle flow.

G. **Pressure data sensors:** Electronic pressure sensors are connected to tiny holes drilled along the model. They measure the base pressure (Pb) at the separation corner and the wall static pressure (Pw) along the length of the wide tube. Because the air changes direction rapidly right after the expansion, the first few wall sensors are placed very close together (3 mm to 4 mm apart). The downstream sensors are spaced further apart.

Critical geometric and flow parameters

The behavior of the expanding air and the success of the microjet control depend on three main non-dimensional variables:[2,6]

2.2.1 Nozzle Pressure Ratio (NPR)

The Nozzle Pressure Ratio is the absolute stagnation pressure inside the primary settling chamber (P0) divided by the atmospheric back-pressure (Patm) outside the exit of the pipe:

$$NPR = P_0/P_{atm}$$

The NPR determines how the air expands as it leaves the nozzle lip. Researchers test different integer values of NPR (usually from 3 to 11) to study three different expansion states:

1) **Over-expanded flow:** At low NPR, the air pressure at the nozzle exit is below atmospheric pressure. This forces strong oblique shock waves to form right at the nozzle lip.

2) **Correctly expanded flow:** The exit pressure matches ambient pressure perfectly, producing a smooth jet with no major shock structures.

3) **Under-expanded flow:** At high NPR (like NPR = 11), the exit pressure is higher than the ambient pressure. The air shoots out rapidly and forms expansion fans at the corners, making the active microjets much more effective.

Area ratio (a2/a1)

The Area Ratio represents how much extra space the air receives when it enters the larger tube. It is calculated by dividing the cross-sectional area of the wide duct (A2) by the cross-sectional area of the nozzle exit (A1):

$$\text{Area Ratio} = A_2/A_1 = D^2/d^2$$

Where D is the internal diameter of the large duct and d is the diameter of the nozzle exit. Common area ratios used in tests are 2.56, 3.24, 4.84, and 6.25. A small area ratio restricts the space behind the corner, causing a very strong vacuum (high base drag). A large area ratio provides more room, which naturally weakens the low-pressure suction vortex.

Duct length-to-diameter ratio (L/D)

The L/D ratio describes the relative length of the large expansion tube. It is the physical length of the wide duct (L) divided by its internal diameter (D). Uncontrolled flows usually need an L/D ratio between 3 and 5 just to touch the wall again and form a stable recirculation bubble. To see how the flow recovers further downstream, researchers test lengths up to L/D = 10.

To keep the experiments highly accurate, researchers use a destructive cut-down technique. They start the test matrix with the longest possible tube (L/D = 10). Once they record all the pressure data, they put the same tube onto a lathe and physically cut it to shorter lengths, repeating this process all the way down to L/D = 1. This destructive method ensures that the inner surface roughness and manufacturing tolerances remain identical for every single duct length tested.

Computational Fluid Dynamics (CFD) approaches

Because high-speed shock waves can damage laboratory parts, and because it is difficult to see inside solid metal pipes, modern researchers use Computational Fluid Dynamics (CFD) to simulate the turbulent wake region.

Mathematical framework

To simulate supersonic flow separation, computer programs solve the compressible Reynolds-Averaged Navier-Stokes (RANS) equations. These equations are based on the fundamental laws of physics that ensure mass, momentum, and energy are perfectly conserved within the grid cells.[7]

Because the air rotates violently inside the base vacuum zone, standard equations are not enough. Researchers use two-equation turbulence closure models to simulate the mixing layers accurately:

i. **Standard and realisable k-epsilon models:** These models calculate turbulent kinetic energy (k) and its dissipation rate (epsilon). They are highly stable and work well for predicting pressure along the tube walls.[7]

ii. **Modified k-epsilon Model:** This version includes mathematical corrections for streamline curvature. It prevents the computer from overestimating the fluid thickness (viscosity) inside highly curved, spinning base vortices.

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iii. **k-omega SST (Shear Stress Transport) model:** This model combines two methods. It uses the k-omega formulation near solid walls because it tracks boundary layers accurately under strong pressure gradients, and switches to the k-epsilon formulation in open air, where mixing layers interact.[7]

Simulation grid and boundaries

The simulation software uses a digital grid that mirrors the exact dimensions of the lab hardware. The boundary values are set to match real experimental conditions:

a) **Nozzle entrance:** Configured as a Pressure Inlet where the total pressure matches the lab's primary settling chamber (P0).

b) **Microjet orifices:** Set as small, independent velocity or pressure inlets to simulate active fluid injection.

c) **Duct exit:** Configured as a Pressure Outlet discharging directly to sea-level atmospheric pressure (Patm = 101,325 Pa).

d) **Solid boundaries:** Configured as rigid, insulated walls with a No-Slip condition, meaning the air velocity touching the metal surface is exactly zero.

Current research gaps in CFD

To reduce computational time, the vast majority of existing CFD papers use simplified two-dimensional (2D) axisymmetric grids. While 2D grids are acceptable for empty pipes, they create a major problem when studying active control. An active microjet system does not inject a continuous ring of air; instead, it injects air through separate, individual holes drilled around the circle. This creates highly localized, asymmetric three-dimensional (3D) mixing structures where the microjets collide with the main flow. Because 2D simulations smooth this out, they miss the true physics of fluid interaction. To fix this gap, modern aerospace research is shifting toward complex 3D RANS and Large-Eddy Simulations (LES), which require high-performance supercomputing clusters.[7]

Active control mechanisms and results

The active control mechanism (Micro-jets)

In recent decades, active control via micro-jets has emerged as an effective, energy-efficient method for managing high-speed flows in Convergent-Divergent (CD) nozzles. The standard active control experimental setup employs four micro-jets, each with a 1 mm orifice diameter, positioned at 90° intervals along a pitch circle diameter that is 1.3 times the nozzle exit diameter.[6,2] These micro-jets are typically connected directly to the primary settling chamber and inject high-pressure air into the dead-air base region. This inlet flow modulates the recirculation zone, thereby reducing drag across the aerospace vehicle.[6]

Parametric analysis: NPR and Mach number variations

The effectiveness of active blowing is highly dependent on the Nozzle Pressure Ratio (NPR) and the operational Mach number.

a. **Supersonic regimes (Mach 1.25 to 3.0):** Micro-jets demonstrate high efficacy in supersonic flows, capable of achieving as much as a 40% increase in base pressure.[2] At a high NPR of 11, the control consistently results in a continuous increase of base pressure across the entire supersonic range from Mach 1.25 to 3.0. This phenomenon occurs because a higher NPR reduces overexpansion, weakening the oblique shock at the nozzle exit so that the flow does not turn away, thereby leaving the vortex intact for the micro-jets to manipulate.[2] Conversely, a low NPR of 3 yields only a marginal change because it is insufficient for the nozzle to flow fully without separation, preventing the shear layer from reattaching properly.[2]

b. **High supersonic variance (Mach 2.5+):** At higher Mach numbers, the control mechanism exhibits complex behavior. For Mach numbers between 2.5 and 3.0, utilizing NPRs of 5, 7, and 9 can actually result in a decrease in base pressure compared to the uncontrolled state.[2]

c. **Sonic regimes (Mach 1.0):** At a sonic Mach number, the control effectiveness of micro-jets is only marginal across all tested area ratios and length-to-diameter (L/D) ratios.[6] This diminished effectiveness is primarily due to the presence of Mach waves and the fact that jets exiting the nozzle are already correctly expanded.[6]

The influence of duct geometry (Area Ratio and L/D)

The geometry of the sudden expansion duct significantly dictates how the base vortex interacts with the active jets.

i. **Area ratio:** As the area ratio increases, the reattachment length also increases, thereby increasing the volume of air in the base region that interacts with the base vortex, ultimately weakening the base suction.[6] Experimental data at Mach 1.0 show that the lowest area ratio assumes the lowest value of base pressure, and the maximum gain from active control occurs at the lowest area ratio of 2.56.[6]

ii. **L/D ratio:** The L/D ratio dictates whether the flow has enough physical space to attach to the duct walls. To ensure smooth flow development and attachment to the enlarged duct wall, a minimum duct length of L/D = 2 is required for lower area ratios, while an L/D = 3 is required for higher area ratios.[6]

Successes and limitations of active control

a. **Non-disruptive flow:** A major success of utilizing micro-jets is that they do not adversely influence the wall pressure distribution or disturb the main flow field in the enlarged duct.[6,2]

b. **Gradient enhancement:** The control effectiveness of the micro-jets is notably enhanced when they are employed under the influence of a favorable pressure gradient.[6]

c. **Adverse drag penalties:** The most critical limitation is that for certain combinations of parameters (e.g., specific NPRs at high Mach numbers), the control can decrease the base pressure rather than increase it, which inadvertently increases base drag.[2] Therefore, precise parametric selection is mandatory to achieve the desired drag reduction.[2]

d. **Sonic inefficiency:** The micro-jet system struggles to provide significant drag reduction in perfectly expanded sonic (Mach 1.0) conditions, proving highly inefficient compared to its supersonic applications.[6]

Discussion

Compare active vs. passive: micro-jets vs. boat-tailing, cavities, splitter plates

Before examining the specific advantages of active control, it is useful to directly contrast the performance of micro-jet blowing against representative passive devices using the data reviewed in Sections 2 and 3.

Passive solutions rely on geometric modifications to alter the shear layer and reattachment without adding mass or energy. Common examples include:

A. **Boat-tailing:** A gradual reduction in afterbody cross-section that reduces the base area and accelerates the flow, raising base pressure by 10–20% at supersonic speeds but only over a narrow Mach range.

B. **Base cavities:** A recess in the base that traps a vortex, acting as a cushion that raises base pressure. Gains are typically modest (5–15%) and sensitive to cavity depth ratio.

C. **Splitter plates:** Plates protruding downstream from the base that divide the wake, reducing large-scale vortical structures. Effectiveness is geometry-dependent and generally below 20% base pressure rise.

Active micro-jets (four 1 mm holes, PCD = 1.3d, independent secondary air supply) achieve substantially higher performance. Under optimal supersonic conditions (Mach 2.5–3.0, high NPR, area ratio 2.56), micro-jets raise base pressure by 40%[2] and up to 152% in other configurations. Even at lower Mach numbers, gains of 20–30% are routinely reported (Table 1).[6]

Table 1 Quantitative contrast

Control method	Typical base pressure increase	Adaptability	Energy required	Mechanical complexity
Boat-tail	10%–20%	None	No	Low (fabrication)
Cavity	5–15%	None	No	Low
Splitter plate	10–18%	None	No	Medium
Micro-jets (active)	40–152%	Yes	Yes (bleed air)	Medium (plumbing valves)

Key observation from the micro-jet data: Not only does active control yield far higher peak performance, but it also allows the blowing pressure to be tuned or turned off entirely when conditions become unfavorable, such as at Mach 1.0 where micro-jets are ineffective. Passive devices, once manufactured, cannot be adjusted or deactivated.

When passive may still be preferred: If the vehicle operates at a single, fixed Mach number and NPR, and if weight/complexity must be minimized, a well-designed boat-tail or cavity may be sufficient. However, for any application requiring maximum drag reduction or adaptation across varying flight conditions, the micro-jet data clearly favor active control.

Why choose active control over passive

The base region behind a blunt trailing body is characterized by a low-pressure recirculating wake that significantly contributes to overall drag, as was demonstrated in the previous sections. Although both passive and active approaches can reduce this drag, there are trade-offs in complexity, performance, and adaptability.

Passive control methods, including boat-tailing, base cavities, splitter plates, ribs, and aerospikes, modify the afterbody geometry to alter the shear layer and reattachment process. They require no external energy, have no moving parts, and are relatively simple to manufacture. However, their effectiveness is inherently bounded by the fixed geometry: a passive device optimized for one Mach number, nozzle pressure ratio (NPR), or area ratio may perform poorly when the flight condition changes. For example, a boat-tail that reduces drag at cruise Mach 2.0 may become ineffective or even detrimental at takeoff or transonic speeds. Moreover, passive devices impose permanent structural modifications that cannot be reversed or tuned.

Active control methods, specifically micro-jet blowing and base bleed, overcome these limitations by introducing mass or energy directly into the wake. As detailed in Section 3, four 1 mm micro-jets supplied from a secondary air source can raise base pressure by as much as 40% under favorable conditions.[2] More dramatically, other studies have reported up to 152% increases at Mach 2.58 with optimized micro-jet configurations. Table 2 shows that active control offers several decisive advantages:

Table 2 Advantages & disadvantages of active & passive control

Attribute	Passive	Active
Adjustability	Fixed geometry	Tunable in real time by varying blowing pressure
Performance ceiling	Moderate	High; can achieve >100% base pressure increase
Off-design robustness	Poor	Good; can be re-optimized for changing NPR/Mach
Structural impact	Permanent modification	Only small holes; base geometry unchanged
Energy requirement	None	Requires compressed air or propellant

When to choose active: For vehicles that operate over a broad range of Mach numbers and NPRs, such as tactical missiles and variable-cycle engines, or where maximal drag reduction is crucial, such as range-extended projectiles, active control is the recommended option. Additionally, it is useful when internal packing requires that the underlying geometry not change. Even though passive methods are simpler, they work best in situations where the performance advantage from active methods is not worth the additional system complexity and the flight circumstances are strictly defined.

One important discovery from the experimental work[2,6] is that active control does not negatively affect the main flow field or the wall pressure distribution, which means the drag reduction is accomplished without unexpected side effects. Nevertheless, the same studies caution that poorly selected active parameters, like low NPR at high Mach numbers, might actively enhance drag by lowering base pressure. This sensitivity highlights the need for careful parameter selection in active control, but it also means that, unlike passive devices, the system can be turned off or altered when conditions become unfavorable.

Real-world aerospace applications: feasibility and penalties

Translating the laboratory sudden-expansion apparatus (Section 2.1) to an actual supersonic vehicle demands an answer to the central engineering question: Where does the high-pressure air for the micro-jets come from, and at what cost?

Supersonic missiles with air-breathing engines

The laboratory setup uses a secondary settling chamber fed from the same high-pressure source as the main nozzle. On a missile with a turbojet, ramjet, or scramjet, the engine compressor already contains air at pressures well above ambient. Tapping a small bleed port from the compressor discharge or an intermediate stage provides a direct analog to the secondary chamber.

a) **Weight penalty:** The additional hardware consists of lightweight tubing (stainless steel or aluminum, estimated at 0.2–0.5 kg for a typical airframe), four micro-jet orifices (drilled directly into the base face), and perhaps a small pressure regulator. No separate high-pressure tank is required.

b) **Energy/thrust penalty:** Bleeding air reduces the engine's net thrust slightly. For micro-jets of 1 mm diameter operating at typical bleed pressures, the mass flow rate is less than 1% of the engine core flow, corresponding to a thrust penalty typically below 0.5%. This is negligible compared to the drag reduction benefit: a 40% increase in base pressure reduces base drag proportionally, and since base drag can constitute a major fraction of total drag,[7] the net vehicle performance improves substantially.

c) **Feasibility assessment:** High. The technology is at Technology Readiness Level (TRL) 4–5, having been validated in laboratory environments and in some sub-scale wind tunnel tests. A flight demonstration on a supersonic UAV or test missile is the logical next step.

d) *4.2.2 Artillery Projectiles (Unpowered)*

e) Projectiles have no onboard compressor. The active control analog is base bleed, which employs a gas generator (a slow-burning pyrotechnic charge) mounted inside the base. This generator produces combustion gases that are expelled through the base, effectively mimicking a continuous jet.

f) **Weight/payload penalty:** The gas generator occupies volume that would otherwise contain explosive filler. For a typical 155 mm shell, the payload reduction is approximately 18%.

g) **Performance gain:** The range extension is 20–35%, as verified in fielded systems (e.g., M864 projectile). The trade-off is widely accepted because the operational advantage of longer range outweighs the reduced explosive mass.

h) **Feasibility assessment:** Operational (TRL 9). Base bleed has been in service for decades and represents the most mature active base-flow control method.

Launch vehicles and rockets (no air-breathing engine)

Rockets carry pressurant gas (typically helium) to expel propellant from tanks. A small fraction of this pressurant could be diverted to base micro-jets.

A. **Penalty:** Helium mass is a small fraction of total vehicle mass (typically <1% of propellant mass). Diverting a few grams per second for micro-jets would marginally reduce pressurant margin, but systems are usually over-designed. No thrust penalty applies because rockets do not ingest air.

B. **Feasibility assessment:** Moderate – conceptually sound but requires flight demonstration to quantify interactions with the plume and base heating.

Active blowing is not only feasible but already operational in the form of base bleed. For engine-equipped missiles, the path to implementation is short, and the penalties are minimal. The laboratory methodology of Section 2.1 was deliberately designed to mirror real-world secondary air supplies, confirming that the transition from lab to flight is primarily an engineering integration task rather than a fundamental research barrier.

Conclusion

This study has reviewed active base-flow control at sonic and supersonic Mach numbers, focusing on micro-jet injection and base bleed within the framework of suddenly-expanded duct experiments.

i. **Micro-jet blowing** (four 1 mm jets, PCD = 1.3d, independent secondary supply) is the most effective research-proven active method. Under optimal conditions (high NPR, under-expanded flow, Mach 2.5–3.0, area ratio 2.56), it achieves up to a 40% increase in base pressure relative to the uncontrolled case, with other studies reporting even higher gains (152% at Mach 2.58). The method is most effective in supersonic regimes (Mach 1.25–3.0) and under favorable pressure gradients. It does not disturb the main flow field or wall pressure distribution. However, it is ineffective at sonic (Mach 1.0) conditions and can actually reduce base pressure if parameters (low NPR at high Mach) are poorly chosen.

ii. **Base bleed** (gas generator) is the most mature operational method. While the underlying physics is similar to micro-jet injection, base bleed has been fielded in artillery systems for decades, delivering 20–35% range extension at the cost of approximately 18% payload reduction. It is the benchmark against which other active methods should be compared.

iii. **Passive methods** (boat-tailing, cavities, splitter plates) remain useful for applications where simplicity and zero energy input are paramount, but they cannot match the peak performance or tunability of active systems (Table 3).

Table 3 Summary ranking of methods

Rank	Method	Peak base pressure increase	Maturity	Best suited for
1	Micro-jets	40–152%	TRL 4–5	Engine-equipped missiles, variable-flight-condition vehicles
2	Base bleed	20–35% range gain	TRL 9	Artillery shells, unpowered projectiles
3	Passive devices	Moderate, bounded	TRL 9	Fixed-geometry, narrow-flight-envelope applications

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Future research areas

Based on the gaps identified in the experimental methodology (Section 2.3), the limitations of active control (Section 3.4), and the broader literature, the following research directions are recommended:

a. **Three-dimensional CFD with realistic micro-jet geometries.** The overwhelming majority of numerical studies employ 2D axisymmetric grids that treat micro-jets as a continuous annular slot. In reality, four discrete jets interact with the base flow in a highly three-dimensional manner, creating streamwise vortices and local pressure variations that a 2D model cannot capture. Future work should employ 3D RANS, DES, or LES on high-performance computing clusters to resolve the true mixing physics.[7]

b. **Optimisation of micro-jet location and configuration.** All studies reported to date use the same pitch circle diameter (PCD = 1.3d) and four jets at 90° intervals. No systematic investigation has varied the radial position of the jets, the number of jets (2, 6, 8), or their azimuthal arrangement. The influence of jet diameter (0.5 mm to 2 mm) also remains largely unexplored. Given the strong parametric sensitivity shown in Section 3.4, optimization studies using design of experiments (DOE) or machine learning could yield substantial improvements.

c. **Development of a predictive analytical model.** Currently, no theoretical model exists to predict base pressure under active micro-jet control. All design relies on empirical correlations or CFD. A reduced-order model based on shear-layer momentum balance and jet entrainment would greatly accelerate preliminary design and reduce reliance on expensive experiments.

d. **Exploration of hypersonic regimes (Mach >5).** The existing literature concentrates on Mach numbers from 1.0 to 3.0. Hypersonic base flow (re-entry vehicles, hypersonic missiles, future launch stages) involves extreme temperatures, chemical reactions, and strong shock-boundary layer interactions. Whether micro-jet control remains effective or even feasible under such conditions is unknown and represents a high-reward research frontier.

e. **Flight demonstration and system integration studies.** Laboratory experiments, however well designed, cannot fully replicate the vibration, acoustic, thermal, and unsteady freestream environment of actual flight. The essential validation required to transfer active base-flow control from TRL 4–5 to TRL 6–7 would be provided by a sub-scale flight test, such as on a sounding rocket or a supersonic UAV. It is also necessary to conduct accompanying engineering research on bleed-air plumbing, controls, and lightweight valves.

f. **Hybrid active-passive systems.** No reported study has systematically combined a passive device such as a boat-tail or base cavity with active micro-jet injection. The passive element could precondition the shear layer, making the active control more effective or allowing lower blowing rates. Such hybrid configurations may offer the best compromise between performance and energy cost.

g. **Control strategies for sonic and over-expanded conditions.** Since active micro-jets are notably ineffective at Mach 1.0 and can degrade performance at low NPR, future research should explore alternative actuation, for example pulsed jets, plasma actuators or adaptive blowing schedules that turn off the jets when they would be detrimental.

In conclusion, active base-flow control, particularly through micro-jet blowing and base bleed, offers a proven and highly effective means of reducing base drag at sonic and supersonic speeds. The laboratory methodology of sudden-expanded internal flow has enabled systematic parametric studies that reveal the strong dependencies on Mach number, NPR, area ratio, and L/D. When correctly applied, micro-jets raise base pressure without disturbing the main flow, delivering substantial drag reductions that translate directly into extended range, higher speed, or increased payload.

The engineering barriers to real-world implementation are modest: for engine-equipped missiles, the air source already exists on board, and the weight penalty is negligible. For artillery, base bleed is already operational. The next decade should see a shift from laboratory characterization to flight validation, optimization, and the extension of active control to hypersonic speeds. With continued research, active base-flow control will become a standard feature in the designer's toolbox for high-speed aerospace vehicles.[8,9]

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Conflict of interest

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