PERFORMANCE OF ACTIVE AND PASSIVE CYLINDER IN CONTROLLING BASE FLOWS

BY

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ABSTRACT

Flow control for drag reduction results in substantial fuel savings, thus contributing to low-cost greener industrial processes. A major problem at transonic Mach numbers is the base drag. This study focuses on the control of base drag by controlling the base pressure. Till date, there are either passive or active control methods for all flow regimes resulting in ineffective control. The present work is an attempt to control the base pressure by passive as well as active means. The Mach numbers considered are for the subsonic, sonic, transonic, and supersonic regimes. Experiments were conducted for the nozzle pressure ratio (NPR) in the range from 2 to 10. The geometric parameters considered were the L/W ratio and area ratios. The base pressure (P_b) and the flow development along the duct wall was measured. Flow visualization was performed for all the cases of the present study. To assess the influence of the control mechanism on base pressure as well as the flow development in the enlarged duct a stationary or rotating cylinder of 2 mm diameter located at various positions from separation to the reattachment point inside the recirculation zone was employed. The investigation on base flows indicates that the base pressure is dependent on the length-to-width ratio, the level of expansion, Mach number, and the location as well as the orientation of the static and rotating cylinder as the control mechanism in the recirculation zone. For subsonic, sonic, transonic and low supersonic Mach numbers, the active, as well as the passive controls, increase the base pressure, thus decreasing the base drag but at higher supersonic flow say Mach 2, the control results in a decrease of base pressure for most of the cases of the present study. L/W = 4 seems to be the minimum length needed for the flow to remain attached with the enlarged duct. The results of different Mach number regimes have been validated with the published data from the National Aeronautics and Space Administration (NASA) and Sandia National Laboratories wind tunnels. While working in sudden expansion, it is mandatory to ensure that the control mechanism does not disturb the main flow field in the duct and it did remain same for with and without control cases. The results reported in this thesis are in an uncertainty band of ± 2.3%.

خلاصة البحث

ملخص البحث يؤدي التحكم في التدفق لتقليل السحب إلى وفورات كبيرة في الوقود ، وبالتالي المساهمة في عمليات صناعية صديقة للبيئة منخفضة التكلفة. وهناك مشكلة رئيسية في أرقام ماخ فوق الصوتية هي السحب الأساسي. تركز هذه الدراسة على التحكم في السحب الأساسي بالتحكم في ضغط القاعدة. حتى الان ، هناك إما أساليب تحكم سلبي أو نشط لجميع أنظمة التدفق مما يؤدي إلى عدم فعالية التحكم. العمل الحالي هو محاولة للسيطرة على ضغط القاعدة عن طريق وسائل في الاعتبار هي للأنظمة دون سرعة (MACH NUMBERS)سلبية وكذلك نشطة. أرقام الماخ الصوت ، الصوتية ، الصوتية ، والأسرع من الصوت. الأنظمة. أجريت تجارب على نسبة ضغط ونسبة (L / W) في النطاق من 2 إلى 10. وكانت المعلمات الهندسية تعتبر نسبة (NPR) الفوهة وتطور التدفق على طول جدار القناة.تم إجراء تصوير التدفق (P_b) المنطقة.تم قياس ضغط القاعدة لجميع حالات الدراسة الحالية. لتقييم تأثير آلية التحكم على ضغط القاعدة بالإضافة إلى تطور التدفق في القناة المتضخمة ، تم استخدام أسطوانة ثابتة أو دوارة قطرها 2 مم تقع في مواقع مختلفة من الفصل إلى نقطة إعادة التعيين داخل منطقة إعادة التدوير. يشير التحقيق في التدفقات الأساسية إلى ، ومستوى التوسيع ، ورقم المات ، والموقع بالإضافة (L / W) أن ضغط القاعدة يتأثر بشدة بن إلى اتجاه الأسطوانة الثابتة والدوارة كآلية التحكم في منطقة إعادة التدوير. لأرقام ماخ دون سرعة الصوت ، الصوتية والمترونية والأصغر من الصوت ، فإن الضوابط النشطة ، وكذلك الضوابط ، يؤدي التحكم MACH 2) السلبية ، تؤدي إلى زيادة كبيرة في ضغط القاعدة ، ومع ذلك ، في هو الحد (L / W = 4) إلى انخفاض ضغط (الأساس لمعظم حالات الدراسة الحالية. يبدو أن الأدنى للطول اللازم للتدفق ليظل مرتبطًا بالقناة المتضخمة. وقد تم التحقق من صحة نتائج أنظمة (NASA) عدد ماخ مختلفة مع البيانات المنشورة من الإدارة الوطنية للملاحة الجوية والفضاء ناسا وأنفاق الرياح في مختبرات سانديا الوطنية. أثناء العمل في مجال التوسع المفاجئ ، يلزم التأكد من أن آلية التحكم لا تزعج مجال التدفق في المجرى.النتائج الواردة في هذه الرسالة هي في نطاق عدم اليقين من %(± 2.3).

APPROVAL PAGE

The thesis of Mohammed Asadullah Thakur has been approved by the following:

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Mohammed Asadullah Thakur

Signature .... Date ....

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THIS THESIS IS DEDICATED TO

MY MOTHER, FATHER, WIFE AND CHILDREN

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May Allah shower his blessing on all of you.

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LIST OF ABBREVIATIONS

AC	Active Control
BL	Boundary Layer
CCD	Charged Coupled Device
CCW	Counter Clockwise
CCWAC	Counter Clockwise Active Control
CFM	Cubic Feet per Minute
CW	Clockwise
CWAC	Clockwise Active Control
DAQ	Data Acquisition
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LES	Large-Eddy Simulation
MATLAB	Matrix Laboratory
MM	Millimeter
MSBC	Moving Surface Boundary-Layer Control
NPR	Nozzle Pressure Ratio
NASA	National Aeronautics and Space Administration
PC	Passive Control
PCV	Pressure Control Valve
R.A.L.	Reattachment Length
R.A.Point	Reattachment Point

LIST OF SYMBOLS

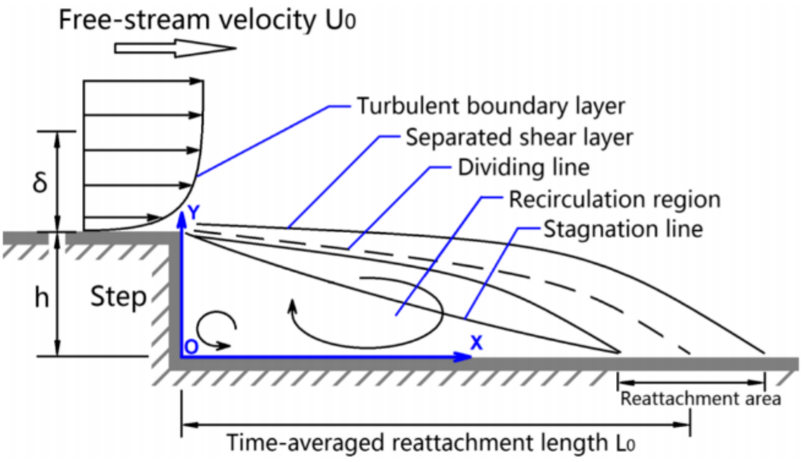
A_1	Nozzle exit area (m^2)
A_2	Cross-sectional area of the square duct (m^2)
A_2/A_1	Area ratio (-)
l_d	Diverging length of the nozzle (m)
l_c	Converging length of the nozzle (m)
L	Duct length (m)
L/W	Length to width ratio (-)
M	Nozzle exit Mach number (-)
P_a	Atmospheric pressure (Pascal)
P_b	Base Pressure (Pascal)
P_w	Wall Pressure (Pascal)
P_0	Stagnation pressure in settling chamber (Pascal)
P_e	Pressure at nozzle exit (Pascal)
Up_a	Uncertainty in atmospheric pressure (%)
Up_b	Uncertainty in base pressure (%)
Up_0	Uncertainty in settling chamber pressure (%)
W	Duct width (m)
W	Nozzle exit width (m)
Γ	Specific heat ratio (-)
Θ_c	Nozzle Converging angle (°)
Θ_d	Nozzle Divergence angle (°)

CHAPTER ONE

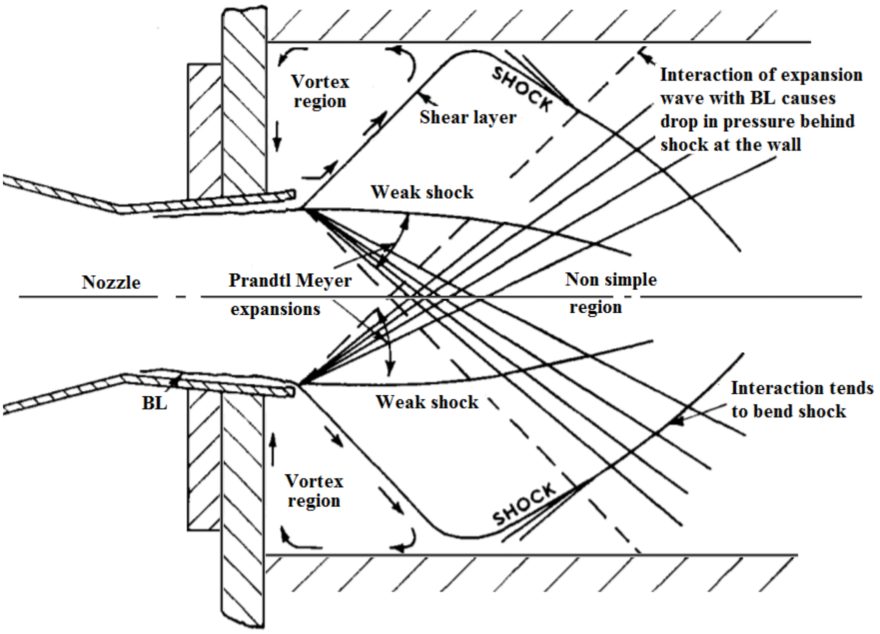
INTRODUCTION

1.1 CONTROL OF FLOWS

The major augmentation to the drag created by the bluff body, a sudden expansion or an abrupt change in cross-section is due to depression on its base, inside the recirculation zone. Reducing base drag holds great importance in many engineering applications but as of now, the knowledge of physics behind the base drag mechanism is still far from satisfactory (Mariotti, Buresti, & Salvetti, 2015). They also concluded that redevelopment after reattachment creates more complication and short recirculation length leads to high base drag. Flow field after a sudden enlargement is a phenomenon marked by complexities such as separation of flow, recirculation vortex, reattachment, boundary layer type as well as the mutual dependency between inviscid and viscous forces (Chang, 2014). Chandrsuda and Bradshaw (1981) related boundary-layer thickness after separation to the step height which characterized the downstream flow. But according to a review of Eaton and Johnston (1981), the use of hot-wire turbulence data and measurement for reattaching flows lacked reliability. So the complexity due to the boundary layer type, recirculation, separation, reattachment, redevelopment after reattachment and interaction between viscous - inviscid flow, at different Reynold numbers, (Ghoniem & Sethian, 1987) and Mach number (Briley, Taylor, & Whitfield, 2003) has been somewhat studied but the control of such flows is not easy. Thus, we can categorise base flow study into two groups, one on basic anatomy of the flow field and the other on control of base flows using various techniques (Viswanath, 1996);(Van Leeuwen, 2009);(Martín-Alcántara, Sanmiguel-Rojas, Gutiérrez-Montes, & Martínez-Bazán, 2014);(Evrard et al., 2016);(Jackson, Wang, & Gursul, 2017). Figure 1(a) shows the mixing flow and recirculation region of the flow past a backward facing step and Figure 1(b) shows the mixed flow in the region of sudden enlargement under the influence of Prandtl-Meyer expansion fans and shock waves.



(a) Incompressible Flow (Ma & Schröder, 2017)



(b) Compressible Flow (Martin & Baker, 1963)

Figure 1.1 Mixing Flow and Recirculation Region

The control of base pressure on a blunt base is a very important field of study in subsonic to transonic (Vikramaditya & Viji, 2019) and supersonic regimes (Forsythe, Hoffmann, Cummings, & Squires, 2002) and finds application in many areas. One of the application is high-altitude rocket nozzles testing at low cost (Rose, Jinu, & Brindha, 2015) but the problem of separation and its prediction is found not to be accurate although is well reviewed by Stark (2013) and numerically investigated by (Nasuti, Onofri, & Martelli, 2007);(Allamaprabhu, Raghunandan, & Morinigo, 2011). The use of a supersonic parallel diffuser by aerospike nozzles is another application of base flow problem (Takahashi, Tomioka, Tomita, & Sakuranaka, 2014). Nozzle exhaust diffusers in rocket test cells used to simulate high altitude conditions is an interesting application. This condition also exists in the exhaust port where hot exhaust gases pass out of valve in an internal combustion engine (Anderson & Williams, 1968). Another example is the flow around the bluff base of a projectile in flight where the flow expansion is inward rather than outward (Wong, 2006). Also, the sudden expansion dump combustor configuration for integral rocket-ramjet is an excellent example (Yang & Yu, 1983). Continued interest in this area is provided by the problem of spacecraft re-entry into the atmosphere with adaptive control to improve performance (Dydek, Annaswamy, & Lavretsky, 2010). Yet another example is the reduction of base drag in launch vehicles investigated under NASA (Naughton, 2002). A detailed analysis of flow through sudden enlargement in the pipe was studied by Teyssandiert and Wilson (1974). For a airfoil with a blunt trailing edge that would have a structural and aerodynamic merits at transonic and supersonic Mach numbers as compared with a sharp trailing edge of conventional airfoil was reviewed in detail by Tanner (1975). So, we can see that the flow separation and recirculation after an abrupt change in cross-section is not only from very low Reynolds number to very high Reynolds number but happens from subsonic to hypersonic flow regimes too. There are many applications but the focus of this work will be mainly on subsonic, transonic and supersonic flows. In missiles, the drag is as high as 50 % of the total drag in no jet condition (Viswanath, 1996).

Out of the few applications stated above, let us take the example of a rocket nozzle base pressure field. The base pressure for a rocket nozzle is reduced due to expansion fans sitting at the edge of the base due to the sudden increase in the area. At the lip of the nozzle, the flow will separate. Thus, the hot gases coming out of the nozzle tend to fill this area. This is undesirable since the high temperature of the gases is continuously felt at the base area. During the jet-on conditions, the base drag will be zero and will be very high for jet-off conditions for rockets and missiles. It is proposed to utilize the use of static and dynamic cylinders to control the base drag. This cylinder when stationary acts in a passive mode and when rotating it acts in an active mode. Depending on different arrangements of location and orientation of cylinder, we intend to control the flow pattern inside the recirculation zone at the base.

1.2 PROBLEM STATEMENT AND SIGNIFICANCE

The sudden expansion is unavoidable. It is a very natural phenomenon but may lead to disastrous consequences. It is observed in a volcanic eruption (Ishihara, 1985), cloud bursting (Baker, Pierorazio, Woodward, & Tang, 2011), flood mitigation dams (Shahmirzadi & Sumi, 2013), atmospheric storms such as hurricanes (Elsner & Kara, 1999), separation in blood flow (Hammad, 2015)and so on and so forth. We cannot avoid it because it happens in most of the engineering application such as pipes, channels, automobiles, aircraft, ballistic missiles, rockets, and spacecraft reentry vehicles & that too in different flow regimes and flow conditions. The existing system can be made more effective and efficient by reducing the drag and hence reduce the energy requirements.

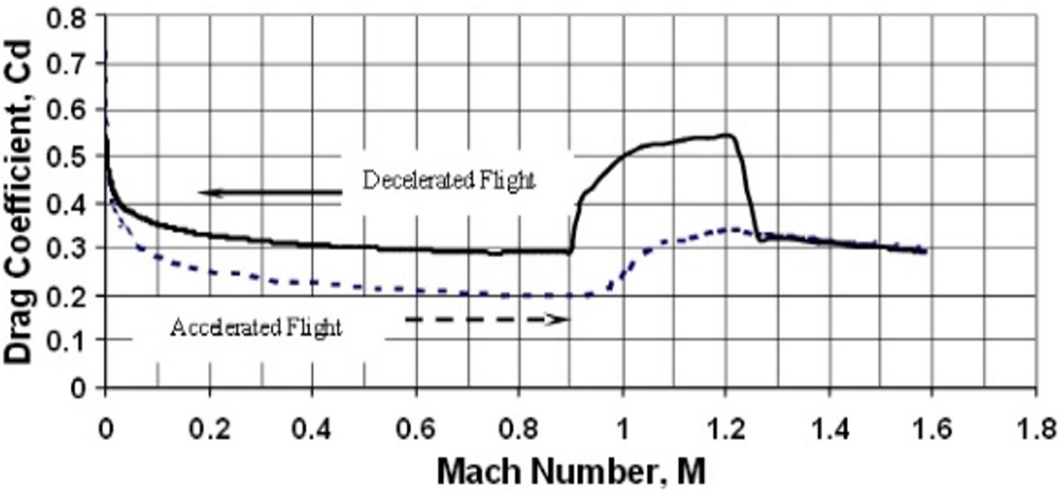


Figure 1.2 Transonic Pressure Drag Coefficient (Priyono, 1994)

As seen from the literature review that in high-speed aerodynamics like in rocket nozzle, the base pressure for rocket nozzle is reduced due to sudden expansion. Thus, resulting separation of flow at the lip of the nozzle and creating a depression behind the vehicle and increasing overall aerodynamic drag. While the motor is firing, the base drag is minimal but at burn out there is a sharp jump in base drag and amounts to 2/3 of the total aerodynamic drag as shown in Figure 1.2.

1.3 RESEARCH OBJECTIVES

The main objective of this work is to manipulate base pressure in order to reduce base drag by using a control cylinder. The specific objectives are:

1. To develop a new and comprehensive technique to control the base flow field in subsonic, transonic, and supersonic regime.
2. To study the physics of the flow when a control cylinder manipulates pressure inside the base region behind abrupt expansion as a result of variation in location, orientation, nozzle pressure ratio, length-to-width ratio, and area ratio for the subsonic, transonic, and supersonic regime.
3. To determine the effect of the cylinder as a passive control device on the flow pattern and the base flow field in subsonic, transonic and supersonic regime.

4. To ascertain the effect of the cylinder as an active control device on the flow pattern and the base flow field in subsonic, transonic and supersonic regime.

1.4 RESEARCH PHILOSOPHY

Designing a simple but effective mechanism to reduce base drag inside a recirculation turbulent zone, knowing the fact that by manipulating flow pattern around the body the drag and lift are being affected (Kumar, Cantu, & Gonzalez, 2011), as the flow separates at the base of high-speed vehicles such as rockets, missiles, and projectiles, it forms a low-pressure recirculation zone lower than the free stream atmospheric pressure. Aerodynamic vehicles fly in different flow regimes such as subsonic, transonic, supersonic (Nagata, Nonomura, Takahashi, Mizuno, & Fukuda, 2016) and hypersonic (Sziroczak & Smith, 2016). To enhance the flow pattern inside the recirculation zone we introduced the cylinder in such a way that its stagnation point can be controlled. The cylinder can act as either a passive control or active control (rotating) depending on the regime and condition the vehicle is experiencing. The results encourage researchers on how to control the base pressure based on demand and supply i.e. when to implement energy-saving passive control or effective dynamic control. We utilized a simple but effective technique which is a combination of passive and active methods to control the base drag.

1.5 RESEARCH SCOPE AND LIMITATIONS

Presently active or passive technique is used to control the base flows behind high-speed vehicles. These high-speed vehicles such as rocket travel at different levels of expansion from highly over-expanded flow at the sea level to a highly under-expanded flow in the outer space. Thus, by using either active or passive control for all the level of expansion, efficiency and effectiveness is not only reduced but leads to a lot of waste of energy. Thus, in line with the problems outlined previously, the new controller based on the