# INVESTIGATION OF BASE AND WALL PRESSURE IN SUDDENLY EXPANDED FLOW THROUGH DUCTS USING RIBS AS PASSIVE FLOW CONTROL

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**by**

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# LIST OF SYMBOLS

| | |
|---|---|
| Re | Reynolds number |
| M | Mach number |
| $C_p$ | Pressure co-efficient |
| $C_f$ | Skin friction co-efficient |
| $P_b$ | Base pressure |
| $P_w$ | Wall pressure |
| $P_a$ | Ambient/ atmospheric pressure |
| $P_e$ | Exit pressure |
| $P_{01}$ | Stagnation pressure |
| $P_{02}$ | Duct exit pressure |
| L/D | Length-to-Diameter ratio of the duct |
| CD | Convergent-Divergent/ de Laval nozzle |
| P | Pressure (Static) |
| $\rho$ | Density (Static) |
| T | Temperature (Static) |

| | |
|---|---|
| $P_0$ | Pressure (Stagnation) |
| $\rho_o$ | Density (Stagnation) |
| $T_0$ | Temperature (Stagnation) |
| $\gamma$ | Specific heat ratio |
| $\dot{m}$ | Mass flow rate |
| A | Area |
| v | Flow velocity |
| $A_t$ | Throat area |
| l | Nozzle length |
| D | Nozzle diameter |
| h | Rib height |
| H | Duct height |
| L | Duct length |
| x | X-axis direction |
| x/H | Pressure tapping position along the length of the duct |
| V | Voltage |
| $V_{supply}$ | Supply voltage |

| | |
|---|---|
| $V_{out}$ | Output voltage |
| GND | Ground |
| $P_{max}$ | Maximum pressure |
| $P_{min}$ | Minimum pressure |
| $P_{applied}$ | Applied pressure |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| NPR | Nozzle Pressure Ratio/ Stagnation Pressure Ratio |
| SFC | Specific Fuel Consumption |
| BFS | Backward Facing Step |
| DAQ | Data Acquisition System |
| DC | Direct Current |
| SAR | Successive Approximation Register |
| ADC | Analog-to-Digital Converter |
| BNC | Bayonet Neill–Concelman Connector |
| DNS | Direct Numerical Simulation |
| CFD | Computational Fluid Dynamics |

**KAJIAN TEKANAN PADA TAPAK DAN DINDING DI DALAM SALURAN DENGAN PENGEMBANGAN ALIRAN DRASTIK MENGGUNAKAN TETULANG SEBAGAI PENGAWAL ALIRAN**

## ABSTRAK

Pengembangan aliran secara drastik memainkan peranan penting di dalam pelbagai aplikasi di bidang automobil, keretapi, pesawat udara, peluru berpandu dan kenderaan angkasa. Seretan asas adalah masalah lazim yang mengurangkan prestasi didalam aplikasi-aplikasi seperti yang disebutkan diatas dan menjadi penyumbang yang ketara terhadap daya seretan jumlah. Tekanan asas yang wujud didalam aliran di belakang jasad adalah punca penghasilan daya seretan asas yang merupakan sebahagian daripada data seretan keseluruhan. Terdapat situasi dimana tekanan asas dinaikkan untuk menurunkan daya seretan asas. Terdapat juga situasi dimana tekanan asas diturunkan supaya pencampuran bahan api yang lebih baik untuk proses pembakaran dapat dicapai. Jadi adalah penting untuk mengawal tekanan asas berdasarkan kehendak aplikasi. Kajian ini membentangkan analisis mengenai tekanan asas aliran supersonik yang berkembang secara drastik di dalam saluran segiempat tepat. Tekanan asas diubah dengan meletakkan rusuk dengan ketinggian yang berbeza di tempat-tempat yang tertentu disepanjang saluran. Pada permulaan, tekanan asas didapati menurun dengan penambahan nisbah tekanan pada nozel (NPR) didalam aliran pengembangan terlampau manakala tekanan asas meningkat didalam aliran pengembangan terkurang. Taburan tekanan pada dinding menunjukkan bacaan turun-naik manakala tekanan asas meningkat dengan kehadiran rusuk.

Rusuk dengan ketinggian 10% dari ketinggian saluran diletakkan tidak jauh dari bukaan keluar nozel di dalam aliran pengembangan terkurang menghasilkan

taburan tekanan asas yang mencukupi terhadap dinding sepanjang saluran tanpa sebarang turun-naik yang tidak wajar. Pada kenderaan berhalaju tinggi seperti roket dan peluru berpandu, kehadiran daya seretan asas menyebabkan pengurangan kecekapan prestasi. Masalah ini menuntut pengawalan jet yang dapat membantu meningkatkan karakter prestasi kenderaan tersebut. Didalam ruang pembakaran, peningkatan gelora setempat akibat pengembangan mendadak bendalir menyumbang kepada pencampuran bahan api yang tidak sempurna, sekaligus menaikkan kadar penggunaan bahan api spesifik dan kos operasi. Kajian ini mencadangkan cara yang munasabah untu mengatasi masalah tersebut dalam keadaan sebenar dengan perubahan terhadap konfigurasi dan kos yang minima.

**INVESTIGATION OF BASE AND WALL PRESSURE IN SUDDENLY EXPANDED FLOW THROUGH DUCTS USING RIBS AS PASSIVE FLOW CONTROL**

## ABSTRACT

Suddenly expanded flows play a vital role in many important applications in the fields of automobiles, trains, aircraft, rockets, missiles and space vehicles. Base drag is a common problem that hinders the performance in the above-mentioned applications, and contributes significantly to the total drag. The base pressure which exists in flows over a body at the rear is responsible for base drag which is a considerable proportion of the total drag. There are situations where the base pressure has to be increased to reduce base drag and decreased to achieve better fuel mixing in combustion processes. It becomes necessary then to control the base pressure depending upon the application. An analysis of the control of base pressure in suddenly expanded supersonic flows in a rectangular duct is presented. The base pressure is altered by placing ribs of different heights at specific locations along the length of the duct. Ribs of 3 different heights namely 10%, 16% and 23% of the duct height have been used. Each rib was in turn placed at 0.283H, 1.75H and 2.75H along the length of the duct. The setup was tested in Mach numbers of 1.00, 1.36, 1.64 and 2.01 individually. The interaction of secondary vortices due to the presence of ribs placed at different locations and varied heights with the primary vortex at the nozzle exit, is the main factor altering the base pressure either increase or decrease. It is observed that the base pressure decreases initially with increase of nozzle pressure ratio (NPR) in overexpanded flows and exhibits an increase in underexpanded flows. The distribution of wall pressure exhibits fluctuations with base pressure increase in the presence of ribs. These observations

have been supported by quantitative data as percentage increases above the base values. The corresponding effect on the wall pressure distribution due to placing of ribs of different heights and locations in the duct have also been quantified. With the placement of ribs, increases in base pressure as high as 57% for rib height (h/H) of 0.23 and wall pressure fluctuations up to 30% for the same height were observed. A rib height of about 10% of the duct height placed not far from the nozzle exit in underexpanded flows yields sufficiently high values in base pressure without undue fluctuations in wall pressure distribution along the duct. In high-speed vehicles such as rockets and missiles, the existence of base drag leads to reduction in performance efficiency. This problem also calls for controlling of jets which can assist in improving the performance characteristics of these vehicles. In combustion chambers, an increased level of local turbulence due to sudden expansion of the fluid leads to improper fuel mixing conditions thereby, increasing specific fuel consumption (SFC) and higher operational costs. Commercial data acquisition system has been used in the present study while the design of a cost-effective DAQ accommodating more channels has been included. The present work suggests feasible methods of overcoming problems in realistic situations with minimal changes in configuration and costing.

# CHAPTER 1

# INTRODUCTION

This Introductory chapter explains the phenomenon of sudden expansion followed by detailing the different aspects of flow over a backward facing step and its equivalence to that of a suddenly expanded flow in a duct. A discussion on the occurrence of base drag under various conditions; both subsonic and supersonic is also included. The research objectives and research questions have been highlighted at the end of chapter 1.

## 1.1 A brief idea of the problem

Suddenly expanded flows play a vital role in many important applications in the fields of automobiles, trains, aircraft, rockets, missiles and space vehicles. Base drag is a common problem that hinders the performance in the above-mentioned applications, and constitutes to about 30% of the total drag (Sethuraman and Khan 2016). Controlling of base pressure leads to reduction in base drag, which is needed in terms of operational as well as performance efficiency.

Fundamental challenges limiting the performance of automotive, aircraft and space applications can be attributed to the pressure at the external base region of the vehicles characterized by sudden expansion of the flow. Flow separation close to the base could cause a region of low-speed recirculation. Lower than atmospheric pressure exists in the base region. The total drag in the transonic region is attributable up to 50 – 60% of the base drag due to pressure differences. In supersonic region, similar