Journal of Mechanical and Aeronautical Engineering Research
[ISSN 2456 8368]
Volume 2 - Issue 2; December 2019; PP 63 - 69
jmaer.wingsofaero.in

Coarse Wall Influence on Supersonic Diffuser – A Computational Analysis

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Abstract

The supersonic diffuser is a device which is used to reduce the velocity of incoming mass flow of air and increase its pressure. A reduction in velocity is required for the air mass to attain the required residence time in the combustion chamber to achieve complete combustion. The primary objective of this paper is to study the effect of coarse wall (protruded extensions) as performance augmenting technique in the supersonic diffuser for diffuser design optimization purpose. The behaviour of flow domain is examined computationally for three different design configurations by varying the protrusion location. Associated drag of each configuration is also simultaneously analysed to obtain an optimal design output. Techniques to improve the performance of supersonic diffuser are studied and new approach methodology is analysed for enhancing the performance with minimum pressure loss. Performance analysis on diffuser geometry and the effect of the coarse wall on compression are analysed using computational tools. Two-dimensional computational flow simulations are performed using ANSYS Fluent software for visualization of effects caused under actual flight conditions.

Keywords: Supersonic Diffuser, Coarse Wall, Computational Fluid Dynamics, Diffuser Efficiency.

1. Introduction

The supersonic diffuser is a device which is designed to reduce the velocity and increase the pressure of the incoming fluid moving in supersonic velocity. There are generally three different types of supersonic compression i.e. external compression, internal compression and a combination of internal and external compression [1]. Diffusers are one of the primary component of a propulsive device, in supersonic flow conditions diffusers also act as a compressor [2]. As the flow is supersonic in nature it is associated with shock waves, which are generated due to the presence of external objects i.e. the aircraft. The strength of the shock wave is determined by the geometry and flow conditions in the diffuser based on which the flow behaviour changes downstream the diffuser. The efficiency of a diffuser is determined based on how efficiently it is able to fulfil its design requirements i.e. reducing the velocity and increasing the pressure with minimal drag.

Diffusers play a vital role in all air breathing propulsive systems, particularly for ramjet and scramjet in which entire compression process is achieved by the diffuser. In gas turbine engines rotatory devices are used to achieve the desired compression, these compressors are inefficient at high Mach numbers due to mechanical and aerodynamic limitations. A diffuser should possess these characteristics (a) minimum drag (external drag), and (b) high pressure recovery (i.e. highest diffuser efficiency). Being an essential part of engine cycle the diffuser efficiency directly influences the engine performance [2].

The primary concern of this research work is to study the possibility of a passive performance-enhancing technique and computationally analysing the technique using computational tools to assess the effectiveness of such a technique in the operational environment. A simplified diffuser design is considered to observe the effect of coarse wall in the diffuser. Different configurations of the diffuser design are considered which were obtained by altering the location of the coarse wall (series of small uniform protrusions). Mach number, and static pressure variation, are analysed to obtain an optimum design output. Drag of different configurations is also estimated, to fulfil the minimum drag criterion of the diffuser. Extensive efforts are made to obtain a passive optimization approach. The research is extensively focused on enhancing the supersonic performance of the diffusers associated with high speed supersonic vehicles (ramjet and scramjet). An optimized design configuration is achieved from the research work, which may be implemented in future designs.

2. Design Requirements

From designers point of view it is better to have numerous weak shock waves in the diffuser with same pressure recovery, than to have a single strong shock wave as a strong shock wave significantly increases the total drag which affects the performance even though the pressure recovery is high across a normal shock. Strong shocks not only causes high drag but also pose a high risk to the structural integrity of the diffuser. As the forces exerted by a normal shock wave is comparatively greater, a highly intact structure is required which in turn increases the weight of the diffuser and thus decreasing the efficiency of the diffuser [3]. A diffuser design is considered to be highly efficient if it has high static pressure, reduced exit velocity, and low drag.

New approach should minimize complexities, yet providing optimum results in terms of velocity reduction and maximized pressure recovery within existing operational limits. Active diffuser performance optimization techniques such as active ramp deflection (adjusting the ramp angle according to the flight conditions)[4] and translation of centre-body (spike) in axisymmetric duct, the spike retraction technique used in Lockheed SR-71 Blackbird's Pratt & Whitney J58 engine [5], increases the complexity of design and functioning, also increasing the cost of manufacturing and operation. A passive diffuser performance enhancement technique can reduce the manufacturing and operational cost at the same time reducing the complexity of design. In applicable cases passive techniques can be used alongside active techniques.

3. Diffuser Performance Parameters

There are three basic characteristics which determine the performance of a diffuser, they define the standards by which the efficiency and usefulness of a diffuser may be assessed.

- Total Pressure Recovery
- Capture Area Ratio
- Total Drag

Total pressure recovery is the magnitude and quality of the pressure recovery, the capture area ratio is also termed as mass flow ratio. The total drag caused by the diffuser geometry also accounts for the performance estimation. Based on the overview obtained from the literature study it is observed that trade – off is involved in each phase of design, as a gain in one performance parameter is often achieved at the expense of the other one. The off – design operation capability can also be considered such as the effect of angle of attack, over-speed, under-speed which should not deteriorate the performance [6].

4. Methodology

Different methodologies are currently employed to increase pressure recovery (Ram effect) at various attitudes and flight regimes [3] such as Variable geometry intake, Bleed of boundary layer [7] [8], Perforation in diffuser walls, Diffuser Length variation, Vortex generators [9].

After considering various optimization techniques to enhance the working efficiency of the diffuser, a need for new research was identified in this field. Analysing the flow patterns, basic aerodynamics suggests that a coarse wall reduces the velocity of the flow to a greater extent than a smooth surface. The reduction in velocity is achieved by increasing the turbulence and increase in drag of the flow. The effect of such coarse wall structure in supersonic flight conditions appeared to be an interesting topic to conduct research upon, as reducing velocity being one of the major objective of a diffuser, an increase in efficiency may be obtained if this technique is proven to be implementable.

4.1. Proposed Methodology

A new methodology is proposed in this research i.e. to use a coarsened wall surface as an optimizing technique through which a reduction in flow velocity is observed in supersonic flow regime. The location of the coarse wall is altered to obtain various configurations so that an optimum location can be identified which produces effective flow velocity reduction with higher pressure recovery and lesser drag. The following configurations are designed in a custom manner to visualize the effect of coarse wall. The configurations which are analysed in this research are

1. Coarsened inner surface of spike
2. Coarsened interior cowl
3. Coarsened interior regions of cowl and spike

A simple supersonic diffuser configuration is used as the ideal configuration which is used for comparisons of performance parameters.

5. Computational Analysis

Interaction of supersonic flow with a coarsened surface generates shock waves, which is an interesting phenomenon to study. Preliminary analysis has proven the effectiveness of such technique in supersonic diffusers and provided a strong motivation to proceed with the research. A comparative analysis of the computational results fetches insight to implement-ability of such technique in reality. Realistic boundary conditions are considered for computational purposes to understand the effect of such technique in flying conditions.

5.1. Computational Setup

The computational setup specified in Table 1 is common to all the simulations which are carried out further. The parameters if altered are mentioned in required regions. The SST k – omega model is chosen to consider the effect of turbulence caused. The boundary conditions are obtained assuming that flight conditions at 10 kilo-meter altitude, the pressure and temperature is assumed accordingly. A solution steering is used to attain the supersonic effects essential for computation. The analysis is done in 2D thus neglecting effect in the third dimension. Table 1 depicts the computational setup.

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Table 1. Computational setup (ANSYS Fluent)

GENERAL	
Solver Type	Density -Based
Velocity Formulation	Absolute
Time	Steady
2D Space	Planar
Time	Steady
Flow Type	Supersonic
MODELS	
Model	Viscous – SST (k –omega)
MATERIALS	
Medium Material	Air
Density	Ideal -Gas
BOUNDARY CONDITIONS	
Inlet	Pressure Far Field
Inlet Mach Number	3
Inlet Pressure	26500 Pascal
Inlet Temperature	226 Kelvin
SOLUTION METHODS	
Formulation	Implicit
Flux Type	Roe - FDS

5.2. Geometric Attributes

A simple design is considered to observe the effect of protrusions, neglecting flow deflection owing to the geometry. Figure 1 shows the domain with names of each section marked in the form of annotations along with the dimensional attributes of the design. The dimension of the protrusion is provided in figure 2. A close view of coarse wall (the protrusion) is illustrated in figure 3.

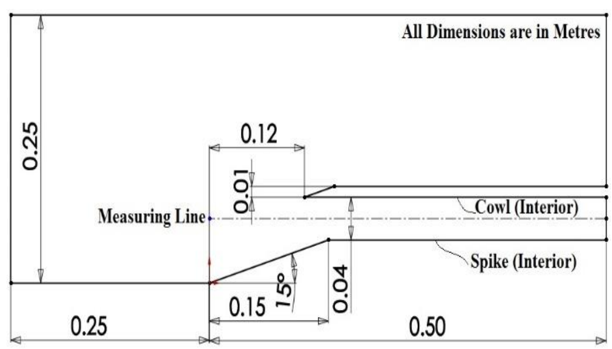

Figure 1. Dimensions and features of the design

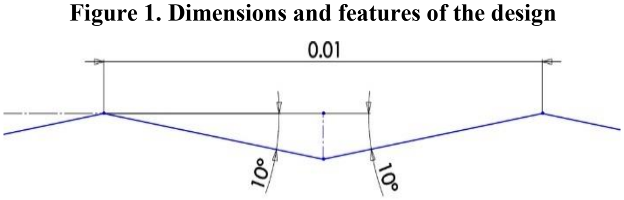

Figure 2. Dimensions of protrusion (Coarsening effect)

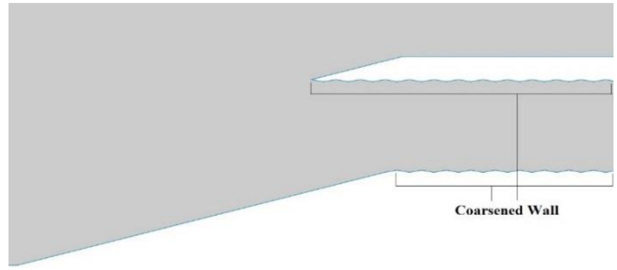

Figure 3. Close view of coarsened surface

5.3. Dimensional and Meshing Attributes

The dimensions mentioned in table 2 are common to all design configurations. A uniform mesh is fixed to obtain a constant element size of one millimetre which resulted in more than 160000 elements for each configuration. The relevance centre is set to fine for attaining a fine mesh in order to get optimum results. Table 2 shows the mesh characteristics.

Table 2. Mesh characteristics

Length (X - axis)	0.75 m
Breadth (Y - axis)	0.25 m
Size Function	Uniform
Relevance Centre	Fine
Element Size	1.e-003 m

5.4. Simple Supersonic Diffuser

The simple supersonic diffuser configuration is used for comparing the effect of coarse wall with normal smooth wall configuration. By setting the element size to one millimetre a total of 162183 elements were obtained with about 163463 nodes after meshing the flow domain. An extended interior portion is taken as reference for better visualization of effect. A simple diffuser design reduces the complexity thus simplifying the analysis. All the required parameters are measured along the measuring line for obtaining an unbiased measurement. Figure 4 shows the meshed domain, figure 5 & 6 shows the mach contour and static pressure contour of simple supersonic diffuser.

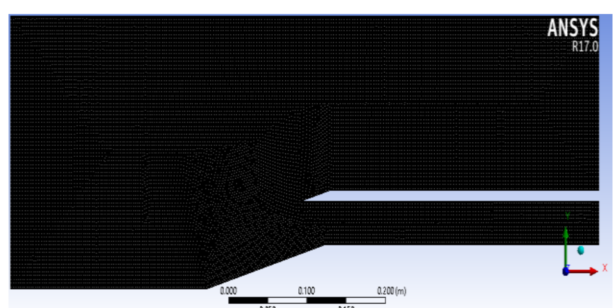

Figure 4. Simple supersonic diffuser geometry meshed

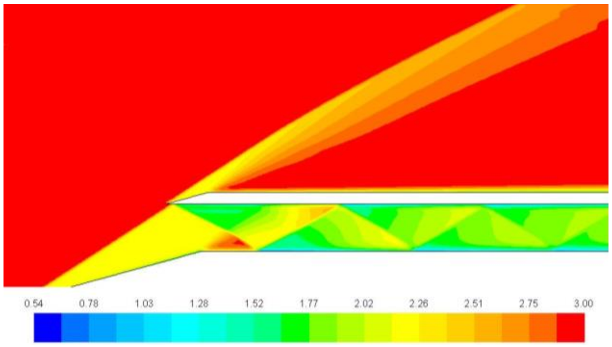

Figure 5. Simple supersonic diffuser Mach contour

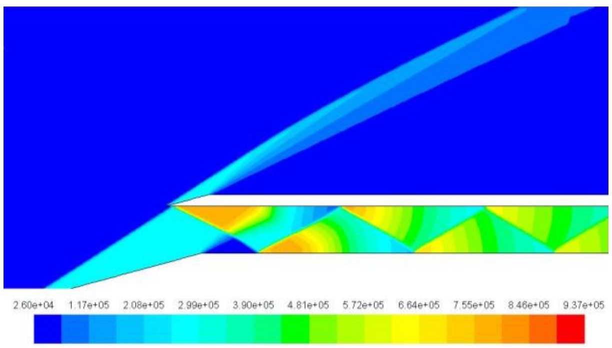

Figure 6. Simple supersonic diffuser static pressure contour

6. Analysis of New Design Configurations

6.1. Coarsened inner surface of spike

The first configuration is obtained by coarsening the inner surface of the spike. The effect of having a diffuser with coarsened inner spike is seen in the velocity and static pressure contours. By setting the element size as one millimetre a total of 162604 elements were obtained with about 163873 nodes after meshing the flow domain. This configuration has the same diffuser design as the simple diffuser with added coarsening effect which is used to compare the results with greater accuracy. Figure 7 shows the meshed domain, figure 8 & 9 shows the mach contour and static pressure contour of coarsened inner surface of spike design configuration.

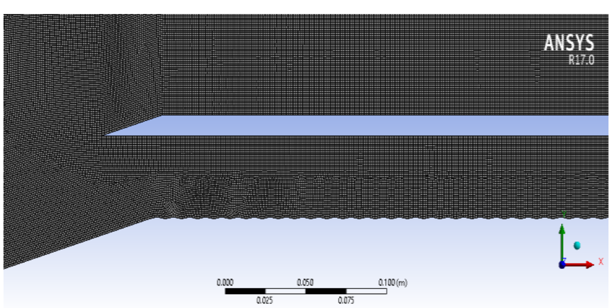

Figure 7. Coarsened inner surface of spike geometry meshed

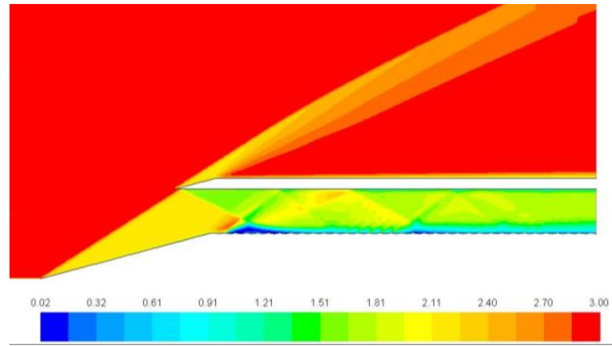

Figure 8. Coarsened inner surface of spike Mach contour

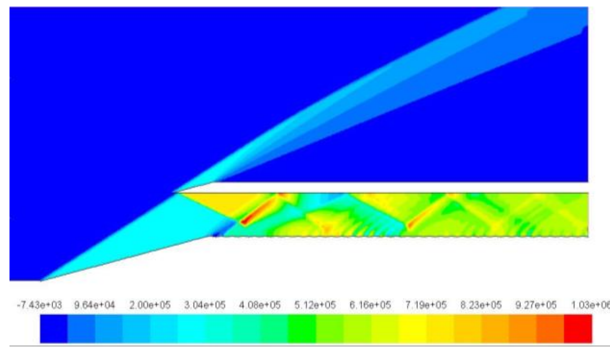

Figure 9. Coarsened inner surface of spike static pressure contour

6.2. Coarsened interior cowl

The second configuration is obtained by coarsening the interior region of cowl. By setting the element size to be one millimetre a total of 162376 elements were obtained with about 163644 nodes after meshing the flow domain. The effect of having a diffuser with coarsened interior cowl is seen in the velocity and static pressure contours. Figure 10 shows the meshed domain, figure 11 shows the mach contour and figure 12 shows the static pressure contour of coarsened inner surface of spike design configuration. The coarsening effect utilizes uniform pattern of the protruded extensions similar to that of the other configurations. Variations can be clearly traced from the contour yet a comparative analysis provides better observation of the variations.

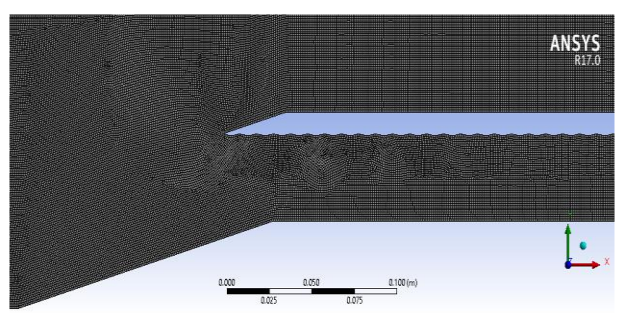

Figure 10. Coarsened interior cowl geometry meshed

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[ISSN 2456 8368]
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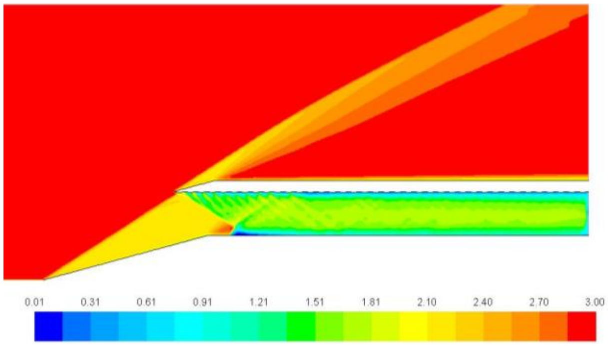

Figure 11. Coarsened interior cowl Mach contour

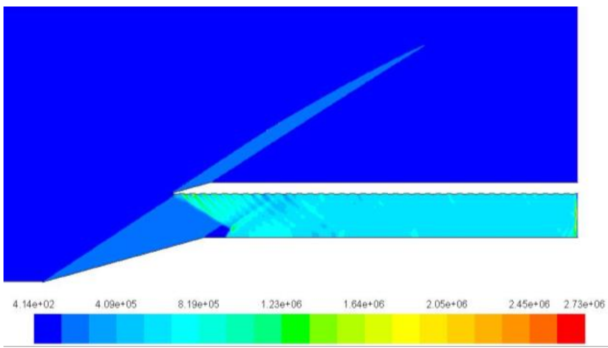

Figure 12. Coarsened interior cowl static pressure contour

6.3. Coarsened interior regions of cowl and spike

This configuration is a combination of the above configurations, the interior regions of the spike and cowl are coarsened. By setting the element size to be one millimetre a total of 165685 elements were obtained with about 166884 nodes after meshing the flow domain which is shown in figure 13. The variations caused due to the coarsening effect in the interior regions of cowl and spike is clearly seen in figure 14 and figure 15. Adding up coarsened regions may add up to drag, which reduces the efficiency. As discussed in the "diffuser performance parameter" section of this paper, gain in one performance parameter is often achieved at the cost of the other. The design of supersonic diffuser requires extensive level of expertise, considering various potential factors.

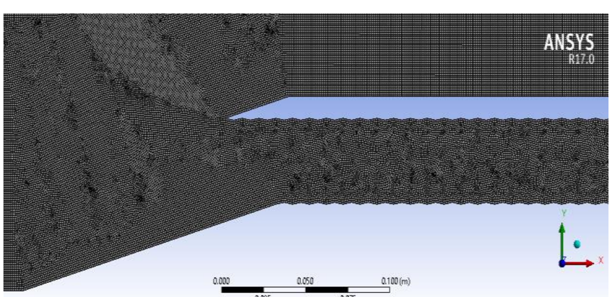

Figure 13. Coarsened interior regions of cowl and spike geometry meshed

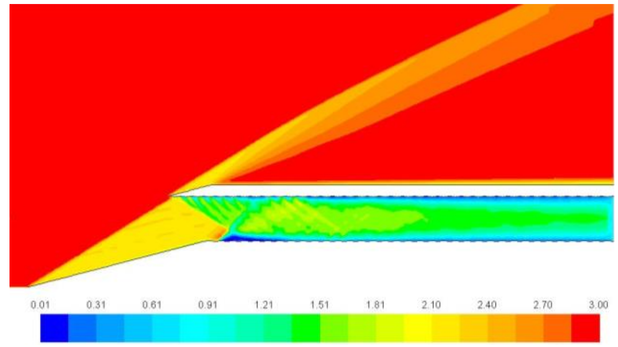

Figure 14. Coarsened interior regions of cowl and spike Mach contour

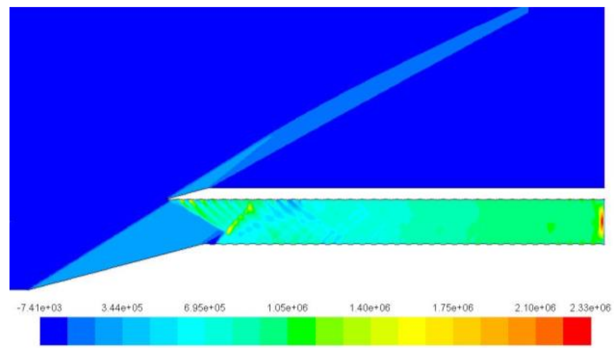

Figure 15. Coarsened interior regions of cowl and spike static pressure contour

7. Discussion of Results

7.1. Drag Estimate

A comparative analysis on the drag component is also required for obtaining an optimum result. Few other configurations such as coarsened exterior spike and completely coarsened diffuser configurations were also studied for performance optimization, but were neglected after preliminary analysis due to excessive drag despite of their higher efficiency owing to velocity and static pressure increase. Table 3 shows the drag estimated for various configurations.

Table 3. Drag estimate

S No	CONFIGURATION	DRAG (N)	Normalized Percentage
1	Simple supersonic diffuser	14327.89	0 (Ideal)
2	Coarsened inner surface of spike	16036.13	11.92
3	Coarsened interior regions of cowl and spike	18727.19	30.7
4	Coarsened interior cowl	18754.26	30.89

7.2. Normalized Percentage Calculation

Normalized Percentage is calculated by the following expression.

$$\frac{\textit{Drag of new configuration} - \textit{Drag of simple diffuser}}{\textit{Drag of simple diffuser}} \text{ X } 100$$

7.3. Comparative Analysis of Mach number and Static Pressure

A comparative analysis is required to understand the variation in parameters, comparisons are made among the velocity contours, static pressure contours, and the drag estimate. The parameters are non-dimensionalized to simplify the comparison. The x-axis is non-dimensionalized by axial length of diffuser (L). The static pressure at each location (P_x) is normalized by ambient pressure (P_a) and plotted along y – axis.

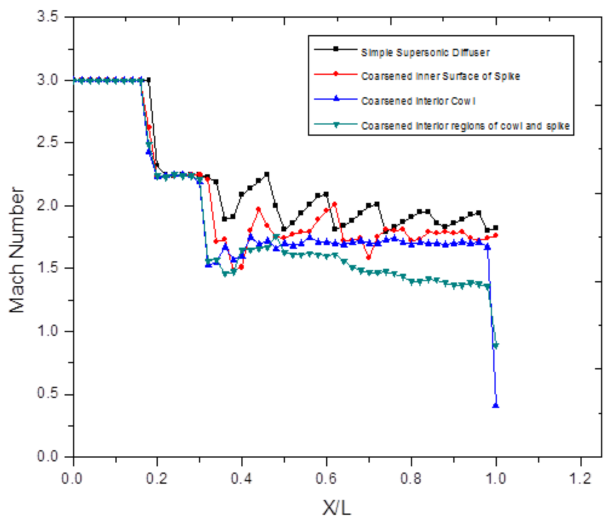

Figure 16. Plot of comparative analysis of mach contours

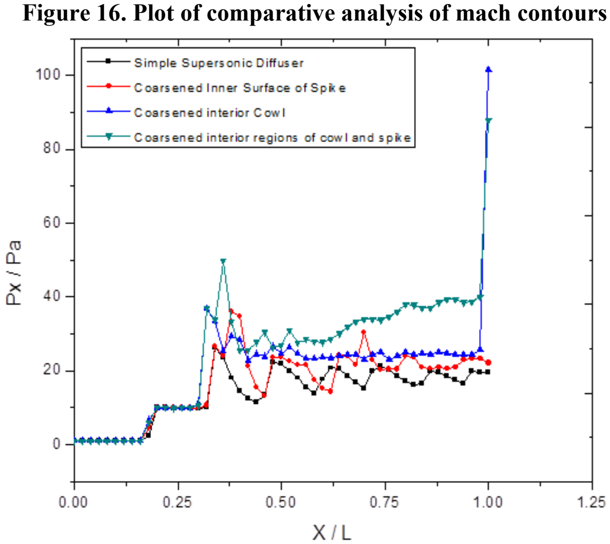

Figure 17. Plot of comparative analysis of static pressure contour

Figure 16 and 17 shows the comparisons of the Mach number and static pressure contour of all the configurations, this helps the designer to select an optimum configuration based on the requirements and operating conditions. Figure 18 shows a comparative analysis of the drag estimate along with the normalised percentage of drag resulted in each configuration. Optimum configuration is that which has optimum performance in all three parameters.

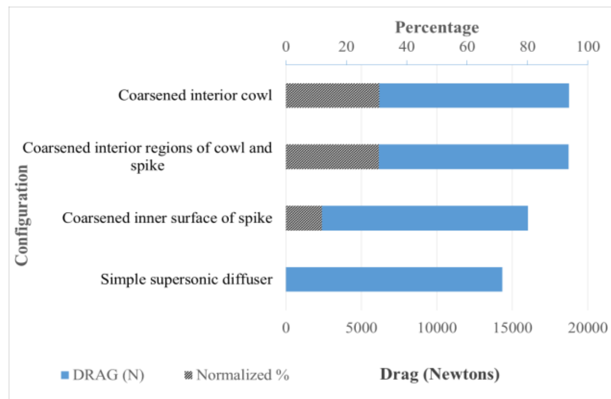

Figure 18. Plot of comparative analysis of drag

7.4. Trade off Analysis

Trade off analysis may be done on the basis of comparison plots of velocity (Figure 16), static pressure (Figure 17), and drag (Figure 18). A ranking of 1 to 4 is provided based on the comparative analysis, where a ranking of 1 indicates a highly efficient configuration and a ranking of 4 shows less efficient configuration (Table 4).

Table 4. Configuration evaluation

RANK-ING	VELOCITY	STATIC PRESSURE	DRAG
1	Coarsened interior regions of cowl and spike	Coarsened interior regions of cowl and spike	Simple supersonic diffuser
2	Coarsened interior cowl	Coarsened interior cowl	Coarsened inner surface of spike
3	Coarsened inner surface of spike	Coarsened inner surface of spike	Coarsened interior regions of cowl and spike
4	Simple supersonic diffuser	Simple supersonic diffuser	Coarsened interior cowl

8. Conclusions

The two dimensional results obtained in the form of contours and plots have shown promising results in terms of velocity reduction and static pressure increase, which are the major deciding parameters in the field of diffuser performance estimation and assessment. Selection of suitable configuration is purely dependant on the designer, suitable configuration is to be selected after thorough analysis of the design requirements, and operational conditions based on which a decision may be made for design implementation accordingly.

Coarsened walls (protrusions) have been computationally proven to reduce the velocity of incoming flow, thus resulting in efficient diffusion. Of the three configurations compared in this paper the “Coarsened interior regions of cowl and spike” has hierarchal ranking of ‘1’ in velocity reduction, ‘1’ in static pressure increase and ‘3’ in drag based on the “Configuration Evaluation” done in Table 4, it results in approximately 30% drag increase compared to the “Simple supersonic diffuser” configuration, thus this configuration provides an optimized output.

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