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Wave Drag Analysis in Cascade Fins in Supersonic Regime

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Abstract — **The endeavor to improve the aerodynamic efficiency of supersonic flying bodies has been constant and significant ever since. Notably it has a significant contribution towards the growth of Aerospace industry. The rigorous experiments carried out on aerodynamic efficiency have led to the optimization of flying body design involving structural, aerodynamic or chemical performance parameters. Aerodynamic efficiency is the basis of energy-efficient flying model, and low drag is the basis of aerodynamic efficiency. The relative impact of drag depends upon the flight regime and specific design requirements. Hence, in the search of improving the aerodynamic efficiency and reducing the undesirable flight properties, specifically in supersonic regime, a channelised study has been carried out, as also being carried out many researchers across the world through different processes. Since shock waves create a considerable amount of drag, which can result in extreme drag on the supersonic body, it forms a significant area of study while aiming at improving the aerodynamic efficiency of a supersonic flying object. Hence, this paper deals with the reduction of wave drag by adopting cascade fin, which is a kind of fin that is still evolving in the aerospace environment. A cascade is a control surface which is composed of an external frame supporting an internal cascade of planar surfaces having small chord length. Various properties of cascade fin impact the aerodynamic efficiency individually and also in consonance with other properties. However specific properties of angle of attack and leading edge shape of cascade fin have been considered in this paper to evaluate their effect in reducing the wave drag of a supersonic flying object. This paper deals with these properties of cascade fin individually in isolation, in order to study and understand their impact in detail. The study on wave drag reduction by varying the angle of attack of cascade fins, in supersonic flow regime, has been carried out by adopting computational fluid dynamics simulation, performed for a Mach number of 2 and angle of attack of 0^0 and 5^0. The study on wave drag reduction by varying the leading edges of cascade fins, in supersonic flow regime, has been carried out by adopting computational fluid dynamics simulation, performed for a Mach number of 2 and angle of attack of 0^0.**

The study of varied leading edges considered have displayed significant variation of wave drag, but in practical application, a particular leading edge needs to be chosen as part of the larger scheme of aerodynamic designing process.

Index Terms— ***Cascade fin, Leading edge, Supersonic, Wave drag***
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I. INTRODUCTION

Grid fins or lattice fins, are unconventional flight control surfaces used on airborne objects, in place of more conventional control surfaces such as planar fins. Unlike planar fins, grid fins are aligned perpendicular to the flow field to forming a truss structure, which allows the lattice walls to be extremely thin, reducing the weight and cost. These grid fins could be stowed, along with the body of a missile, without increasing the overall dimensions. The internal grid provides webbing structure for a tail fin, yielding a high strength to weight ratio compared to a planar fin. Due to small chord, lower hinge moment and higher control effectiveness are possible with grid fins which further leads to the necessity of small and light actuators. Grid fins does not stall in the conventional sense and does not demonstrate a sharp break in its loading properties even up to total flow angles of 45^0 to 50^0. The main drawback of lattice fin is high drag and therefore not so high aerodynamic efficiency (C_L/C_D).

Cascade fin is an advanced control surface, which reduces drag by removal of the cross members. It consists of planar members placed parallel to each other, supported by root and an optional tip end plate. Thus, deriving the advantages of grid fins of delayed stall and low hinge moments, and at the same time reducing drag. Some basic parameters effecting the cascade fins aerodynamics are gap to chord ratio, number of planar members, tip end plate presence, cross sectional shape and thickness.

The cascade fins till now has been studied mainly in subsonic regime and not much analysis have been done under supersonic regime. Drag is an important parameter of cascade fins which requires further extensive study [1].

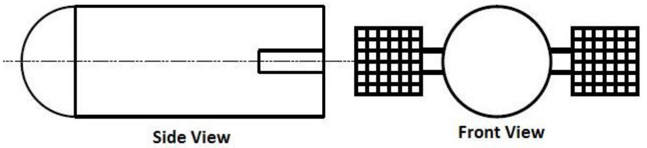

Figure 1 - Missile having grid fins with cross and horizontal members [1]

II. CFD ANALYSIS

Numerical analysis, not only places reduced strain on resources but also provides a essential in depth technical precursor analysis of an experimentation process in a new branch of study. Modern CFD methods can be used for computing flows past complex grid fin type configurations, and that these methods can bring improved predictions over the earlier vortex lattice and/or shock expansion methods [2].

Grid Independence Study

Grid Independence study is an important part of CFD analysis and the same was carried out in each part of benchmark validation and the study of wave drag variation with the variation of aerodynamic parameters of cascade fins.

III. GEOMETRY SELECTION

Geometry selection forms the initial and critical part of CFD analysis. The cascade fins under consideration comprises of flat plates and the variation in aerodynamic parameters of inherent flat plates will alter the aerodynamic characteristics of the cascade fins. In order to have an in depth analysis, alteration of two basic parameters of angle of attack and leading edge of the fins have been considered. The basic geometry of the cascade fin is as under.

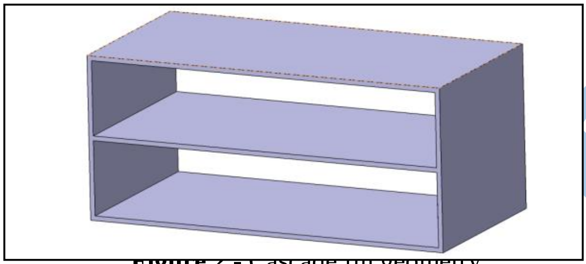

Figure 2 - Cascade fin geometry

Span (b) = 200mm; Gap (g) = 50mm; Chord (c) = 100mm; Thickness (th) = 2.5mm; U∞= 40m/s;
α = angle of attack varying from 00 to 530 (can be altered);
Pressure = 101325 Pa; Temperature = 288K;
Freestream Turbulence Intensity = 0.08%;
Freestream turbulence scale = 0.1778;
Mach number = 0.1176; Reynolds Number = 30800;
ρ = 1.225kg/m3

IV. VALIDATION OF CFD MODEL

The benchmark test process is the process of numerical analysis performed on a case which is replica of the real time testing or previous results of numerical simulations. While performing the benchmark testing, the results of the test was further compared with other available results.

For current benchmarking process, the pre validated results of cascade fins at subsonic speeds has been done, as no major work on cascade fins at supersonic speed is available in public domain. Further the validation of CFD model at supersonic speed has been done by pre-validated results of flat plate at supersonic conditions. The results of previous experiments are compared with the results of the numerical simulations using advanced solvers like Fluent.

A. *Subsonic Validation*

Subsonic validation is done on a similar cascade fin configuration under subsonic conditions in order to validate that performing an analysis in CFD, provides a similar and aerodynamically same output as that of experimental results. Subsonic benchmarking was done with data established in [3] vide the experiments as part of “Numerical study of subsonic flow over a cascade of three plates”. As the effect of altering leading edge of cascade fins is to be studied, the geometry and flow conditions, as considered in the above experiment are replicated. Comparision of experimental results and CFD analysis showed that they match within limits.

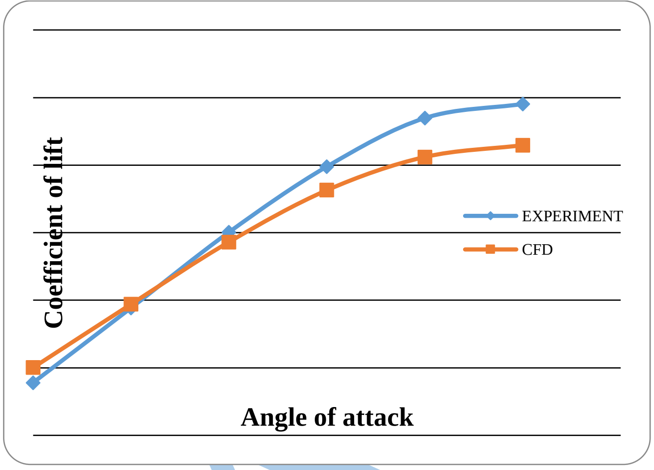

Figure 3 - Comparison of Coefficient of lift

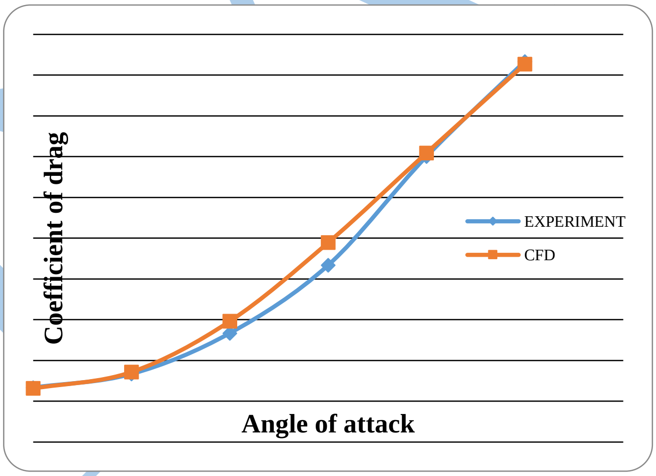

Figure 4 - Comparison of Coefficient of drag

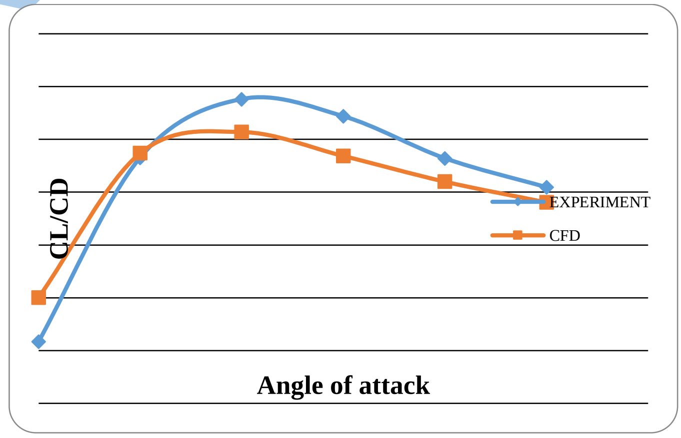

Figure 5 - Comparison of Coefficient of C_L/C_D

B. *Supersonic Validation*

Supersonic validation was done with a flat plate configuration under supersonic conditions. This was done in order to validate that performing an analysis in CFD, provides a similar and aerodynamically same output as that of experimental results, under supersonic conditions too.

This benchmark validation was carried out with the flat plate analysis data obtained while analyzing turbulent flow over a Flat Plate at 4.5 Mach [4]. The previously obtained experimental results of study of boundary layer and skin friction of a flat plate in a supersonic flow has been validated by NASA by simulation and this simulation result is validated by ANSYS for this study.

The domain and mesh as considered by NASA has been followed as such in order to validate the supersonic benchmark .The grid consisted of 46 points in the streamwise (x-) direction and 81 points in the transverse (y-) direction [4].

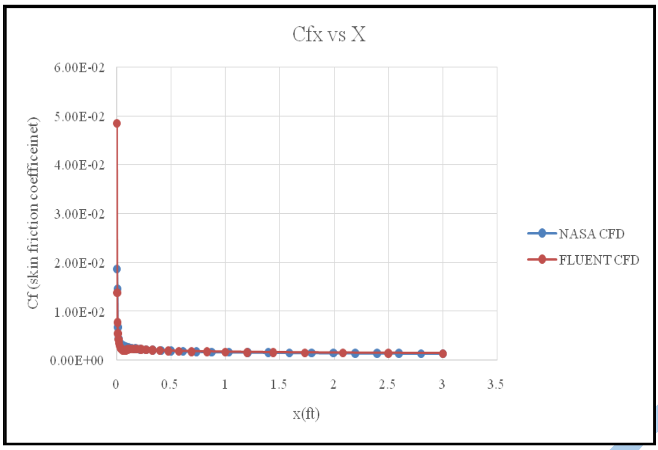

Figure 6 – Comparison of Skin friction coefficient

The supersonic results as studied in the CFD analysis was in correlation with the experimental results obtained.

V. VARIATION OF AERODYNAMIC PARAMETERS OF CASCADE FINS

A. *Variation of Angle of Attack*

The study of wave drag reduction with the variation of an important aerodynamic parameter of the angle of attack forms an essential study of the subject.

The study of supersonic flow at M=2 over the cascade fin plate has been studied for 0^0 and 5^0 angles of attack and the flow visualization using velocity and pressure contours have been carried out for increase in angle of attack cases.

At high mach numbers of supersonic flow, the flow in the surrounding area of fins adjusts through expanded and shock waves. From the images it can be found that the magnitude of pressure changes are evident at supersonic speeds due to expansion and shock waves.

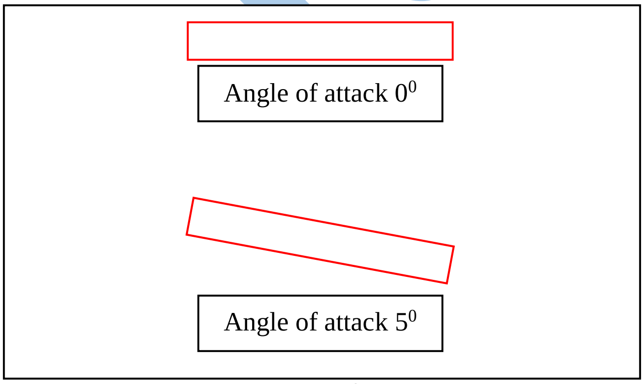

Figure 7 – Angle of attack variation

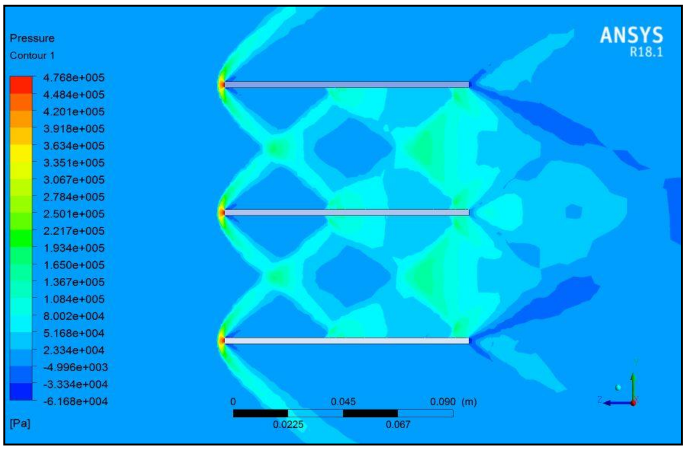

Figure 8 – Pressure contour at symmetry plane : 0^0

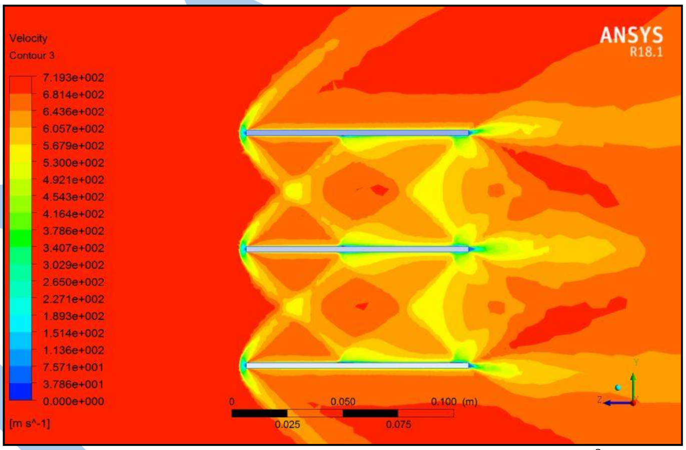

Figure 9 – Velocity contour at symmetry plane : 0^0

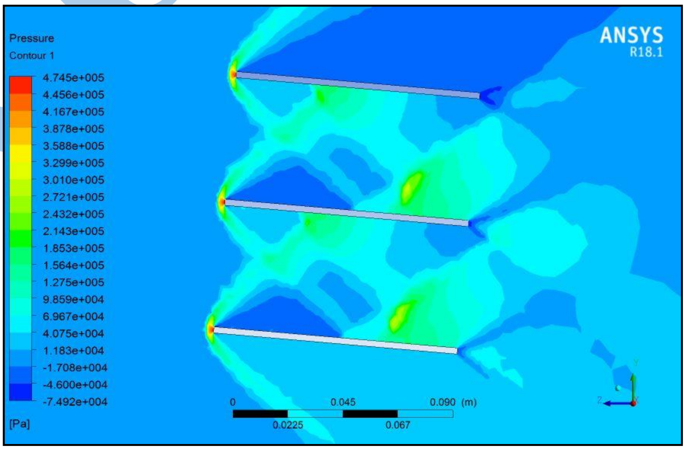

Figure 10 – Pressure contour at symmetry plane : 5^0

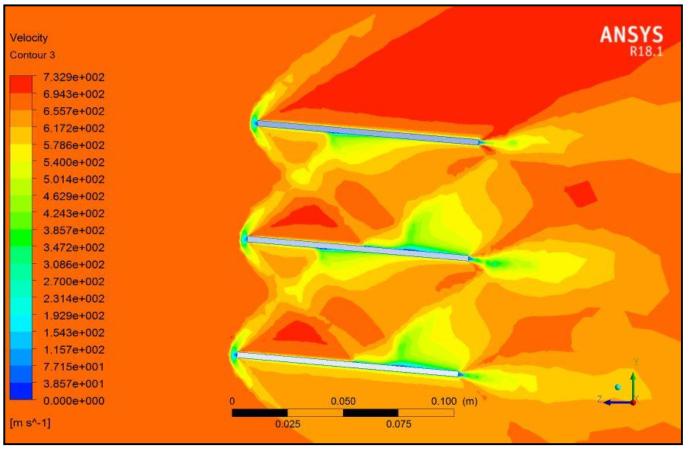

Figure 11 – Velocity contour at symmetry plane : 5^0

B. *Variation of Shape of Leading Edge of Cascade Fins*

The prominent shape variation of leading edges of flat plates in general are the blunt (semi circular or ogive) and sharp (at various angles) leading edges. The same were adopted in the project analysis, initially with semi circular and sharp leading edges. Wave drag is associated with a structure at supersonic relative velocity and it varies significantly with the change in structure of the flying object. In this paper, as mentioned above, the effect of altering the leading edge of the cascade fins is to be studied and it is expected that the wave drag associated with the cascade fins with different leading edges to be different. The coefficient of drag with different leading edges was studied and compared, in order to arrive at the conclusion of optimum leading edge of cascade fin which offers the minimum wave drag under supersonic conditions.

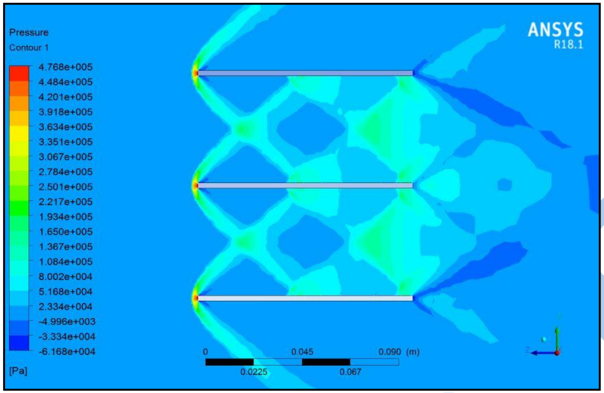

Figure 12 – Pressure contour at symmetry plane : Flat leading edge

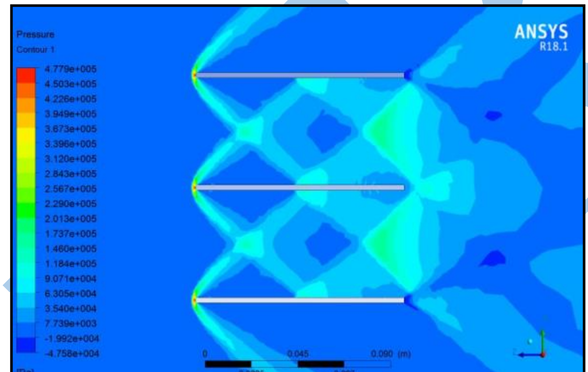

Figure 13 – Pressure contour at symmetry plane : Semi-circular leading edge

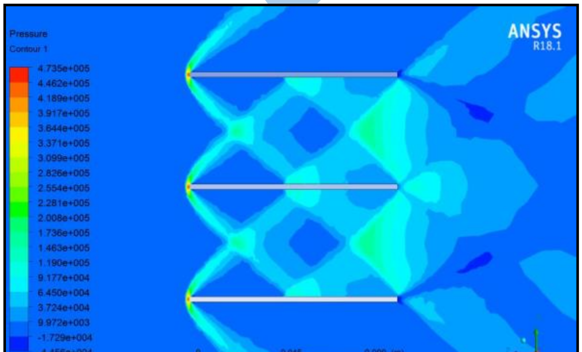

Figure 14 – Pressure contour at symmetry plane : Sharp leading edge

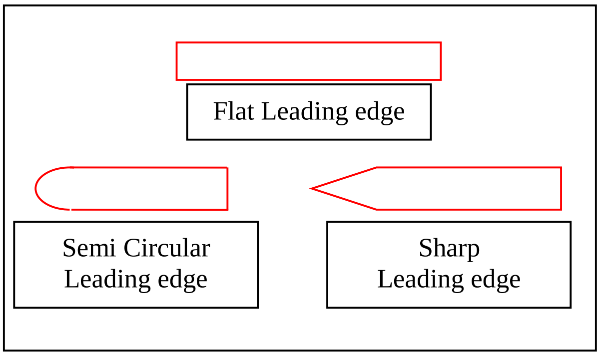

Figure 15 – Leading edge shapes

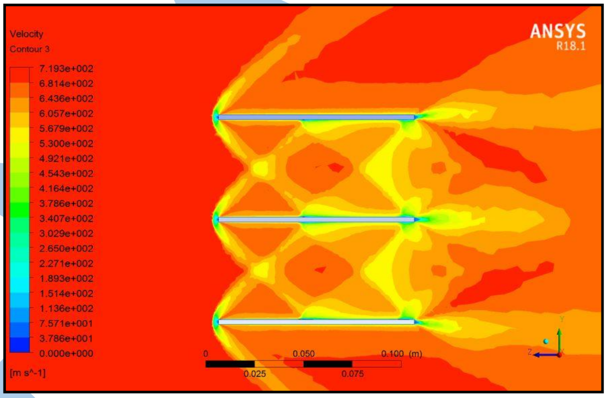

Figure 16 – Velocity contour at symmetry plane : Flat leading edge

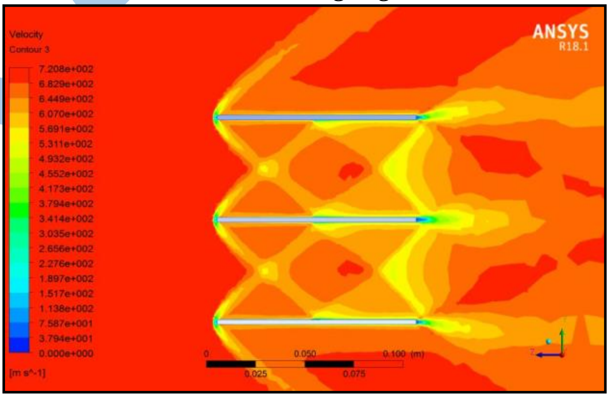

Figure 17 – Velocity contour at symmetry plane : Semi-circular leading edge

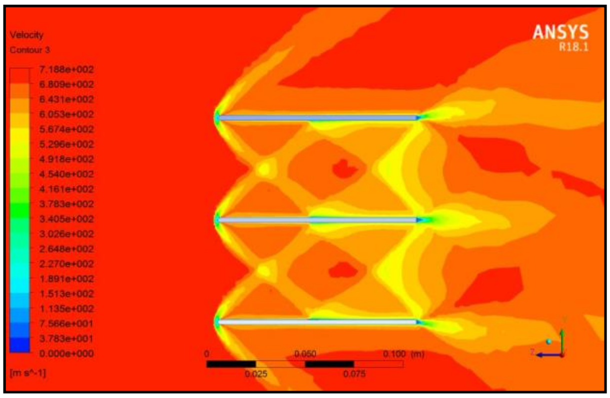

Figure 18 – Velocity contour at symmetry plane : Sharp leading edge

VI. CONCLUSION

The major phenomena observed during the study are shock wave-shock wave interaction, shock wave-boundary layer interaction and diamond shock wave formation.

A. Variation of Angle of Attack

Cascade fins display lesser wave drag at 0^0 angle of attack and the wave drag tend to maginally increase while the angle of attack is increased to 5^0. From the study conducted, the wave drag is anticipated to increase with further increase of angle of attack.

B. Variation of Shape of Leading edge

The flat leading edge of cascade fins displayed maximum wave drag amongst the leading edges considered. The sharp leading edge was expected to display lesser wave drag than semi circular leading edge, however the angle of 45^0 sharp leading edge displayed higher wave drag. From the analysis, it is expected that the wave drag may be lesser by increasing the sharpness i,e., reducing the angle of the sharp leading edge.

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