Numerical Simulation of Shockwave/Boundary-Layer Interaction for Different Mach Numbers

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Abstract

This paper focuses on studying various sonic viscous flows in which the interaction of the shock wave and boundary layer dominates over the compression ramp corner. The interaction of the shockwave with the boundary layer is studied numerically by solving the Navier-Stokes system of equations for an unsteady flow using Mach numbers 1.5, 3.0, 7.0, and 10.30. The flow is modelled using the finite volume method with linear tetrahedral elements. Results include pressure coefficient and Mach number profiles. Dimensionless coefficient of pressure is calculated using a computational method and compared with experimentally obtained pressures for upstream and downstream surfaces for ramp angle 30°. The construction of a numerical grid, taking into account, the effect of pressure jumps associated with shock waves on the boundary layer has been discussed. Comparison with the experimental data for the coefficient of pressure depicts that the turbulence model is appropriate for the calculation of total pressure.

Keywords - Hypersonic, Supersonic, Boundary layer, Shockwave, Finite Volume Method

Abbreviations-

M	Mach number
SW	Shock wave
BL	Boundary Layer
M_∞	Freestream Mach number
Rex	Local Reynolds number
FVM	Finite Volume Method
SWBLI	Shockwave boundary layer interaction
P	Pressure
S	Source
u	Velocity in the x-direction
Cp	Coefficient of Pressure
t	Time

Greek letters-

τ	Shear stress
μ	Dynamic viscosity
ρ	Density
ϕ	Flux
Γ	Diffusion coefficient

1. INTRODUCTION

A shock front is a compression wave in supersonic flows that affects the flow properties across upstream and downstream locations. Typically, shock is a region where immense pressure, temperature, and momentum gradients occur.

The presence of any obstacle in the supersonic flow-field creates oblique shock, strength of which is dependent upon the local Mach number and the ramp angle. The oblique shock that appears to be in contact with the fore-front of the bow is called as attached bow-shock, and beyond the maximum deflection angle, the separated shock waves bend and locate themselves at a short distance away from the body.

The boundary layer (BL) is a thin region adjacent to the solid surface, where the viscous effects are under dominance. At the solid boundary, the fluid in contact assumes the velocity of the solid boundary. This is typically known as no-slip condition in the literature. The boundary layer develops in the region adjacent to the solid surface, in which the velocity gradients do exist. The velocity gradients are present due to the viscous nature of the fluid. A boundary layer may be laminar or turbulent in nature, which is strictly governed by the local Reynolds number. In supersonic flows, the boundary layers generated are turbulent in nature, exhibiting high dissipation.

In laminar flows the boundary laminar flow occurs when the flowing fluid comes into contact with a layer of solid material. The boundary layer is created by the interaction of the fluid and a solid surface. The BL can detach from the surface even if the pressure is too high or the surface is curved. Even if the Reynolds number is high, the boundary layer can separate off from the surface.

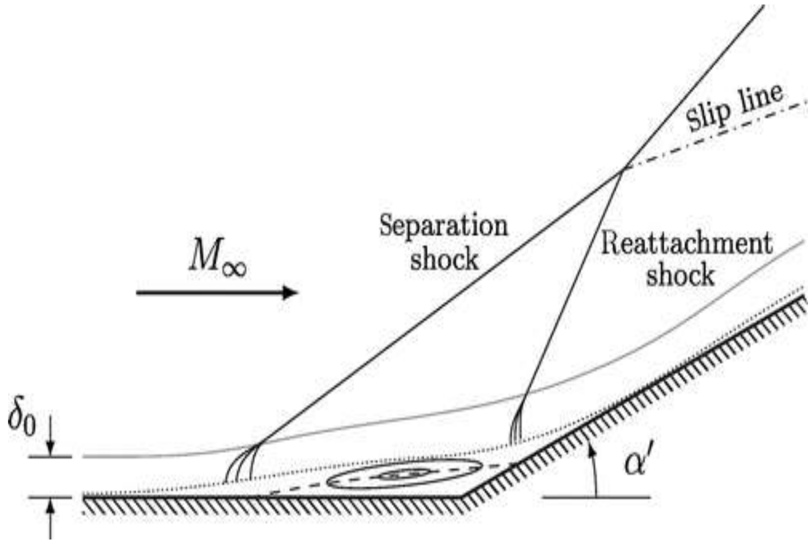


Figure 1. Shockwave-Boundary Layer Interaction over a compression ramp [1]

Oblique shock waves can be generated when the supersonic flow is turned into itself, results in the rise in pressure and temperature sharply. As the pressure rises, the boundary layer gradually thickens until it comes in contact with the shock and then quickly thins again. This property can lead to the separation and reattachment of the boundary layer. The interaction mechanism between the BL and SW depends upon several factors, including: ramp angle, Mach number, and the type of BL. In turbulent flow, the interaction region can extend up to the wall. Previous studies have shown that shock / BL interactions have a significant effect on the distribution of pressure, velocity, and heat transfer along the wall. The model developed by the ramp and the flat plate is a case of SWBLI. The shape is simple, but the phenomenon observed in this problem is complex. BL detachment is generated by the interaction of the SW/BL with the strong gradient developed in the compression zone. The major parameters affecting SWBLI [2] are Mach number, temperature, BL, inclination angle, Reynolds number and chemical state of the fluid.

The interaction between the SW and the BL produces a relatively weak shock on the compression front of the flat plate as shown in Figure 1. The shock wave caused by the ramp when comes in contact with the plate, the BL and upstream movement of pressure wave across the subsonic portion of the BL causes separation of flow which depends on the Mach number and ramp angle of the viscous fluid flow interaction parameters. There is a possibility that the presence of the bubbles causes detachment and reattachment shocks, the interaction of which creates a SW that comes in contact with the BL over the ramp based on the transfer of shock, shear layer, and the Mach number. Pressure and heat transfer increase rapidly downstream of reattachment due to flow recompression and peak occurs shortly after reattachment near the region where the boundary layer thickness is minimum.

The interaction of the shock wave with the boundary layer (SWBL) forms a recirculation zone and a large effect zone downstream and upstream of the shock point of the incident shock wave as shown in Figure 1. Numerical modelling by solving the first principles of conservation-law is a basic idea for evaluating SWBLs. The phenomenon of SWBLI for Mach number above 1.2 has been studied for the past 50 years. The shockwave- boundary layer interactions are essential for hypersonic problems. Neil D. Sandham [4] focused on the fundamental problems of shock waves caused by supersonic free currents and wedges in shear wave dynamics. Primarily focus was on the modelling the issues that arise when wedges create flow fields in supersonic free- flow. The ability to perform direct and large vortex simulations has made it possible to study the interaction between fluids and their dynamics. He further concluded that his work could also be used to study the physical mechanisms involved in the flow. SW/ BL interaction was frequently observed in high-speed currents by Ribhu Pal & Prince Raj Lawrence Raj [5] in which they observed large flow discontinuities and high heat transfer coefficient. The interaction between the BL and SW can cause blockages and increase flow rates. Numerical studies of the interaction between the BL and SW were performed at very high velocity concludes that the resulting separated bubbles were due to the strong interaction between the BL and SW. A detailed study of hypersonic currents governed by the interaction between SW and BL over the compression regime was conducted. The flow is investigated by the numerical simulation of the Navier-Stokes equation. The boundary layer interaction between the compressed corners and the shock wave was calculated using two explicit Taylor-Galerkin schemes [6] in which the temperature of the wall affects the condition of the BL in the form of wall thickness, coefficient of viscosity, Reynolds number. This effect becomes more important as the separation region is increased.

2. NUMERICAL SIMULATION METHODOLOGY

This section provides a case for evaluating the accuracy, power, and performance of the Navier-Stokes equation in context of a mesh applied to a hypersonic flow solution for validation. This simulation ignores high temperature effect which leads to the chemical reactions.

In this study the simulation analysis has been done using a 2-D solver. The properties of fluid are taken as constant, with heat capacity ratio = 1.4 and Prandtl number = 0.74. In this study, the pressure coefficients and Mach no. downstream and upstream of the obtained corner is compared with the experimental results. The reason for the discrepancy between the experiment and the calculation is explained and will get the required turbulence model, numerical grid, and calculated parameters.

2.1 Hypersonic flow across a compression corner

In this study, a case study performed by Holden et al. (2006) [3] is examined for validation. This demonstration is extensively examined using computational and experimental techniques. The properties of fluid are provided with Mach number of 10.3. This validates the hypersonic flow scheme and explain to the understanding of the physical properties of the SW / laminar BL interaction problem. The boundary conditions for the flat plate problem are dimensions AB = 0.5, BC = L = 4.004, BD = 8.661, AF = 0.5, DE = 5.0, with a 30 ° tilted ramp. Entrance boundary conditions have been applied to AF and FE. Non-slip restrictions are imposed on BCG. At GE, boundary conditions are free and the free stream condition is assumed to be the initial condition.

Following is the detail of the boundary, along with the boundary conditions considered for simulation.

Table 1. Boundary with boundary conditions

Boundary	**Boundary condition**
Inlet	Velocity inlet
Far-field	Pressure far field
Outlet	Pressure outlet
Flat plate and ramp section	Wall (No slip)
Symmetry	Axis

FVM is a technique for expressing and calculating partial differential equations in terms of the algebraic equations. "Finite volume" refers to the tiny volume that surrounds every node on the mesh. This method is conservative because the flow that goes into a particular volume is similar to the flow that goes out of an adjacent volume. The advantage of FVM is that it can easily be mapped to enable unstructured meshes. The conservation of a general flow variable is represented as a balance between different processes that likely to enhance or reduce it.

$$\frac{\partial(\rho\phi)}{\partial t} + div(\rho\phi u) = div(\Gamma grad\phi) + S\phi$$

The expression can be expressed as –

$$\text{Rate of increase in flux of fluid element} + \text{Net rate of flow of flux out of fluid element}$$
$$= \text{Rate of increase of flux due to diffusion}$$
$$+ \text{Rate of increase of flux due to source}$$

The CFD code is used to handle the most important transport phenomena: diffusion (transport by point-to-point variation of φ), convection (transport by fluid flow), and source terms (related to formation or the reduction of φ) and the rate of change over time. The SWBLI numerical model for slopes is based on ANSYS / FLUENT used finite-volume discretization for the generation of the grid. The selected viscosity model can be achieved with two equations. The viscosity is estimated with the help of 3-factor Sutherland equation accessible in Fluent-19.

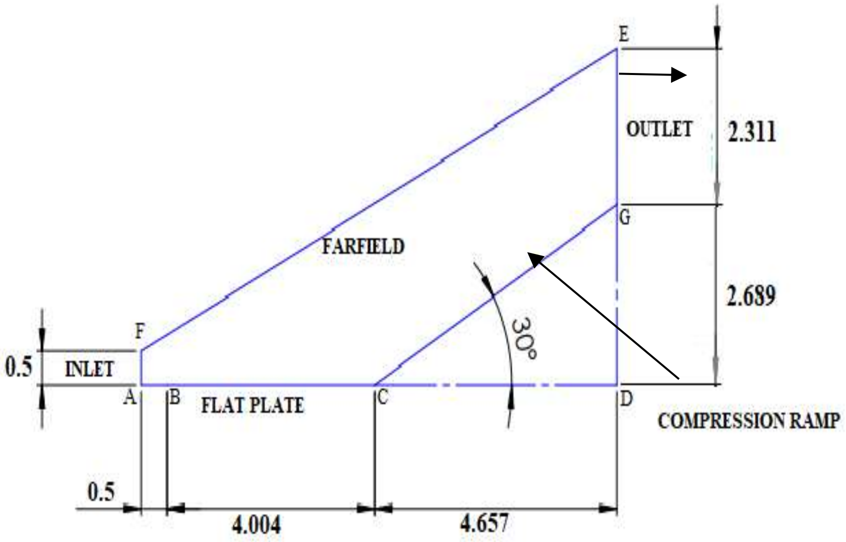


Figure 2 Computational domain with corresponding dimensions

The Fluent Handbook recommends a Sutherland formula with moderate temperature and pressure and is compared to the modelling of the flow field assuming a constant molecular viscosity (assumed at 273 K) with the results achieved by the Sutherland viscosity model accessible in Fluent-19 adopted for the entire flow field in the presented calculations. BL

separation depends primarily on the viscosity in the BL adjacent to ramp where the air temperature approaches the temperature of the wall at 290K.

3. RESULTS AND DISCUSSION

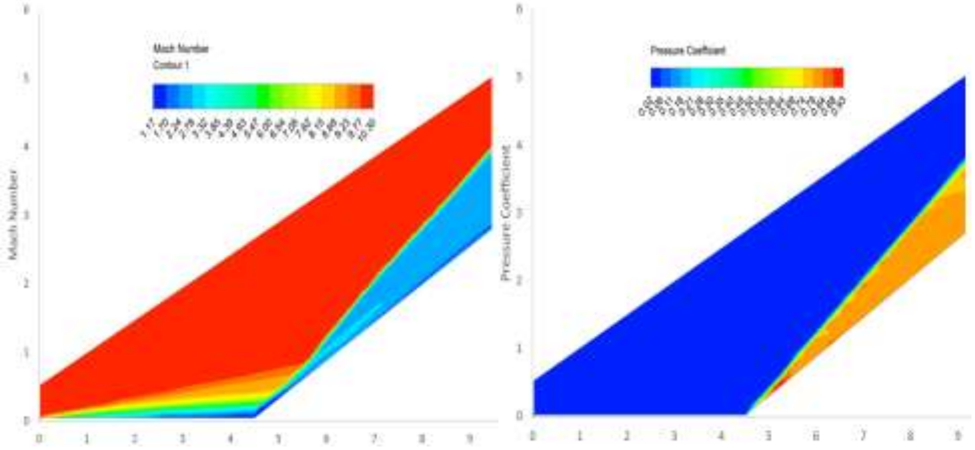


Figure 3. Mach number contour and Pressure Coefficient Contour obtained at M=10.3 using ANSYS-FLUENT 19.2

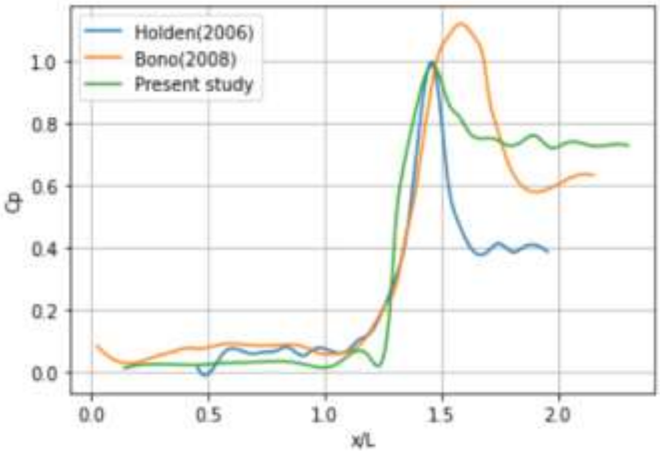


Figure 4. Variation of Coefficient (Cp) of pressure over the Flat plat and Compression Ramp arrangement.

From the above Mach number contour, it is clear that at Mach number 10.3, the shockwave and boundary layer interaction induce separation. A recirculation region is formed near the compression corner.

The coefficient of pressure (C_p) obtained after simulation shows a similar trend, and the value of the maximum coefficient of pressure (C_p) is identical to the result obtained by Holden (2006) and Bono (2008).

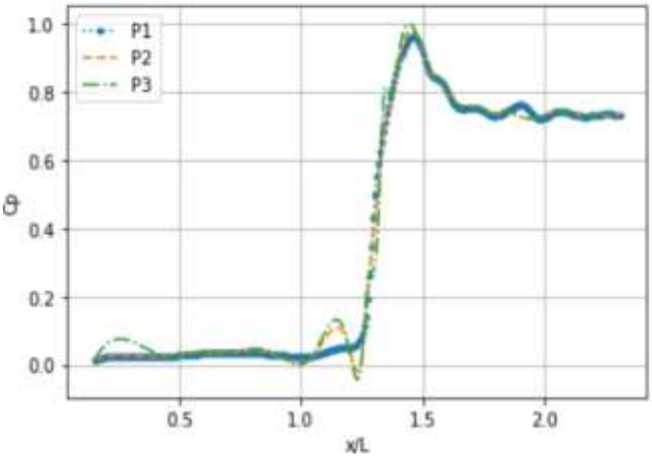


Figure 5 Grid Independence Study for variation of Coefficient of pressure along with the Flat plat and Ramp arrangement

In the Grid independence test P1, P2, and P3 are the curves obtained by computation at Mach number 10.3.

Table 2 Meshing Properties of Computational Domain for GIT

Properties	**Computational Domain**		
Element size (in mm)	(6 x 6)	(5 x 5)	(4 x 4)
No. of Grids (in millions)	0.61	0.80	1.25
Max. Aspect Ratio	5.31	7.12	9.54
Max. Orthogonality	0.998	0.998	0.999
Max. Skewness	0.80	0.82	0.84

It is observed after computation that there is no significant change in Coefficient of pressure (C_P). However, there is a slight variation in $C_{P_{max}}$. The trend in the variation in Coefficient of Pressure (C_P) is similar in all three cases, which are compared and show good agreement with the result obtained [6]. This indicates that the solution obtained can be considered to be grid-independent.

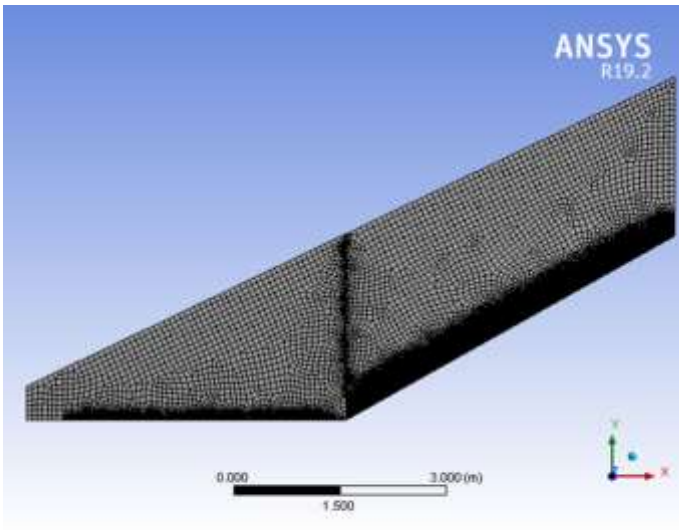
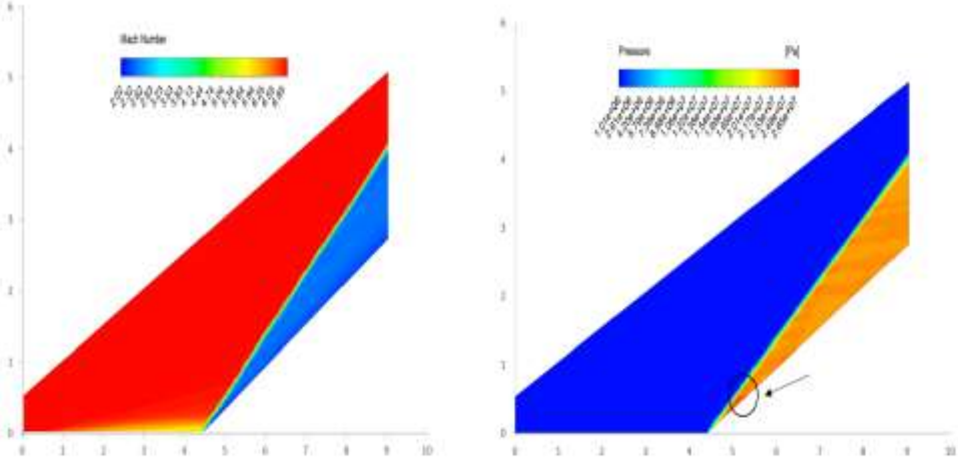


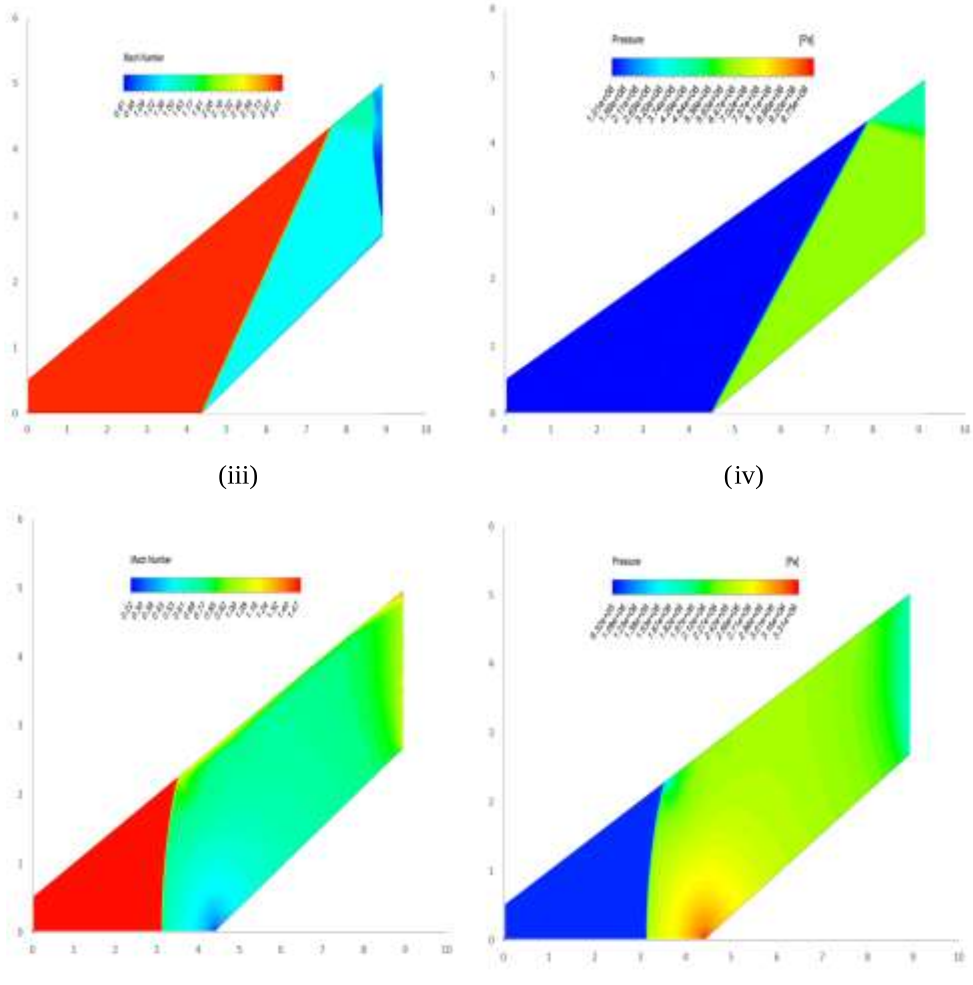
Figure 6. Mesh Generation in ANSYS Fluent 19.2

To study the boundary layer effects, the elements are dense over the flat plate and ramp section to get the enhanced and detailed output contour. In this present study the element size taken is 0.005 x 0.005, and the domain area is 18.931m^2. The present computation is carried out by providing boundary conditions as the inlet is considered velocity inlet, flat plat along with compression ramp is considered the wall, far-field is considered pressure far-field and outlet as pressure outlet.



(i)

(ii)



(iii) (iv)

(v) (vi)

Figure 7 Mach number contours for (i)M=7, (iii)M=3, (v)M=1.5, and Pressure contours for (ii)M=7, (iv)M=3, (vi)M=1.5 with tetrahedral elements computed in ANSYS-FLUENT 19.2

The different Mach numbers considered here from Supersonic to Hypersonic range are simulated for a contour comprising a flat plate and ramp section without a gap in the arrangement. At Mach number (M=7), strong oblique shock is observed over the compression ramp, whereas at Mach number (M=3), an oblique shock along with Mach reflection is obtained, but this oblique shock is not as strong as observed at M=7. At Mach number (M=1.5), near the transonic range, a shock that approaches the weak oblique shock is observed in front of the compression corner over the flat plate as the wave is turned into itself when it approaches the sharp compression corner.

For different Mach numbers considered, initially pressure at Inlet is provided as 10 bar for all the cases considered, Prandtl number considered is 0.74, and variation in pressure is obtained, which shows that at high Mach numbers, high-pressure gradient is obtained at the sharp compression-corner. The separation and reattachment of shock are observed as the Mach number varies from Supersonic to Hypersonic for the computed domain.

4. CONCLUSION

- Variations of Mach number and Pressure are determined based on simulation. Good conformity is observed between the computational and experimental results.
- Significant pressure-rise and separation and reattachment of shock are seen at a high Mach number.
- This simulation gives the idea that a turbulent model (Realizable k- ε) provides better prediction of flow separation at adverse pressure gradient relieves the user from more time consuming for developing an appropriate mesh that leads to an optimal solution.
- Shock obtained over the compression corner shows that the angle between the ramp and shock decreases as the Mach number increases from 1.5 to 7.

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Biographies

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