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Linear and Non-Linear Turbulence Models of shock/boundary-layer interaction at Hypersonic Flows

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Abstract- Association of shock waves with a turbulent boundary layer assumes a significant job in the structure and operability of fast aviation vehicles and air-breathing motors. The antagonistic pressure slope of the shock is frequently sufficiently able to isolate the boundary layer. The target of present research paper bargains hypersonic viscous streams overwhelmed by solid shock wave boundary layer associations over wing-fold and wing-fuselage intersection setups have been broke down. The impacts of the control surface diversion point, driving edge shape and viscous association parameter on the stream field have been assessed. Moreover, the variations of angle of attack with linear and nonlinear turbulent eddy viscous models have been studied. Scaling laws for the upstream impact, pinnacle warming, Pressure co-effective, Skin contact and streamlined coefficients have been set up by methods for numerical re-enactments and hypothetical contemplations. Both Linear and Non-Linear disturbance models are considered during reproduction of SWBLI. Tecplot assumes a pivotal job for deciphering and post processing CFD information to numerical data for differentiating by and large. Also, great emphasis has given to enlarge the interaction zone in order to visualize the precise conditions hindered around the separation bubble and wall. CFL number variations have affected to ascend the contour levels substantially to attain the exact vectors for boundary conditions.

Keywords- High speed flows, Shock wave, Boundary layer, Separation bubble, Turbulence modeling, Shock Interaction

I. INTRODUCTION

Probably the most genuine and testing issues experienced by the fashioners of hypersonic vehicles emerge as a result of the seriousness of the warming burdens, coefficients, and the steepness of the stream slopes that are produced in stun wave–limit layer communication (SBLI) locales. The qualities of these streams are hard to foresee precisely due in no little measure to the critical intricacy brought about by shear-layer progress, which happens at extremely low Reynolds numbers and can prompt improved warming burdens and huge scale precariousness. In any event, for totally laminar streams, thick communication can corrupt considerably the exhibition of control and impetus frameworks [1]. It is fascinating that both of the two significant issues experienced with the U.S. Space Shuttle program were related with SBLI.

1)The originally was the alleged Shuttle Flap Anomaly that brought about the catastrophe on the specialty's lady trip because of a disappointment in the structure stages to account accurately for the impact of genuine gas consequences for the stun cooperation districts over the control surfaces.

2) The subsequent issue was the main edge basic disappointment brought about by the effect of froth that had been cracked and discharged from the bus tank because of the dynamic burdens brought about by a stun connection. Figure 1.1 a is a case of the stun structures that are created among the van, the fundamental tank, and the strong reusable supporters.

Tragically, the harm this caused brought about a lamentable mishap.

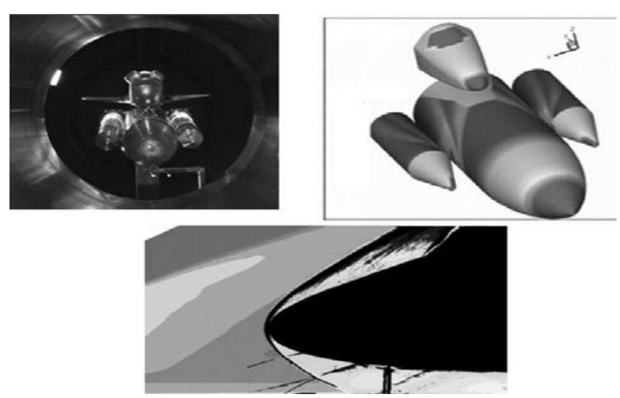


Figure 1.1 a: Shock interactions on OTS shuttle configuration [1]

In spite of the escalated test and computational examination, a few parts of pertinent material science engaged with these streams remain inadequately comprehended and a portion of the physical science can't generally be replicated just through the choppiness alterations. Significant physical marvels (1.1 b) incorporate enhancement of the disturbance by temperamental shock waves in the boundary layer (1) and outer stream (2); concealment of choppiness by the rarefaction waves (3); development of another boundary layer in the close divider area of the appended stream (4); arrangement of Taylor-G ¨ Ortler vortices (5); and appearance of the procedure, which resembles relaminarization in the partition locale (6) because of the ideal weight inclination in turn around stream and a lessening in the Reynolds number (because of the switch stream speed decreasing in the detachment district). These components are basic and must be considered for the improvement of sufficient numerical models for calculations of such streams.

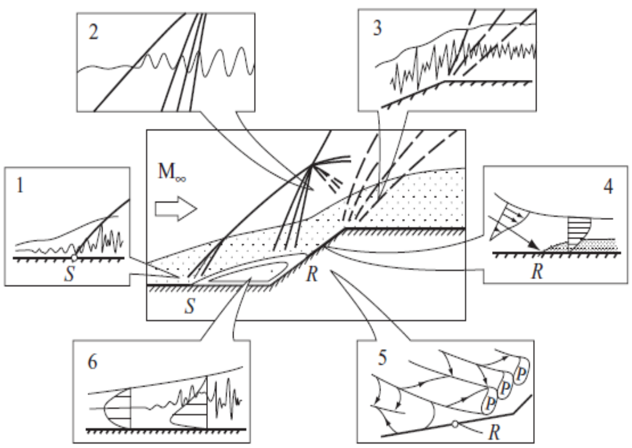


Figure 1.1 b : Specific physical features of flow over compression-decompression ramp configuration

The flowfield structure is dictated by the free-stream Mach number; stun strength(e.g., inviscid-static-pressure ratio($\xi = p2/p1$); Reynolds number2 Reδ dependent on the approaching limit layer thickness δ; and divider temperature proportion Tw/Taw, where Tw is the divider temperature and Taw is the adiabatic-divider temperature and geometry.(i.e., level versus calculated surface on the grounds that a sunken surface presents extra streamline shape that may cause vortices). For this arrangement, we inspect the run of the mill STBLI systems, talk about the flowfield structure, and present commonplace computational outcomes. Space impediments block a thorough overview of calculations.

The pressure incline (CR) and pressure decompression slope (CDR) cooperations (see Fig. 1.2) are portrayed by a mind boggling mean flowfield structure and different association systems.

For an adequately little edge α (i.e., where there is no or exceptionally little partition), the pressure waves blend into a solitary stun (Fig. 1.3a). The downstream surface weight essentially corresponds with the inviscid-stream case. The mean surface skin-rubbing coefficient is wherever $cf > 0$ and there is no mean turned around stream. The flowfield is precisely anticipated with the standard two-condition Wilcox k-ω model and the Jones-Launder k-ε model.

For adequately enormous α (contingent upon M∞, Re,δo and Tw/Taw), the limit layer isolates at point S upstream of the CR and reattaches at point R downstream in fig 1.3 b. A pressure wave framework shapes upstream of the CR because of the redirection of the limit layer by the partition bubble with a relating ascend in the mean surface weight blending into a stun wave (i.e., the division stun). A "level" in the mean surface weight frames in the district of switched stream between focuses S and R, as appeared in the speed profiles. The surface-skin grinding $cf = 0$ at the two points .A subsequent pressure wave framework shapes in the region of mean-reattachment point R as the stream is redirected by the corner surface and the outer stream packs to combine into a stun (i.e., the reattachment stun). The two stun waves converge to shape a λ-stun with a slip line (see fig.1.3 b) and an auxiliary extension fan, as appeared in Fig. 1.2a, or a feeble stun reaching out from a triple point at a low M∞. Such an optional extension fan is generally frail in tests at$M\infty \leq 3$ however ends up recognizable at the higher Mach numbers. The limit layer over expands about the second corner with feeble pressure waves emerging promptly downstream of the extension fan. These components are basic and must be considered for the improvement of satisfactory numerical models for calculations of such streams are tested in figures 1.4. SWBLI with and without interactions are elaborated in the ref[2] precisely.

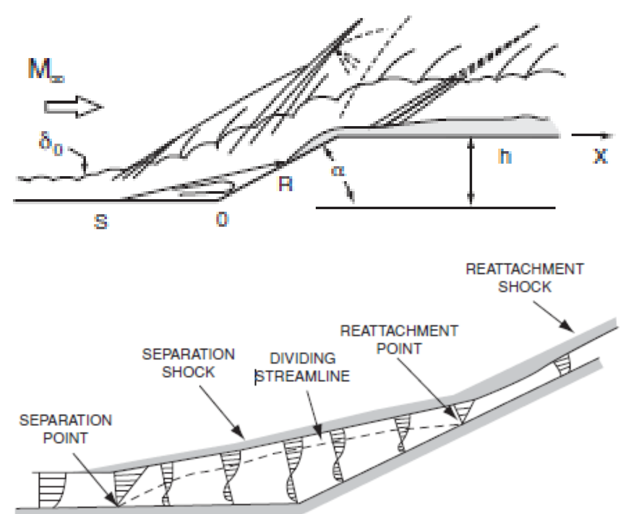


Figure 1.2: Compression-Decompression Corner or Ramp with Enlargement of Seperation(S) and Re-Attachment(R)

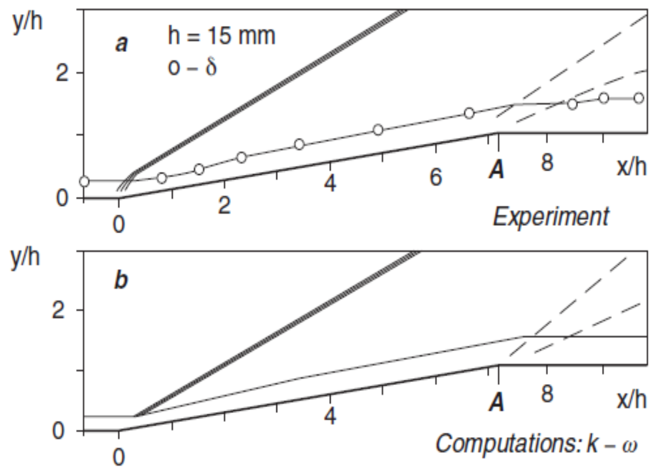


Figure 1.3 a : Comparison between experiment and RANS with the standard *k-ω* turbulence models for compression/decompression ramp flow at smaller angle.

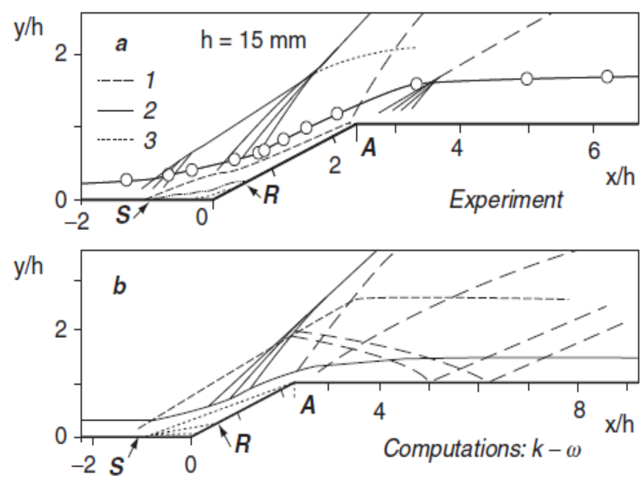


Figure 1.3b : Comparison between experiment and RANS with the standard *k-ω* turbulence models for compression/decompression ramp flow at higher angle.

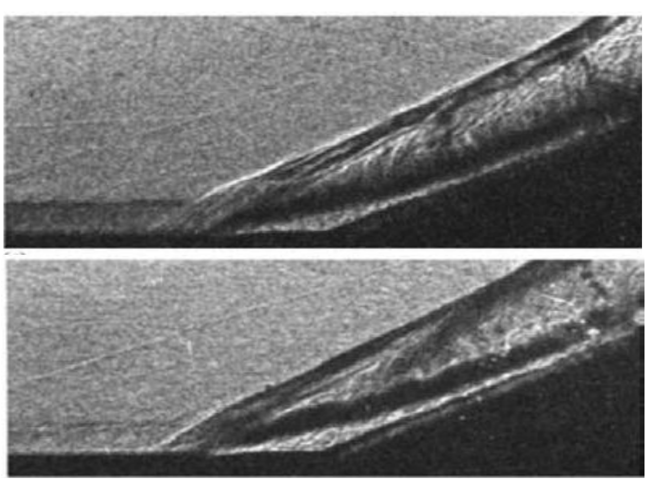


Figure 1.4 : experimental schlieren images at two different instants of time of interaction in Compression Ramp

II.TURBULENCE MODELS

The group of Reynolds-found the middle value of Navier-Stokes (RANS) models is the biggest in the field of choppiness. These models endeavor to close the disturbance conditions utilizing thickness terms. A typical variable determined in these models is k, or the dynamic vitality per unit mass of fierce fluctuations.There are a few confinements with RANS models as they depend on the meaning of tempestuous thickness [8]. These impediments are:

Absence of physical depiction
Disturbance initiated auxiliary streams
Streamlined arches
Whirling streams or streams with pivots
Transitional streams among tempestuous and laminar
Temperamental streams like inner burning motors
Dormant areas in streams

The possibility of unsettling influence and how it is experimentally addressed in CFD reenactment tasks are locked in with the pic 2.1 . Dividers are rule wellspring of vorticity and unsettling influence and its quality offers climb to brutal power and warm farthest point layers: definite desire for frictional drag for external streams and weight drop for inward channel streams endless supply of neighborhood divider shear weight gauges. In this particular condition, the grandiose assortments of field factors (speed, temperature commercial weight) are in the uncommonly close divider regions showed up by following picture.

The zone near the dividers is known as breaking point layer and has also been disengaged into sub-layers. Unsettling influence and farthest point layer are two immovably related focuses. While as a rule stream is disengaged into two zones: limit layer and free-stream, limit layers themselves are isolated into 4 zones: gooey sub-layer, support layer, log-law region and outside layer. Log-law region is in like manner called "inertial sublayer". Outer layer is generally called "disfigurement layer". Log-locale and inertial sublayer is sometimes all things considered called "spread layer"

Usage of amazingly fine work to decide these shaky profiles is in most of the applications computationally preposterously expensive for utilization of CFD contraptions to the mechanical scale. Along these lines, remarkable close divider medications have been made since managing conditions can't be fused down to divider. This incited the progression of divider works and near divider treatment. However, roughness isn't a heartbreaking thing under all conditions. The image depicts the features of "brutal developments" similarly as relatively few of the points of interest as well.2.1 Turbulence models in Computational Fluid Dynamics

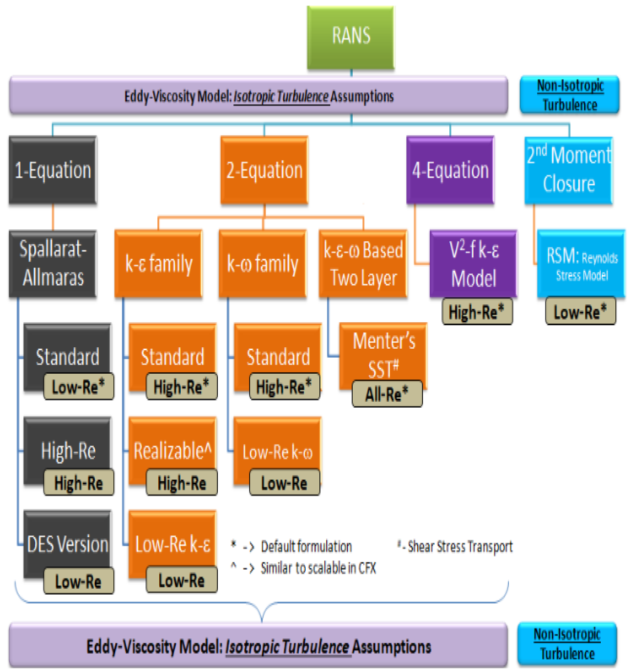


Figure 2.1: Turbulence models in Computational Fluid Dynamics with Linear and Non –Linear Eddy Viscosity

WALL TREATMENT AND THE WALL FUNCTIONS

•**"high-re number wall treatment"** alludes to the situation where boundary layers are demonstrated as far as experimental (and entrenched) connections known as divider capacities. divider laws are utilized to ascertain divider shear stress[7]. in the divider capacity model, the main hub close to the divider is expected to lie outside of the log-law locale that is y+ ≥ 30

•**"low-re number divider treatment"** alludes to the situation when limit layers are settled and not demonstrated. the re-number here alludes to turbulent reynolds number characterized as returb = k2ν/ε.

- note that it is identified with the manner in which limit layers are settled and has nothing to do with the "mean flow reynolds number".
- a "low reynolds number" disturbance model doesn't utilize divider works, that is doesn't include any suspicions about the close wall variety of speed.
- examples incorporate k-ω sst or low reynolds number k-ε (a variation of k-ε that doesn't utilize divider capacities and coordinates directly through the limit layer). when "low-re number divider treatment" is utilized, after prerequisites on work are forced: the (y+) ought to be of the request for 1. Under no conditions, the y+ should increment over 5.
- the number of components in the limit layer ought to be ~ 10. this guarantees the work comparing to y+ ≥ 30 falls in the log-law locale.

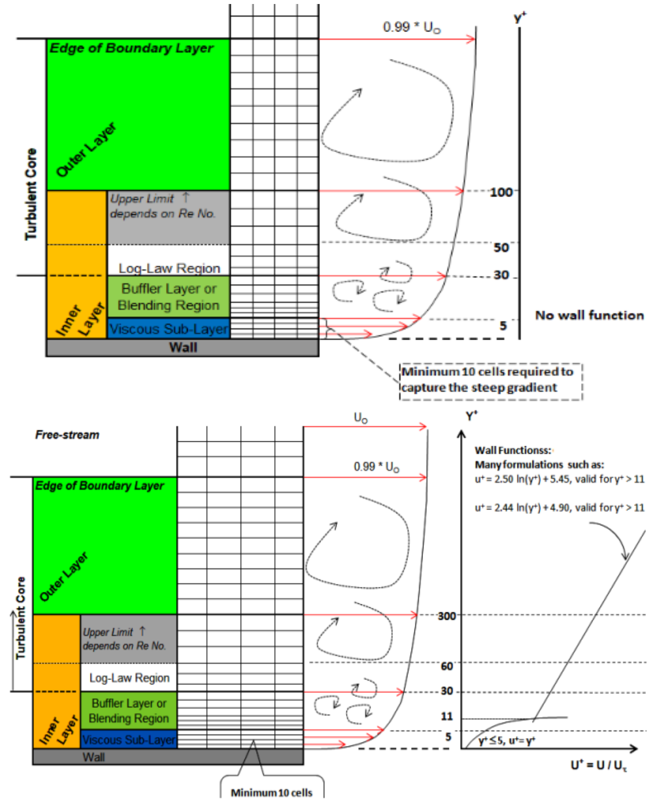


Figure 2.2: Wall Turbulence with quality of grid sze and without quality

CHARACTERISTICS OF TURBULENCE MODELS

k-ε model: Velocity scale: k1/2, Length scale: k3/2/ε, Eddy consistency: ρ Cμ k2/ε

Advantages:

- Good results for some, modern applications managing divider limited streams with low weight inclinations.
- Stable and numerically powerful.
- Computationally more affordable, no affectability of free-steam conditions.
- Realizable rendition of k-ε model is useful for complex streams with enormous strain rates, distribution, revolution, division, solid pressure inclinations.

Disadvantages:

- Limited capacity to foresee optional stream qualities such division and reattachment, (for example, stream over aerofoil with non-zero approach, traverse a chamber).
- Not exact in streams with high streamline shape and abrupt changes in the mean strain rate, (for example, back-confronting step), solid twirling stream, (for example, tornados, hydrocyclones and blended tanks).
- Like any vortex consistency model, neglects to foresee the situations where choppiness transport or non-harmony impacts are significant in streams. It depends on isotropic choppiness.

Spalart-Allmaras model
Key qualities:

- In standard structure, it is a Low-Re number model and thus no divider capacity is utilized. That further forces a limitations to have work fine enough so that y+ is < 1.0 all over the place.
- Since this is a Low-Re number model, it very well may be utilized with "Programmed Wall Treatment" or "All y+ treatment" techniques for disturbance demonstrating.
- This disturbance model had particularly been produced for streamlined stream reproduction for airplane business.
- This models is a decent decision for applications where the limit layers are generally joined and partition is absent or gentle division is normal. Run of the mill models would be stream over a wing, deliver frames, rockets, fuselage or other aviation outside stream applications.
- The Spalart-Allmaras model for RANS conditions isn't suggested for streams commanded by free-shear layers, (for example, planes), streams where complex distribution happens (particularly with warmth move) and normal convection.
- The Spalart-Allmaras models with DES can be utilized for streams commanded by free-shear layers, (for example, planes), streams where complex distribution happens (particularly with warmth move) and common convection.

Reynolds Stress Model (RSM) or Second Moment Closure Methods

Key attributes:

- Reynolds stresses are not demonstrated as Boussinesq Hypothesis. In any case, displaying is as yet required for some terms in the vehicle conditions.
- Recommended for complex 3-D violent streams with huge streamline ebb and flow and whirl, however the model is computationally escalated, hard to meet than vortex consistency models, for example, k-ε or Spalart-Allmaras models.
- Anisotropy of choppiness is represented, quadratic weight strain choice improves execution for some, essential shear streams.
- Most reasonable for bended pipes state U or S-twists, turning stream entries, combustors with huge bay twirl and violent wind separators.

Standard k-ω Model (SKO): Velocity scale: k1/2, Length scale: k1/2/Cμω, Eddy consistency: ρ k2/ω
Key qualities:

- Specific scattering rate ω = k/ε understood rather than ε
- Demonstrates better execution for divider limited and low-Re streams and potential to deal with transitional streams (however will in general foresee the progress early).
- Suitable for complex limit layer streams with unfavorable weight slope and division (outer streamlined features and turbomachinery).
- Separation is ordinarily anticipated to be higher and sooner than tentatively watched qualities.

Shear Stress Transport (SST) k-ω Model
Key attributes:

- Specific dispersal rate ω = k/ε unraveled in inward layer (log-layer and thick sub-layer) and advances to a k-ε model away from the divider (however not same as standard k-ε conditions).
- The limit conditions for SST model are equivalent to the k-ω model and is moderately less delicate to the free stream estimation of ω.
- Suitable for complex limit layer streams with unfriendly pressure inclination and detachment (outer optimal design and turbomachinery).

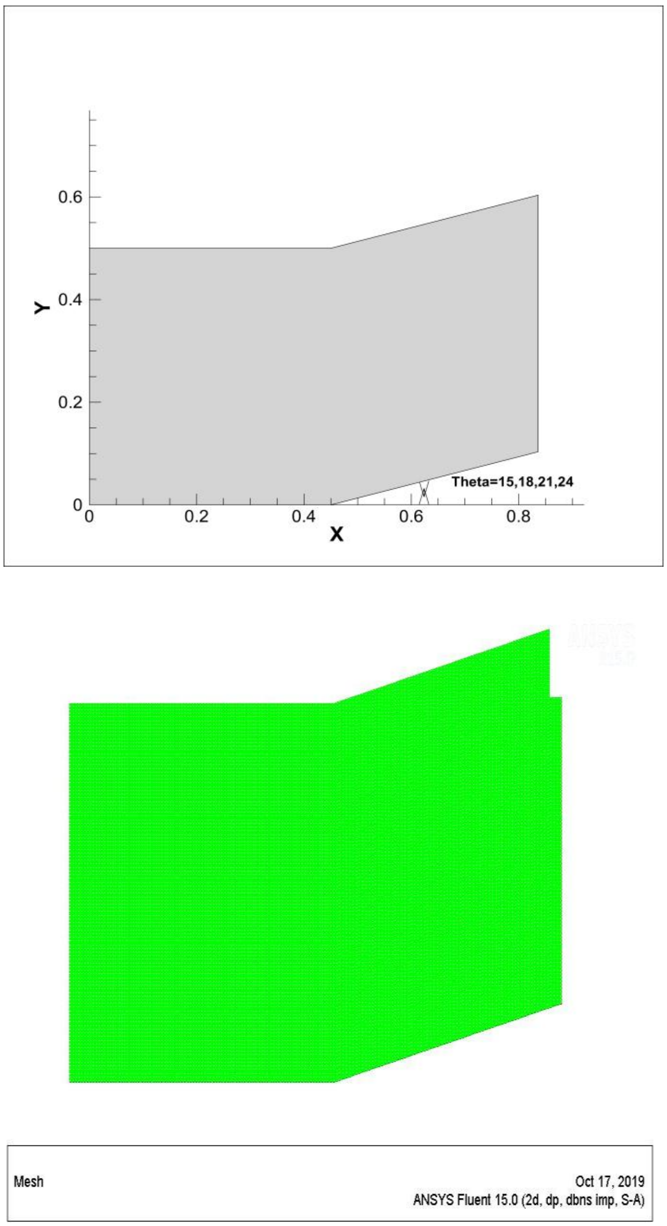
Enormous Eddy Simulation (LES):
Key qualities:

- This model purposes all vortexes with scales bigger than matrix scale and subsequently prescribed for wide-band aeroacoustic commotion forecasts.
- Time step size is administered when size of the littlest settled whirlpools which requires the neighborhood Courant-Friedrichs-Lewy (CFL) number to request of 1.
- In ANSYS FLUENT, channel irritations at speed gulfs can be forced while utilizing LES disturbance model.
- FLUENT likewise prescribes "Limited Central Differencing" for force if there should arise an occurrence of LES on unstructured work.

III. PROBLEM DESCRIPTION

The geometry, shown schematically in Fig. 3.1 a, consists of a Compression Corner with Four different Ramp deflection angles of 15,18,21,24 Degrees. The strength of the shock wave increases with surging the deflection angle substantially , resulting in a stronger interaction with the boundary layer. The inviscid shock from tip of shock generator interacts with the turbulent boundary layer developed over the flat plate. Free stream conditions are M∞ = 14.1, T∞ = 88.88K T(wall)=297.22 and p∞ = 1000 N/m2 with unit Reynolds number Re∞ = 37 × 106 m−1. The plate is maintained under isothermal conditions of 300 K. Initially the experiments were done for flow over flat plate to obtain undisturbed turbulent boundary layer properties like δ, δ+, θ and Cf at different locations. Wall data like pressure, skin friction and heat transfer rates were measured along the flat plate in the interaction region[6].

The boundary conditions are identified in Fig.3.1b. Inlet profiles for the computations are obtained from separate Ramp simulation at freestream and wall boundary conditions identical to those illustrated in the graphs. The value of the momentum thickness reported in the experiments is matched to obtain the mean flow and turbulence profiles at the inlet boundary of the computational domain. The inlet profile for the mean flow variables are modified at the shock entry point to post-shock conditions calculated analyticallyin ref [5]. Post-shock conditions are also prescribed at the top boundary. At the wall, isothermal (Tw = 297.22 K), no-slip boundary conditions are applied and extrapolation condition is used at the exit boundary of the domain[5].



Fugure 3.1: Geometry of Compresion ramp with structural mesh

Modeling and Meshing

Here, I used a tool GAMBIT for modeling and meshing the geometry as per parameters shown in Figure 3.1. During meshing, I have maintained the quality of aspect ratio of 6.957. As a result, the model attained 127536 Quadrilateral Cells, 254072 faces and 128537 Nodes as shown in Figure 3.1.

Analyzing

There are umpteen software's available for analyzing fluid dynamic models among those FLUENT is the best tool to make analysis easily. The main reason behind choosing fluent is easy to use, Flexibility, Accuracy, allows for efficient execution, interactive control, and complete flexibility, for various operating systems.

CFL Variation

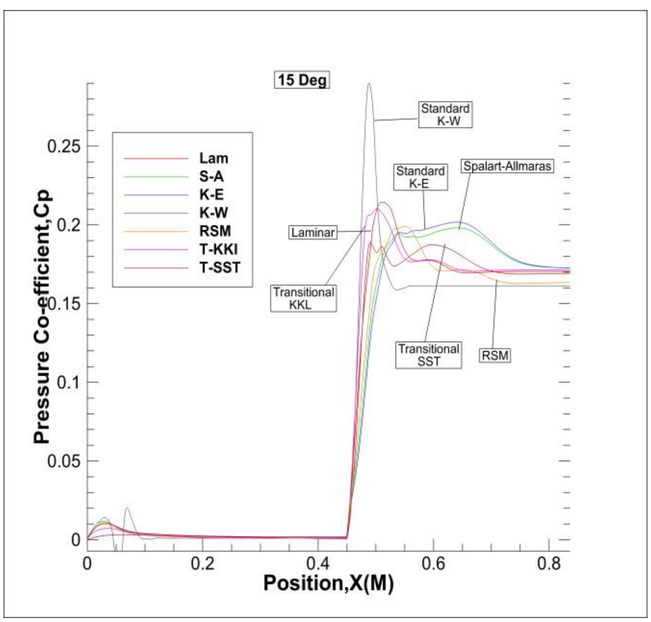
Different Courant-Friedrichs-Lewy (CFL) numbers are used in the computations. In the computations, a CFL of 0.2 is used at the beginning and it is gradually increased to 0.4 in the first 200 iterations. It is further increased to 1.0 at 1000 iterations and to 5.0 at 5000 iterations, and to 6.0 at 8000 iteration. A maximum CFL of 7.0 is used after 10000 iterations. The Computation converges in 7-9 cpu hrs and it takes 10000 iterations to reach the steady state solution.

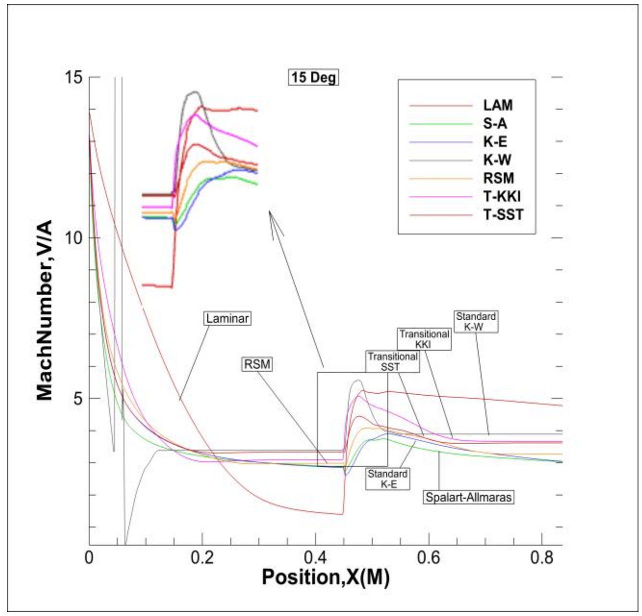
IV. RESULTS AND DISCUSSION OF FLOW PHYSICS

In this work we have investigated two-dimensional Ramps over wing-fold arrangements. Furthermore, streams over hindrances whose setups are common of wing-fuselage point geometries. These designs have been chosen with the target to discover scaling laws to portray the neighborhood wonders happening in the flowfield over a hypersonic vehicle. Following the test investigations of Holden and Delivery and Coet we have recognized some geometric and stream parameters that influence the weight recuperation, the partition and the warmth move rate, and have played out a parametric report to assess their impact on the flowfield[4]. Specifically, the impacts of the incline edge (for example the avoidance point of the control surface), the compass edge, the main edge shape (through the variety of the span of arch of the main edge) and the gooey and association parameter have been precisely contemplated in Inviscid,Linear and non-Linear swirl consistency models. For a large portion of the two-dimensional calculations, we have played out a lattice affectability concentrate to determine the impacts of matrix goals on our discoveries. Be that as it may, we have set up that a similar scaling laws hold both for two-dimensional (for this situation freely of lattice goals) arrangements as like three-dimensional ones; subsequently, it is trusted that. in any event subjectively in ref [3]. The discoveries for the three-dimensional case will remain. For all experiments, we have first played out an examination to survey the significance of (conceivable) flimsiness impacts through the angle of 15, 18, 21, and 24 degrees.

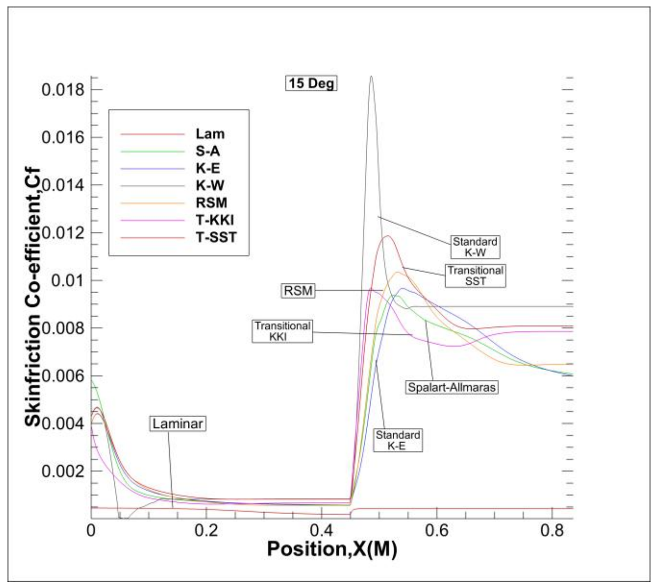
15°**flare at Mach 14.10**

In deflection15 degrees imparted by the ramp induces a shock the strength of which exceeds the capacity of the boundary layer to withstand the compression, but the separation didn't occurs at a point located upstream of the ramp apex. As in the shock reflection, separation shock has not formed due to the angle of the compression waves induced by the separation process. Downstream of shock, the fluid in the boundary layer near the wall doesn't attain re-circulation, and the bubble topology is identical in this case. The compression waves coalesce into a single shock. Reattachment on the ramp gives rise to reattachment shock, which is less inclined than the separation shock because of the change in flow direction and because the Mach number downstream of the separation shock is lower. The pressure co-efficient has surged to0.3 in K-W case and 0.15 to 0.2 range for the rest of models, immediately after the interaction at the wedge. As per characteristics of shock the parameters and co-efficient fell down to the range of 3 to 5 mach ,so the hypersonic speed transformed into supersonic at 10K iterations, It will move to range 1 to 1.5 in fig 4.1 ,if I further proceed my iterations.Similarly,The mean surface skin friction co-efficient is everywhere Cf>0 , and there is no mean reverse flow.Here,the skin friction coefficient was ascended after the interaction point to the range from 0.002 to 0.012 in fig 4.2 except the K-W that reaches to 0.018.The flow was accurately predicted in 15 in all cases except Standard K-W model.





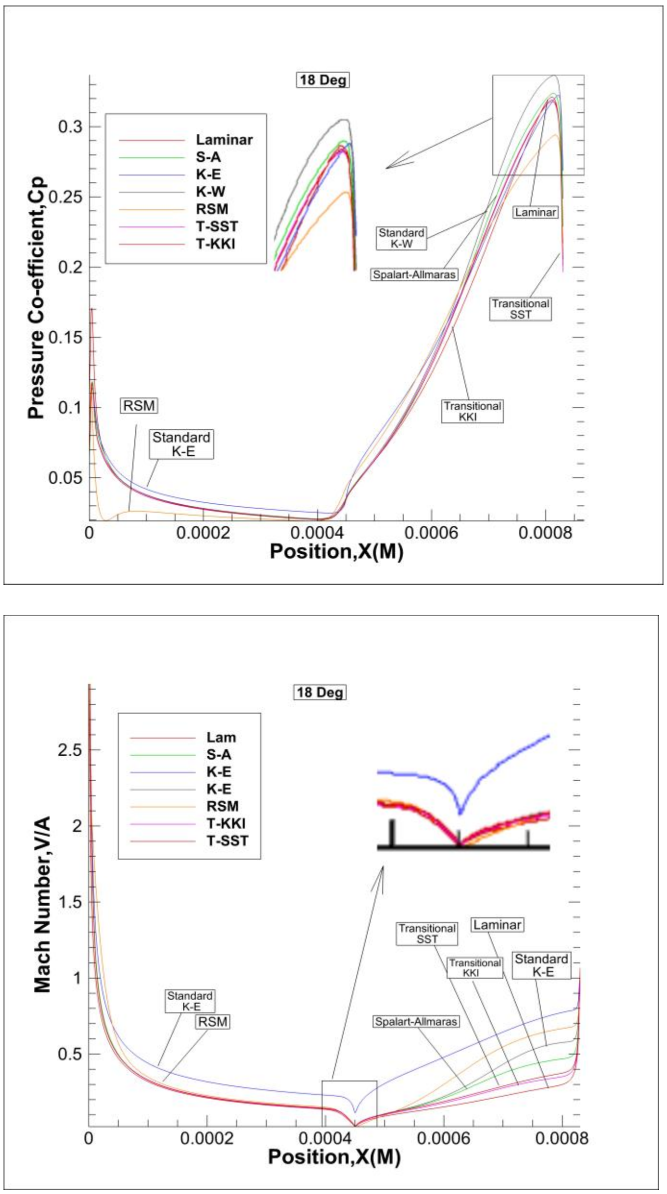
4.1Comparision of Pressure co-efficient and mach number with various turbulence effects at mach 14.1



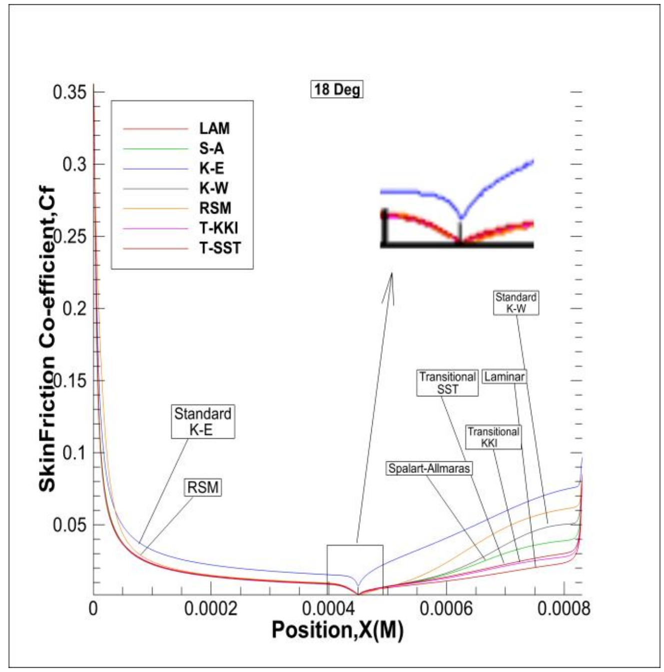
4.2 Comparision of Skin friction co-efficient with various turbulence effects at mach 14.1

18°**flare at Mach 14.10**

In deflection18 degrees imparted by the ramp induces a shock the strength of which exceeds the capacity of the boundary layer to withstand the compression, but the separation occurs partially at a point located upstream of the ramp apex. As in the shock reflection, separation shock has not accurately formed due to the angle of the compression waves induced by the separation process. Downstream of shock , the fluid in the boundary layer near the wall doesn't recirculates precisely , and the bubble topology is identical to that of the previous case. Reattachment on the ramp gives rise to reattachment shock , which is less inclined than the separation shock because of the change in flow direction and because the Mach number downstream of the separation shock is lower.The pressure co-efficient has surged to0.32 from 0.005 in all cases ,immediately after the interaction at the wedge.As per characteristics of shock the parameters and co-efficient fell down to the range of 1.8 from 14.1 mach in fig 4.3 ,so the hypersonic speed transformed into supersonic at 10K iterations, It will move to range 1 to 1.5,if I further proceed my iterations.Similarly,The skinfriction coefficient was ascended after the interaction point to the range from 0.003 to 0.012 in all turbulence models in figure 4.4 . The flow was accurately predicted in 18 in all cases exept Standard K-W.



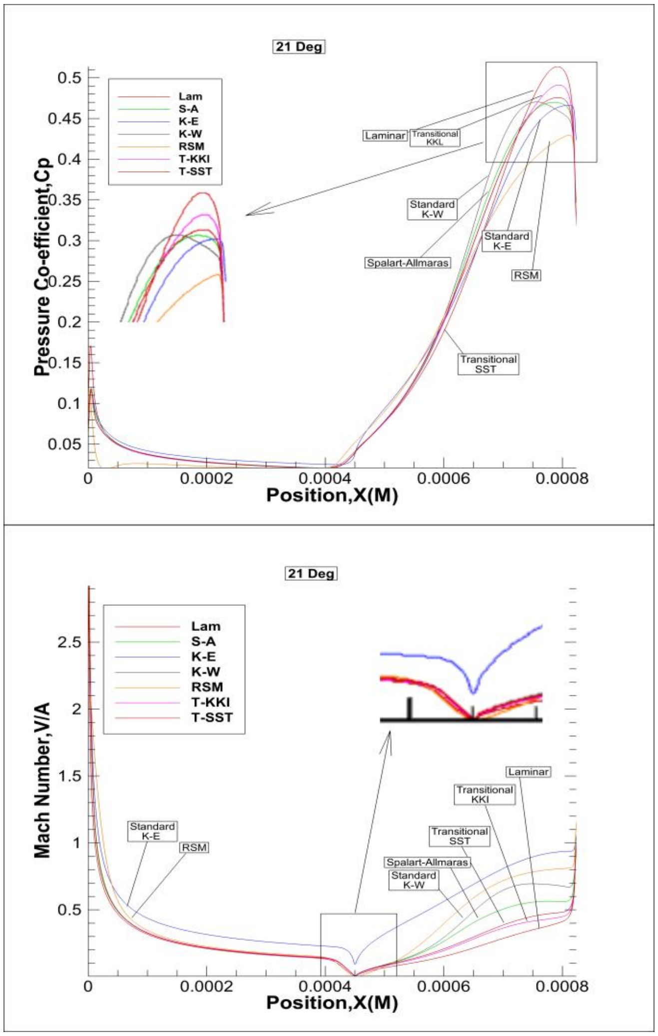
4.3Comparison of Pressure co-efficient and mach number with various turbulence effects at mach 14.1



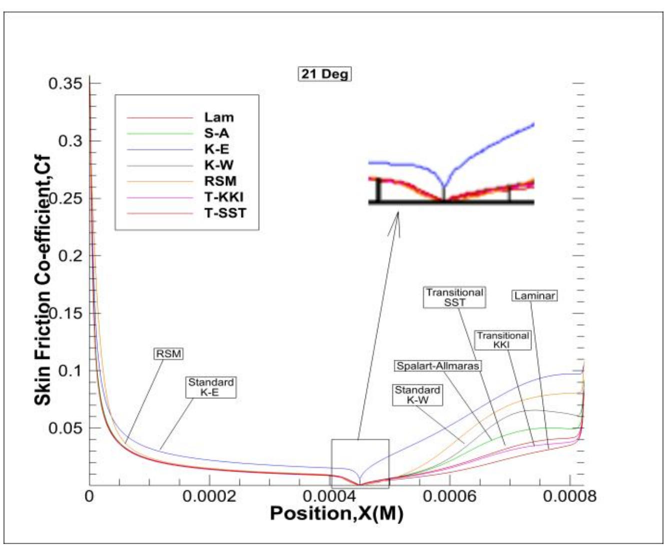
4.4Comparison of Skin Friction co-efficient with various turbulence effects at mach 14.1

21°**flare at Mach 14.10**

In deflection21 degrees imparted by the ramp induces a shock the strength of which exceeds the capacity of the boundary layer to withstand the compression, the separation occurs as usually at a point located upstream of the ramp apex. As in the shock reflection, separation shock has occured accurately formed due to the angle of the compression waves induced by the separation process. Downstream of shock , the fluid in the boundary layer near the wall starts recirculation precisely , and the bubble topology is identical to that of the previous case,but here the size and shape has increased due to the intensity of the shock interaction. Reattachment on the ramp gives rise to reattachment shock , which is less inclined than the separation shock because of the change in flow direction and because the Mach number downstream of the separation shock is lower.The pressure co-efficient has surged to0.5from 0.05 in all cases ,immediately after the interaction at the wedge as show in figure 4.5.As per characteristics of shock the parameters and co-efficient fell down to the range of 1.6 from 14.1 mach ,so the hypersonic speed transformed into supersonic at 10K iterations, It will move to range 1 to 1.5,if I further proceed my iterations.Similarly,The skin friction coefficient was ascended after the interaction point to the range from 0.003 to 0.1 gradually in all turbulence models in fig 4.6. The flow was accurately predicted in 15 in all cases except Standard K-W.



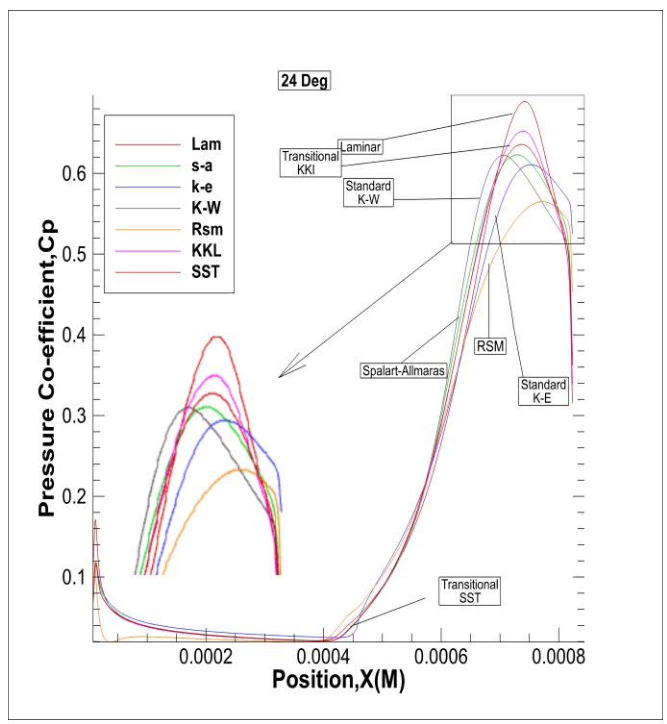
4.5 Comparison of Pressure co-efficient and mach number with various turbulence effects at mach 14.1

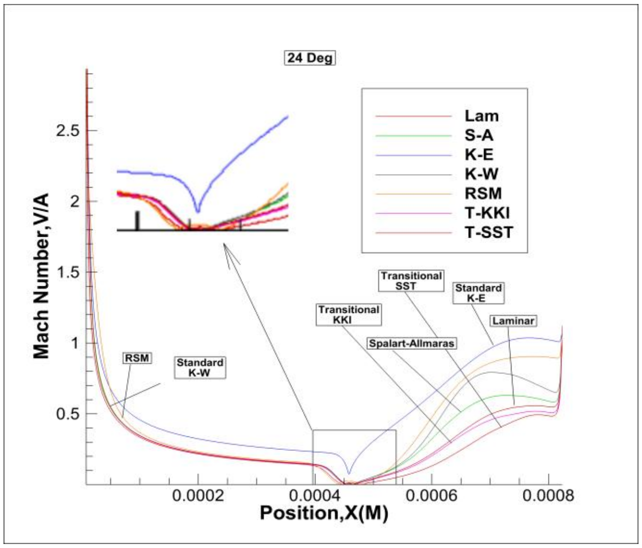


4.6 Comparison of Skin friction co-efficient with various turbulence effects at mach 14.1

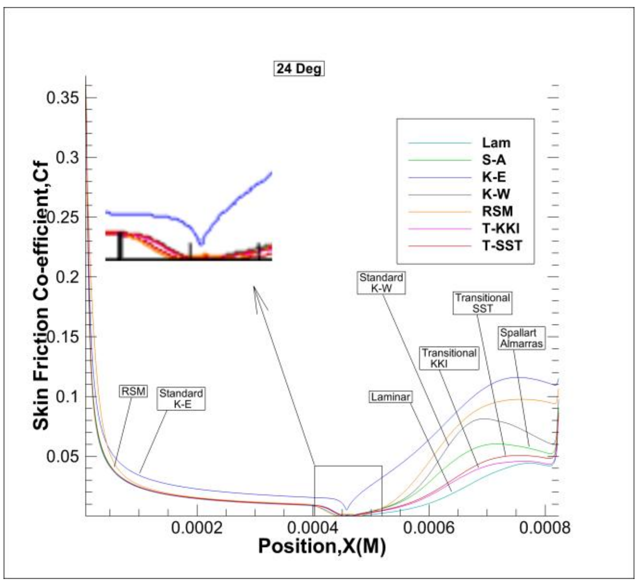
24°**flare at Mach 14.10**

In deflection24 degrees imparted by the ramp induces a shock the strength of which exceeds the capacity of the boundary layer to withstand the compression, the separation occurs as usually at a point located upstream of the ramp apex. As in the shock reflection, separation shock has occurred precisely and completely formed due to the angle of the compression waves induced by the separation process. Downstream of shock , the fluid in the boundary layer near the wall starts recirculation precisely , and the bubble topology is identical to that of the previous case,but here the size and shape has increased due to the intensity of the shock interaction. Reattachment on the ramp gives rise to reattachment shock , which is less inclined than the separation shock because of the change in flow direction and because the Mach number downstream of the separation shock is lower. The pressure co-efficient has surged to0.7from 0.1 in all cases ,immediately after the interaction at the wedge.As per characteristics of shock the parameters and co-efficient fell down to the range of 1.4 from 14.1 mach at fig 4.7 ,so the hypersonic speed transformed into supersonic at 10K iterations, It will move to range to 1 to 1.3,if I further proceed my iterations.Similarly,The skin friction coefficient was ascended after the interaction point to the range from 0.05 to 0.12 gradually in all turbulence models in fig 4.8. The flow was accurately predicted in 15 in all cases except Standard K-W.





4.7 Comparison of Pressure co-efficient and mach number with various turbulence effects at mach 14.1



4.8 Comparison of Skin friction co-efficient with various turbulence effects at mach 14.1

V. CONCLUSION

The point of this work was to assess the impact of some geometrical and stream parameters on the highlights of two-dimensional laminar and fierce hypersonic streams overwhelmed by solid shockwave limit layer connections with rather expanded isolated districts, and survey their consequences for the streamlined exhibitions. It has been discovered that, for streams over wing-fold and wing-fuselage crossroads setups, parameters like incline and clear points, driving edge obtuseness or thick communication parameter strongly affect detachment, pressure recuperation and warm loads. An about direct reliance of the upstream impact with the fold diversion point has been anticipated; the pinnacle warming has been found to associate with the upstream impact by a power law reliance. Besides, the upstream impact has been found to diminish straightly with the comparability parameter, though a direct relationship between's the drag coefficient, scaled by a similar parameter, and the upstream impact has been built up.

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