Numerical Studies on Lip Shock Flow Behaviors over Backward Facing Sharp Edge Step with Hybrid RANS-LES

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Abstract- *In the present research, a 2D numerical model is developed to investigate supersonic turbulent fluid flow over a backward facing sharp edge step by using hybrid RANS-LES model. It pertains to the Spalart-Allmaras model involving a viscosity-like variable (ṽ). The model also takes into account the additional important factors like production, diffusion and destruction terms above and beyond the very common aspects related to the present research problem. The numerical simulations are performed using the stated turbulence model with the inflow free stream Mach number of 2.5 corresponding to free stream pressure and velocity of 15350 N/m2 and 651.9 m/s2, respectively. The simulation predictions are compared with the corresponding experimental results existing in the literature. The hybrid RANS-LES model gives fairly better and consistent results throughout the entire flow region and hence, it is used for all further studies. It is also observed that the sudden viscous layer separation is the main cause of the shock generations. Furthermore, the uneven pressure recovery is because of the sudden expansion flow over the sharp edge step. And also, the sudden expansion flow increases the shock intensity which results in uneven flow characteristics. Certainly, the present study is very much advantageous to realize the flow behaviors over any kind of backward facing sharp edge steps.*

Keywords- Supersonic, Turbulent Flow, Backward Facing, Sharp Edge Step, Hybrid RANS-LES, Lip Shock.

I. INTRODUCTION

Fluid flow over backward-facing step is one of the central frameworks and has gained specific focus on account of not just simplicity but for voluminous industrialal applications. In applied aerodynamics, it is also used to study many complicated structures, including separation and reattachment. In the field of research of high Mach number flow, the backward facing step is always considered as a complex configuration for ignition in a scramjet, where the recirculation vicinity has a significant role in stabilizing the firing of the engine. Steps on the surfaces of hypersonic or supersonic aircrafts make the flow regime more complicated and hence significant investigations are very much essential for improving the lively design of aircrafts.

II. LITERATURE REVIEW

Smith [1] performed experimental examinations on the flow field and heat transfer downstream of a rearward facing step in supersonic flow. Launder and Sharma [2] used the energy dissipation model of turbulence to analyse the flow field around a spinning disc. Armaly et al. [3] conducted both experimental and theoretical studies on backward facing step flow. Spalart and Allmaras [4] introduced a one-equation turbulence model for assessing aerodynamic flows. Anderson and Wendt [5] reported illustrious and comprehensive descriptions of computational fluid dynamics. Neumann and Wengle [6] used both DNS and LES for examining passively controlled turbulent flow of backward-facing step. Hamed et al. [7] performed the numerical simulations of fluidic control for transonic cavity flows. Chen et al. [8] studied experimentally on fine structures of supersonic laminar as well as turbulent flow over a backward-facing step by using Nano-based Planar Laser Scattering (NPLS). Liu et al. [9] investigated numerically on the influences of inflow Mach number and step height on supersonic flows over a backward-facing step. Terekhov et al. [10] done the experimental studies on the separated flow structure behind a backward-facing step over and above the passive disturbance.

III. OBJECTIVES OF PRESENT RESEARCH WORK

From the reported researches, to the best of author' understanding, it is noticed that there is not a single complete numerical study on flow over a backward facing sharp edge step (involving shock generations) by using hybrid RANS-LES technique. With this perspective, the present research demonstrates the numerical studies on flow behaviors over a backward facing sharp edge step using hybrid RANS-LES method. Furthermore, the numerical model also involves additional important features namely production, diffusion and destruction terms besides the common issues relating to the present physical problem. Furthermore, the specified model also includes both compressibility and eddy viscous effects. The model is very well demonstrated for the meticulous numerical studies on fluid flow characteristics pertaining to flow over a backward facing sharp edge step by introducing the inflow free stream velocity along with the corresponding Mach number as the key model parameters. Eventually, the numerical predictions from the present case of flow over backward facing sharp edge step using the hybrid RANS-LES/Spalart-Allmaras turbulence model also involving viscosity-like variable, are compared with the experimental results of literature. The model predictions pertaining to the stated key model parameters are also along the expected lines and are in very good agreement with the corresponding experimental results. Finally, the presence of pretty strong lip shock (caused by viscous layer separation) exactly near the lip of separation is realized.

IV. DESCRIPTION OF PHYSICAL PROBLEM

Backward facing sharp edge step having wide range of applications in applied aerodynamics is investigated in the present research. The geometric configuration along with initial and boundary conditions are referred from the experimental research report of Smith [1].

A. Geometric model

Figure 1 represents the setup configuration for testing the backward facing sharp edge step flow over sharp edge geometry separating at a step height H = 0.01125 m, upstream distance from inlet to step L_u = 0.1016 m and downstream distance from sharp edge step to outlet L_d = 0.2032 m. The distance from downstream to upper boundary layer Z = 0.15875 m, spanwise distance L= 0.3048 m and width B = 0.025908 m. The separation and reattachment points are represented by S and R respectively and are expected to be observed after performing numerical simulation.

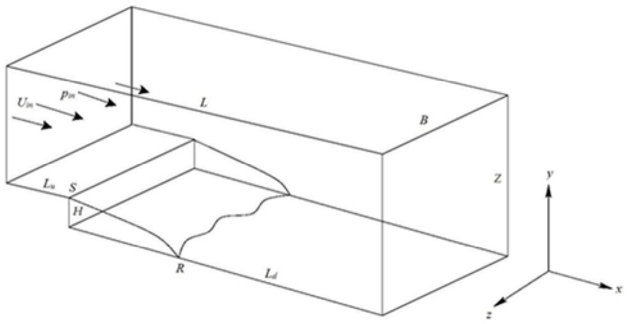

Figure 1. Flow specification of the backward facing sharp edge step

B. Initial and boundary conditions

The inflow free stream velocity U_{in} = 651.9 m/s, for which the known static free stream pressure pin = 15350 N/m2 corresponds to the Mach number M_a = 2.5. At the left side ahead of the step, the initial temperature is maintained at 169.2 K. The initial conditions which are set on the upstream are very much useful throughout the simulation along the spanwise direction, for getting the flow characteristics beyond the step.

For the turbulence, the hybrid RANS-LES (otherwise termed as Detached Eddy Simulation, DES) model is taken into account.

The boundary conditions for the geometry represented by figure 2 are as follows:

- Pressure p = 15.35 kPa, everywhere else for pressure for the hybrid RANS-LES model.
- Temperature T_{in} = 169.2 K, everywhere else for temperature for the hybrid RANS-LES model.
- Velocity U_{in} = 651.9 m/s at the inlet, no-slip wall at the lower boundary, slip wall at the upper boundary and zero velocity gradient at the outlet are set for both the models.

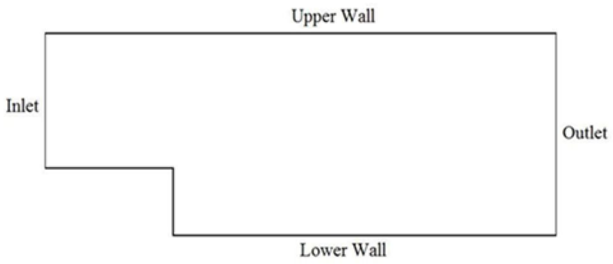

Figure 2. Backward facing sharp edge step boundary representation

V. MATHEMATICAL FORMULATION

A. Generalized governing transport equations

The most generalized governing transport equations of mass, momentum and energy expressed in the conservative form of Navier-Stokes equation for compressible flow accompanying the influences of turbulence are as mentioned underneath.

Continuity:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho \bar{u}_j)}{\partial x_j}=0 \qquad (1)$$

Momentum:

$$\frac{\partial(\rho \bar{u}_i)}{\partial t}+\frac{\partial(\rho \bar{u}_i \bar{u}_j)}{\partial x_j}=-\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}(2\mu S_{ij}+\tau_{tij}) \qquad (2)$$

Energy:

$$\frac{\partial(\rho E)}{\partial t}+\frac{\partial}{\partial x_j}\left(\bar{u}_j(\rho E+p)\right)=\frac{\partial}{\partial x_j}\left((k+k_t)\frac{\partial \bar{T}}{\partial x_j}+(2\mu S_{ij}+\tau_{tij})\bar{u}_i\right)+S_h \qquad (3)$$

Where,

$$\left.\begin{aligned} u_i &= \bar{u}_i + u'_i \\ p &= \bar{p} + p' \\ T &= \bar{T} + T' \end{aligned}\right\} \qquad (4)$$

Total energy, $E=e+k=h-\frac{p}{\rho}+\frac{v^2}{2}$

$$(5)$$

The Reynolds stress term is modeled in terms of the eddy viscosity and is expressed as:

$$\tau_{tij}=2\mu_t(S_{ij}-S_{nn}\delta_{ij}/3)-2\rho k\delta_{ij}/3 \qquad (6)$$

The eddy viscosity is defined as a function of the turbulent kinetic energy k, and the turbulent dissipation rate ε, and is expressed as:

$$\mu_t = c_\mu f_\mu \rho k^2/\varepsilon \qquad (7)$$

In addition, all the model terms/symbols/coefficients/functions have their usual meanings and values.

B. Hybrid RANS-LES turbulence modelling

The Spalart–Allmaras turbulence model is a one-equation model for the eddy viscosity. The use of this model is otherwise known as Hybrid RANS-LES modelling or Detached Eddy Simulation (DES) modelling. The differential equation is derived by using empiricism and arguments of dimensional analysis, Galilean invariance and selected dependence on the molecular viscosity. Grid resolution does not need to be finer for this model, however, one can essentially apprehend the velocity field gradient with the associated algebraic models.

The transport equation for the working variable (otherwise termed as Spalart–Allmaras variable) i.e. viscosity-like variable (ṽ) is expressed as follows:

$$\frac{\partial(\rho\tilde{v})}{\partial t}+\tilde{u}_j\frac{\partial(\rho\tilde{v})}{\partial x_j}$$
$$=c_{b1}\tilde{S}\rho\tilde{v}+\frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}(\mu+\rho\tilde{v})\frac{\partial\tilde{v}}{\partial x_j}+c_{b2}\frac{\partial\tilde{v}}{\partial x_j}\frac{\partial(\rho\tilde{v})}{\partial x_j}\right]-\rho c_{w1}f_w\left(\frac{\tilde{v}}{d}\right)^2 \qquad (8)$$

The eddy viscosity can be expressed as follows:

$$\mu_t = \rho\tilde{v}f_{v1} = \rho v_t \qquad (9)$$

Furthermore, all the model terms/symbols/coefficients/functions have their usual meanings and values.

VI. NUMERICAL PROCEDURES

A. Numerical scheme and solution algorithm

The aforesaid governing transport equations are transformed into generalized form as follows.

$$\frac{\partial}{\partial t}(\rho\varphi)+\nabla.(\rho\mathbf{u}\varphi)=\nabla.(\Gamma\nabla u)+S \qquad (10)$$

The transformed governing transport equations are discretized by expending a pressure based coupled framework relating to finite volume method (FVM) using the SIMPLER algorithm, where ϕ represents any conserved variable and S is a source term. The established pressure based, fully coupled solver is used to predict flow behaviors of the related flow variables in connection with supersonic turbulent flow over a backward facing sharp edge step.

B. Choice of grid size, time step and convergence criteria

Figure 3 shows that the grid of the computational domain is considered to be non-uniform and also grid is refined near the vicinity where the high gradient is expected. . In the present work, the simulation of both the turbulence models with different wall distance from grid is carried out on the computational domain. A comprehensive grid-independence test is performed to establish a suitable spatial discretization, and the levels of iteration convergence criteria to be used. As an outcome of this test, we have used 210 × 160 non-uniform grids for the final simulation. Corresponding time step taken in the simulation is 0.000001 seconds. Though, it is checked with smaller grids of 240 × 180 in numbers, it is observed that a finer grid system does not alter the results significantly.

Convergence in inner iterations is declared only when the condition $\left|\frac{\varphi-\varphi_{old}}{\varphi_{max}}\right| \leq 10^{-4}$ is satisfied simultaneously for all variables, where φ stands for the field variable at a grid point at the current iteration level, φold represents the corresponding value at the previous iteration level, and φmax is the maximum value of the variable at the current iteration level in the entire domain.

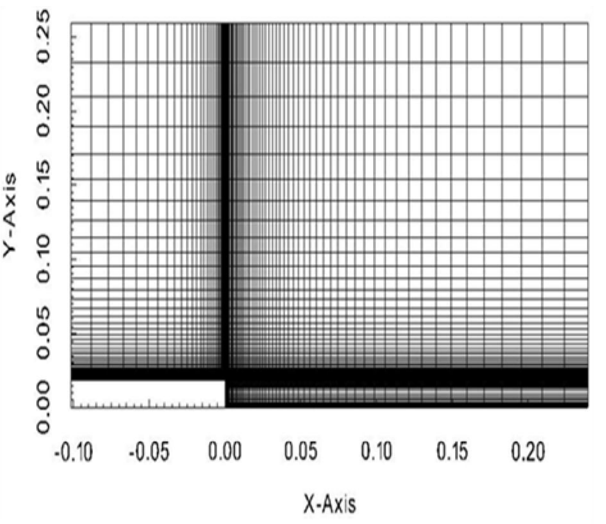

Figure 3. Mesh for backward facing sharp edge step

VII. RESULTS AND DISCUSSION

With the already described model conditions, the numerical simulations are performed for investigating the fluid flow behaviors of the associated flow variables pertaining to supersonic turbulent flow over a backward facing sharp edge step.

A. Comparison with experiments

The simulation accuracy is greatly reliant on grids and non-dimensional sublayer-scaled distance y+ i.e. $u_t y/\nu$. Figure 7 exhibits the influences of various y+ on simulation accuracy of the RANS-LES turbulent model plotted against the related experimental data. Even though, for capturing velocity gradients fine grid resolution is not necessary for hybrid RANS-LES model, however, the non-uniform structured grid with refinement in the vicinity of expected high gradient is very much suitable and appropriate for better solver convergence and resolution near the wall. That is why, in the present investigation the refinement near the wall and the separation line is maintained with y^+ of 1 and 11 and the corresponding results are as shown in figure 7. The computational time for $y^+ = 1$ is very considerably greater than $y^+ = 11$. Nevertheless, $y^+ = 1$ with the hybrid RANS-LES has less computational time comparable to Direct Numerical Solution (DNS) and also both converge with the associated experimental data over and done with the same accuracy.

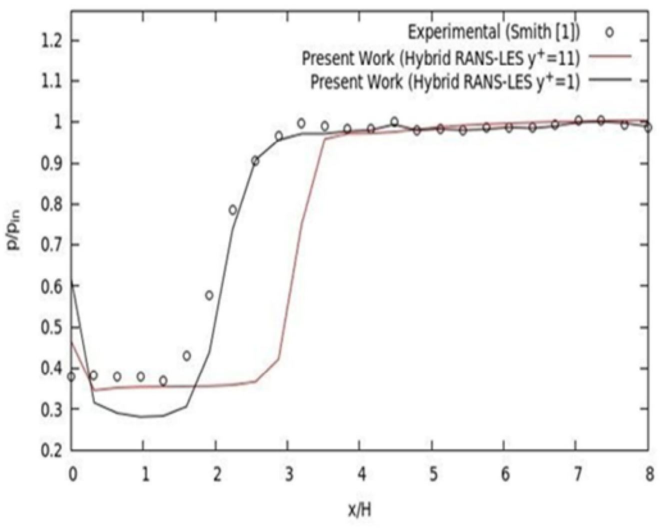

Figure 4. Influence of y^+ over simulation accuracy

B. Pressure recovery distributions

Figure 5 depicts the spanwise pressure recovery distribution which is plotted against the non-dimensional distance along the wall behind the step. The figure shows a sudden pressure drop at the tip of separation which is due to sudden expansion of flow. The pressure fluctuation is directly responsible for the presence of shock. In this figure pressure fluctuates two times representing two shock waves which are generated across the flow field. The sudden fluctuation indicates the intensity of shock wave. In other words, this plot represents the pressure recovery taking place under the shock waves which also includes several losses to the flow field.

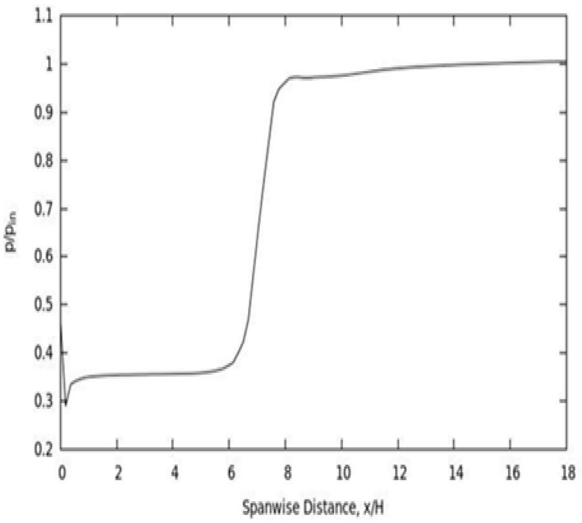

Figure 5. Pressure recovery distributions along flow direction.

C. Flow fields of pressure gradient distributions involving presence of lip shock

Figure 6 represents the shock formation in the flow field captured from the pressure gradient standard deviation. Furthermore, figure 7 shows the presence of lip shock exactly near the lip of separation and the appearance of this shock is due to viscous layer separation. In addition, from figure 7, it is also easily noticeable that the intensity of lip shock is quite strong. Although, the lip shock appears in the lower part of the expansion fan, however, the present investigation reveals that the intensity of the lip shock is considered to be really an important part of the flow field. This shock is slightly curved in nature due to sudden expansion. The intensity is greatly strong for high Mach flow and causes losses to the flow field as observed from the present study.

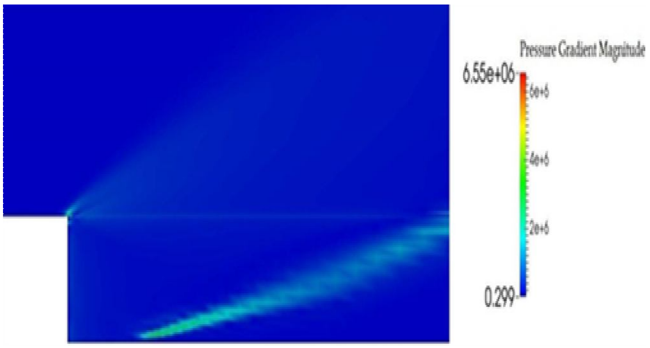

Figure 6. Shock representation of the flow field

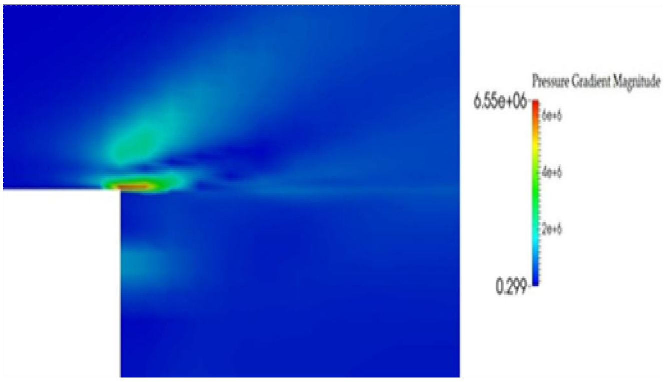

Figure 7. Lip shock representation near the separation edge

Also, the presence of lip shock can be seen in recovery curve of figure 5, which appears to be a hump like structure at the separation edge.

VIII. CONCLUSION

A 2D numerical model is established to study fully supersonic fluid flow over a backward facing sharp edge step by incorporating hybrid RANS-LES turbulence model. It relates to the Spalart-Allmaras model which includes a viscosity-like variable ($\tilde{v}$). The model also considers the added essential issues namely production, diffusion and destruction factors in addition to the very normal aspects associated with the present investigation. The simulations are done by the said turbulent model with the inflow free stream Mach number of 2.5 associated with free stream pressure and velocity of 15350 N/m^2 and 651.9 m/s^2, respectively. The simulation results are compared with the corresponding experimental results available in the literature. The hybrid RANS-LES model gives reasonably better and accurate results throughout the entire flow domain and hence, it is considered for all further investigations. It is also witnessed that the sudden viscous layer separation is the central cause of the shock generations. Additionally, the uneven pressure recovery is on account of the sudden expansion flow over the sharp edge step. Furthermore, the sudden expansion flow increases the intensity of shock which leads to the uneven flow behaviors. Indeed, the present investigation is really valuable to understand the flow characteristics over any type of backward facing sharp edge steps. However, a numerical model pertaining to use of backward facing rounded step (i.e. geometric variations in step) is underway and is planned for the future to eliminate the lip shock completely from flow field for realizing the smooth and favourable flow.

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