Numerical Modeling on Lip Shock Characteristics over Backward Facing Sharp Edge Step Using Hybrid RANS-LES

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ABSTRACT *In the currentinvestigation, a 2D numerical model is developed to study supersonic turbulent fluid flow over a backward facing sharp edge step with hybrid RANS-LES model. It relates to the Spalart-Allmaras model involving a viscosity-like variable ($\tilde{v}$). 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. It is witnessed that the sudden viscous layer separation is the vitalreason of the shock generations. Additionally, the sudden expansion flow over the sharp edge step rises the shock intensity which results in uneven flow characteristics. Indeed, the current study is very much helpful to capture the flow performances over any type 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 has gotseveral industrial applications. 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.*

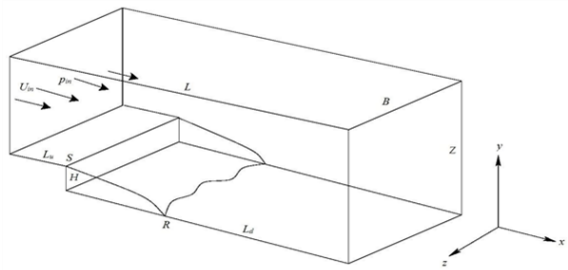
From the statedstudies, to the best of author' understanding, it is noticed that there is not a single complete numerical study on flow over a backward facing sharp edge step (involving shock generations) by using hybrid RANS-LES technique. With this perspective, the present research demonstrates the 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.To conclude, the existence of very strong lip shock (due to viscous layer separation) preciselyclose the lip of separation is captured.

II. Description of Physical Problem

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 tobe observed after performing numerical simulation.



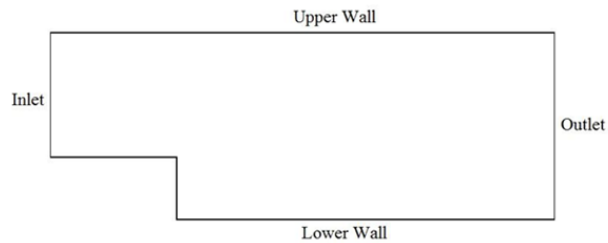


Fig 1. Flow specification of sharp edge step. **Fig 2. Boundary representation ofsharp edge step.**

B.Initial and boundary conditions

Figure 2 shows the inflow free stream velocity U_{in} = 651.9 m/s, for which the known static free stream pressure p_{in} = 15350 N/m^2 corresponds to the Mach number Ma = 2.5. At the left side ahead of the step, the initial temperature is maintained at 169.2 K. The stated initial conditions along with no-slip wall at lower boundary, slip wall at upper boundary and zero velocity gradient at outlet are also set.

III. Mathematical Formulation and Numerical Procedures

A. Generalized governing transport equations

The most generalized governing transport equations of mass, momentum and energy for turbulent and compressible flow are as mentioned below.

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

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

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

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

Total energy, $$E = e + k = h - \frac{p}{\rho} + \frac{v^2}{2} \quad (5)$$

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

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

The eddy viscosity is defined as a function of the turbulent kinetic energy k, and the turbulent dissipation rate ε, and is expressed as: $$\mu_t = c_\mu f_\mu \rho k^2/\varepsilon \quad (7)$$

B. Hybrid RANS-LES turbulence modelling

The Spalart–Allmaras turbulence model otherwise known as Hybrid RANS-LES model or Detached Eddy Simulation (DES) model is a one-equation model for the eddy viscosity. The transport equation for the working variable (otherwise termed as Spalart–Allmaras variable) i.e. viscosity-like variable ($\tilde{\nu}$) is expressed as follows:

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

The eddy viscosity can be expressed as: $$\mu_t = \rho\tilde{\nu}f_{v1} = \rho\nu_t \quad (9)$$

C. Numerical techniques

The transformed governing transport equations are solved by expending pressure based coupled framework relating to finite volume method (FVM) using the SIMPLER algorithm.Figure 3 shows the grid of the computational domain. As an outcome of thecomprehensive grid-independence test, we have used 210 × 160 non-uniform grids for the final simulation. Corresponding time step taken in the simulation is 0.000001 seconds.

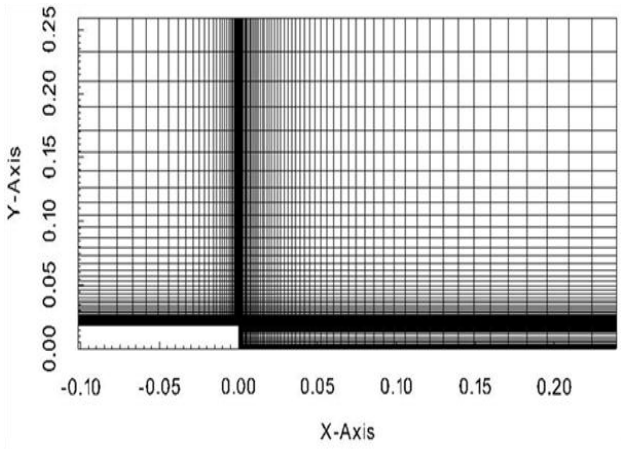


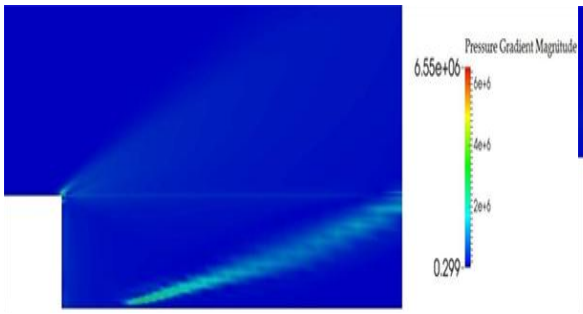
Fig 3. Mesh for backward facing sharp edge step.

IV. Results and Discussions

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.

Flow fields of pressure gradient distributions involving presence of lip shock

Figure 4 represents the shock formation in the flow field captured from the pressure gradient standard deviation. Furthermore, figure 5 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 5, 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.Also, the presence of lip shock can be seen in pressure recovery curve of figure 5, which appears to be a hump like structure at the separation edge.



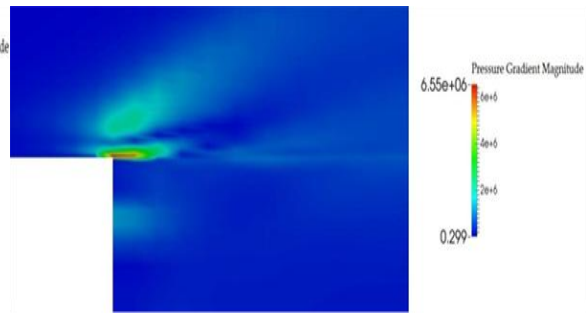


Fig 4. Shock representation of the flow field. **Fig 5. Lip shock existence near the separation edge.**

V. Conclusion

A 2D numerical model is developed to investigate supersonic fluid flow over a backward facing sharp edge step using hybrid RANS-LES turbulence model. It pertains 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 reveal thatthe hybrid RANS-LES model gives reasonably better and

accurate results throughout the entire flow domain. It is also observed that the sudden viscous layer separation is the central cause of the shock generations. Besides, the sudden expansion flow increases the intensity of shock which leads to the uneven flow behaviors. Certainly, the present study is really valuable to understand the flow characteristics over any type of backward facing sharp edge steps. But, the development of a numerical model relating to use of backward facing rounded step is in progress to diminish the lip shock entirely from flow field for gettingeven flow behavior.

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