

Numerical Studies on Flow Features past a Backward Facing Sharp Edge Step Introducing Hybrid RANS-LES

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Abstract

The current investigation involves the development of a 2D numerical model for examining the fluid flow behaviors over a backward facing sharp edge step deploying the hybrid RANS-LES turbulent model which also includes a viscosity-like variable. The model encompasses key issues like production, diffusion and destruction terms. The simulations are done with inflow free stream Mach number of 2.5 corresponding to free stream pressure and velocity of 15350 N/m^2 and 651.9 m/s , respectively. The simulation predictions of density, vorticity and Mach number are observed to be fairly consistent and also along the expected lines all over the whole flow regime. It is observed that both vorticity intensity and Mach number are quite high at the expansion fan near the lip of the separation as well as near the reattachment shock, whereas, the fluid density is quite low at the same. Furthermore, it is also noticed that the recirculation vicinity which is also otherwise called as dead air region has experienced the least fluid density, vorticity along with the Mach number owing to non-viscous rotation. In addition, both density field and Mach number benefit us in understanding whether the fluid flow is compressible or incompressible nature. In addition, the sudden change within the flow field causes the vorticity generation resulting in uneven flow performances.

Keywords: Density, Vorticity, Mach number, Backward Facing, Sharp Edge Step, Hybrid RANS-LES.

1. Introduction

Steps on the surfaces of hypersonic or supersonic aircrafts make the flow region more challenging and hence significant researches are really essential for refining the dynamic design of aircrafts. Smith [1] executed experimental studies on the flow field and heat transfer downstream of a rearward facing step in supersonic flow. Launder and Sharma [2] applied the energy dissipation model of turbulence to investigate 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] presented a one-equation turbulence model for evaluating aerodynamic flows. Anderson and Wendt [5] testified illustrious and complete descriptions of computational fluid dynamics. Neumann and Wengle [6] used both DNS and LES for investigating passively controlled turbulent flow of backward-facing step. Hamed et al. [7] done the numerical simulations of fluidic control for transonic cavity flows. Chen et al. [8] experimentally investigated on fine structures of supersonic laminar and turbulent flow over a backward-facing step through the Nano-based Planar Laser Scattering (NPLS). Liu et al. [9] numerically studied on the influences of inflow Mach number and step height on supersonic flows over a backward-facing step. Terekhov et al. [10] accomplished the experimental investigations on the separated flow structure behind a backward-facing step over and above the passive disturbance.

From the reported studies, to the best of author's information, it is observed that there is not a single extensive numerical study on flow over a backward facing sharp edge step by means of hybrid RANS-LES technique. With this standpoint, the current investigation establishes the numerical studies on flow characteristics over a backward facing sharp edge step by means of hybrid RANS-LES method. Furthermore, the numerical model also includes key features namely production, diffusion and destruction terms apart from the usual issues pertaining to the present physical problem. Additionally, the specified model also includes both compressibility and eddy viscous effects. The model is thoroughly demonstrated for the careful numerical studies on fluid flow behaviours relating to flow over a backward facing sharp edge step by using the inflow free stream velocity and the corresponding Mach number as the important model parameters. Eventually, a 2D numerical model is developed to investigate the flow characteristics, pertaining to density, vorticity and Mach number distributions, over a backward facing sharp edge step using the hybrid RANS-LES/Spalart-Allmaras turbulent model which also includes a viscosity-like variable. Finally, the simulation predictions of density, vorticity and Mach number are found to be quite consistent and also along the expected lines throughout the entire flow regime.

2. Description of Physical Problem

A. Geometric model

Figure 1 embodies 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 denoted by S and R respectively and are likely to be obtained after carrying out numerical simulation.

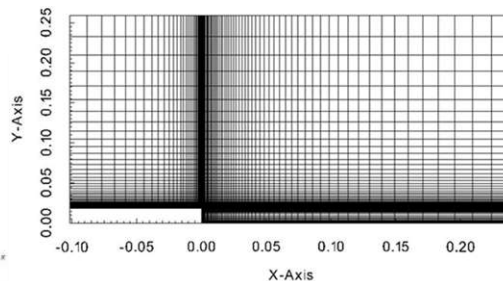
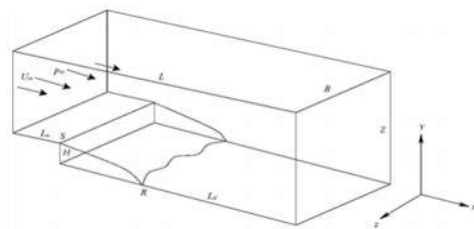


Fig 1. Backward sharp edge step. Fig 2. Mesh of backward sharp edge step.

B. Initial and boundary conditions

The inflow free stream velocity $U_{in} = 651.9$ m/s, for which the identified static free stream pressure $p_{in} = 15350$ N/m² 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 initial conditions which are set on the upstream are really useful during the simulation along the spanwise direction, for obtaining the flow features beyond the step.

3. Mathematical Formulation and Numerical Procedures

A. Generalized governing transport equations

Very generalized governing transport equations of mass, momentum and energy stated in the conservative form of Navier-Stokes equation for compressible flow in association with the influences of turbulence are as follows.

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

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

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

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

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

The Reynolds stress term is modeled in terms of the eddy viscosity and is represented by:

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

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

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

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

B. Hybrid RANS-LES Turbulence Modelling

The Hybrid RANS-LES/Spalart-Allmaras turbulence model also otherwise called as Detached Eddy Simulation (DES) model is a one-equation model for the eddy viscosity. The differential equation is derived from empiricism and arguments of dimensional analysis, Galilean invariance and selected dependence on the molecular viscosity. Grid resolution is not necessarily finer for this model, but, one can essentially capture the flow field with the related algebraic models.

The transport equation for the working variable (otherwise known as Spalart-Allmaras variable) i.e. viscosity-like variable ($\tilde{\nu}$) is represented by:

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

$$\text{The eddy viscosity is represented by: } \mu_t = \rho \tilde{\nu} f_{v1} = \rho \nu_t \quad (9)$$

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

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 2 demonstrates that the grid of the computational domain is taken to be

non-uniform and also grid is refined near the vicinity where the high gradient is expected. A comprehensive grid-independence test is carried out to develop an appropriate spatial discretization, and the levels of iteration convergence criteria to be used. As a consequence 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.

4. Results and Discussions

A. Density distribution

It is quite obvious that the high Mach inflow is the cause of more density gradient within the flow field. Moreover, it is rather apparent that because of the shock generation, density recovery behind the sharp edge step is also not flawless enough for smooth and sound fluid flow. Additionally, the physics behind the density gradient due to two parallel shocks can simply be understood from the coloured density field together with the corresponding vertical scale bar, as illustrated in figure 3. If the flow field experiences density variation more than five present then the flow is considered to be compressible flow which may be observed from the density field. In other words, the density field helps us in understanding whether the flow is compressible or incompressible nature.

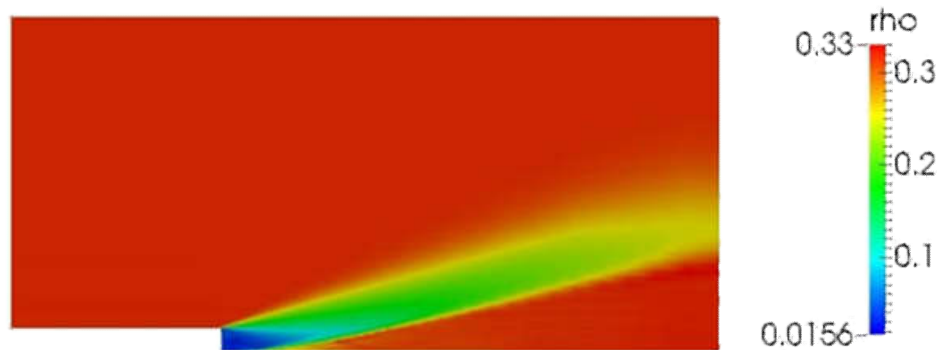


Fig 3. Density field for flow past backward facing sharp edge step.

B. Vorticity distribution

Figure 4 demonstrates the coloured vorticity distribution together with the corresponding vertical scale bar, within the flow field. It may be observed that the vorticity intensity is quite high at the expansion fan near the lip of the separation as well as near the reattachment shock. Owing to viscous layer separation at the separation edge, the generation of lip shock has taken place, in addition, the interaction of shock and expansion fan has led to the generation of vorticity. The vorticity generation is due to sudden change within the flow field. Furthermore, the vorticity generation becomes predominant because of the turbulent boundary layer separation.

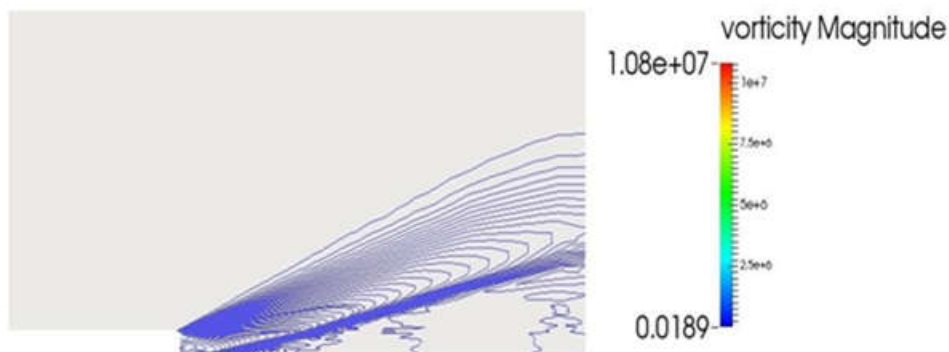


Fig 4. Vorticity distribution for flow past backward facing sharp edge step.

C. Mach distribution

The physics behind the Mach number gradient due to two parallel shocks can simply be understood from the coloured Mach number field together with the corresponding vertical scale bar, as illustrated in figure 5. If the Mach number is more than 0.3 then the fluid region is considered to be compressible which may be observed from the Mach number field. In other words, the Mach number field helps us in understanding whether the fluid region is compressible or incompressible nature. However, no such changes or extra special effect is observed near the upper region of flow field.

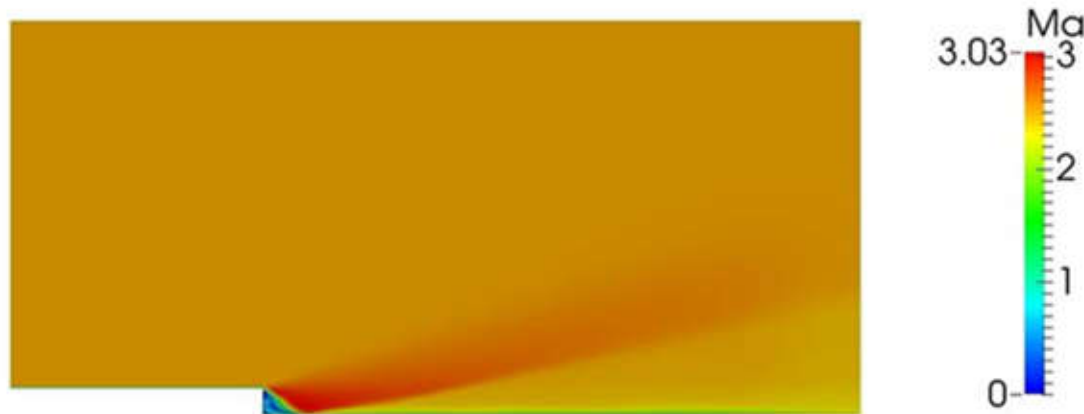


Fig 5. Mach field for flow past backward facing sharp edge step.

5. Conclusion

A 2D numerical model is developed to predict the fluid flow behaviors over a backward facing sharp edge step with the hybrid RANS-LES turbulent model which comprises a viscosity-like variable ($\tilde{\nu}$). The model also incorporates fundamental terms namely production, diffusion and destruction in to account. The numerical simulations are conducted with inflow free stream Mach number of 2.5 corresponding to free stream pressure and velocity of 15350 N/m^2 and 651.9 m/s^2 , respectively. The simulation results of density, vorticity and Mach number are witnessed to be quite consistent and also along the lines of expectations within the entire flow regime. It is noticed that both vorticity intensity and Mach number are rather high at the expansion fan near the lip of the separation and near the reattachment shock, while, the fluid density is rather low at the same. In addition, it is also observed that the recirculation vicinity which is also otherwise termed as dead air region has felt the lowest fluid density, vorticity together with the Mach number because of non-viscous rotation. Furthermore, both density field as well as Mach number helps us in realizing whether the fluid flow is compressible or incompressible nature. Also, the sudden change within the flow field leads to the vorticity generation causing the uneven flow behaviors. Definitely, the present simulation predictions will be very much useful to get more flow performances.

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