Numerical Simulation on Supersonic Turbulent Flow past Backward Facing Rounded Step Utilizing Hybrid RANS-LES

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Abstract

A 2D computational model is developed to study the supersonic flow past backward facing rounded step using the hybrid RANS-LES turbulence model, which makes use of a viscosity-like working variable ($\tilde{v}$). Furthermore, the model also encompasses more significant contests like production, diffusion and destruction terms apart from the very usual issues relating to the current studies. The numerical simulations are executed with the stated turbulence model with the inflow free stream Mach number of 2.5 corresponding to the free stream pressure and velocity of 15350 N/m^2 and 651.9 m/s^2, respectively. The simulation results disclose that the gradual expansion goes on over the rounded step causing the delay in viscous layer separation. Indeed, it results in the formation of relatively shorter shear layer together with the fairly shorter recirculation region, approaching towards the dead air region of the bottom wall. Furthermore, it is very clear from the current study that there is diminishing of shock owing to the use of rounded step.

Keywords: Supersonic, Turbulent Flow, Backward Facing, Rounded Step, Hybrid RANS-LES.

1. Introduction

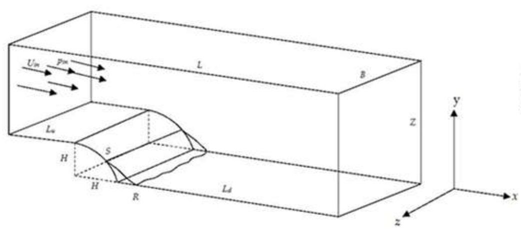
Flow over backward-facing step is one of the suitably vivacious perspectives and has increased clear-cut attention because of not just minimalism but for extensive industrial and scientific practices. The experimental investigations on flow field along with the heat transfer, downstream of a rearward facing step in supersonic flow is carried out by Smith [1]. The energy dissipation model of turbulence is introduced by Launder and Sharma [2], to examine the flow field within the vicinity of a spinning disc. Both experimental and theoretical investigations on backward facing step flow are also reported by Armaly et al. [3]. A one-equation turbulence model is used by Spalart and Allmaras [4], to analyse aerodynamic flow behaviours. The fundamental and yet comprehensive along with the illustrious discussions about the CFD is also reported by Anderson and Wendt [5]. Both DNS and LES are utilized by Neumann and Wengle [6], to investigate the passively controlled turbulent flow of backward-facing step. The numerical simulations of fluidic control for transonic cavity flows is also conducted by Hamed et al. [7]. The experimental investigations on fine structures of supersonic laminar along with turbulent flow over a backward-facing step by using Nano-based Planar Laser Scattering (NPLS) are also done by Chen et al. [8]. The numerical studies on the effects of inflow Mach number and step height on supersonic flows over a backward-facing step are carried out by Liu et al. [9]. The *e*xperimental studies on the separated flow behavior behind a backward-facing step together with the passive disturbance are also executed by Terekhov et al. [10].

From the aforementioned studies, to the best of author' understanding, it is observed that there is not a single full numerical investigation on supersonic turbulent flow over a backward facing rounded step by means of hybrid RANS-LES method. With this outlook, the current study exhibits the numerical studies on flow characteristics over a backward facing rounded step by considering the hybrid RANS-LES method. Furthermore, the numerical model also includes additional significant factors like production, diffusion and destruction terms above and beyond the normal issues concerning the current physical research problem. In addition, the specified model also introduces both compressibility as well as eddy viscous effects. The model is superbly demonstrated for the thorough numerical investigations on fluid flow behaviors relating to flow over a backward facing rounded step by presenting the inflow free stream velocity together with the corresponding Mach number as the important model parameters. Finally, the model predictions with reference to the stated important model parameters are along the lines of expectations as well. Ultimately, the current case of fully supersonic turbulent fluid flow over the backward facing rounded step simulated through the hybrid RANS-LES also accompanying the viscosity-like variable witnessed that the diminishing of shocks is only due to the geometric changes in the steps.

2. Description of Physical Problem

A. Geometric model

Figure 1 illuminates the system structure for analysing the backward facing rounded step flow over rounded step geometry involving step height H = 0.01125 m, upstream distance from inlet to step L_u = 0.1016 m, downstream distance from rounded step to outlet L_d = 0.2397 m and the rounded step radius H = 0.01125 m. The distance from downstream to upper boundary layer Z = 0.15875 m, spanwise distance L= 0.3048 m along with the width B = 0.025908 m. Besides, both separation (S) and reattachment (R) points are likely to be witnessed from the numerical simulation.



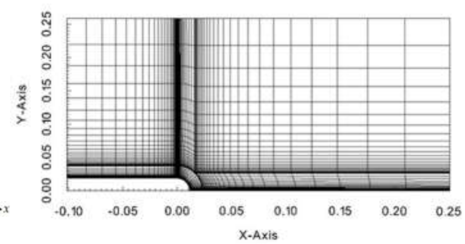


Fig 1. Backward facing rounded step. Fig 2. Mesh of backward rounded step.

B. Initial and boundary conditions

The inflow Mach number Ma = 2.5 Ma, associated with the specified inflow static pressure of about p_{in} = 15350 N/m^2 along with the free stream velocity of U_{in} = 651.9 m/s. The temperature to the left of the rounded step is maintained at T_{in} = 169.2 K. For fully feeling the effects of turbulence, the hybrid RANS-LES model is introduced.

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.

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

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

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

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

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 ($\tilde{v}$) is represented by:

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

The eddy viscosity is represented by: $\mu_t = \rho\tilde{v} f_{v1} = \rho v_t$ (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 result of this test, 175 × 175 number of non-uniform grids are used for the final simulation. Corresponding time step chosen in the current simulation is 0.000001 seconds.

4. Results and Discussions

A. Pressure distribution

Figure 3 shows the coloured pressure field together with the vertical scale bar, demonstrating the gradual decrease in pressure near the vicinity of the expansion fan region, while, the reattachment shock region has also noticed gradual increase in pressure. Furthermore, the recirculation vicinity i.e. dead air region has realized the least pressure because of inviscid rotation. Additionally, the supersonic turbulent flow over the backward facing rounded step has also witnessed gradual pressure fluctuations between expansion fan as well as reattachment shock wave regions. In addition, it is rather apparent that due to the gradual expansion (because of very less pressure gradient) over the rounded step there is smooth and flawless fluid flow. In other words, the pressure gradient between the expansion fan and reattachment shock is very considerably low. Hence, the relatively less pressure gradient helps the flow field to be efficient, effective and uneven. Besides, figure 3 also illustrates the physics behind the pressure gradient owing to two parallel weak shocks.

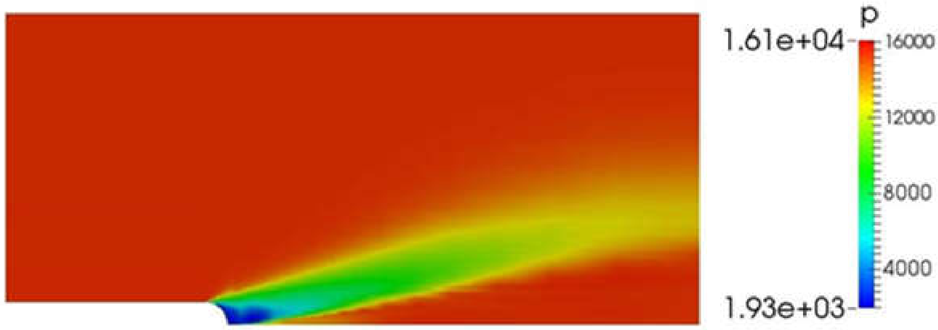


Fig 3. Pressure field for flow past backward facing rounded step.

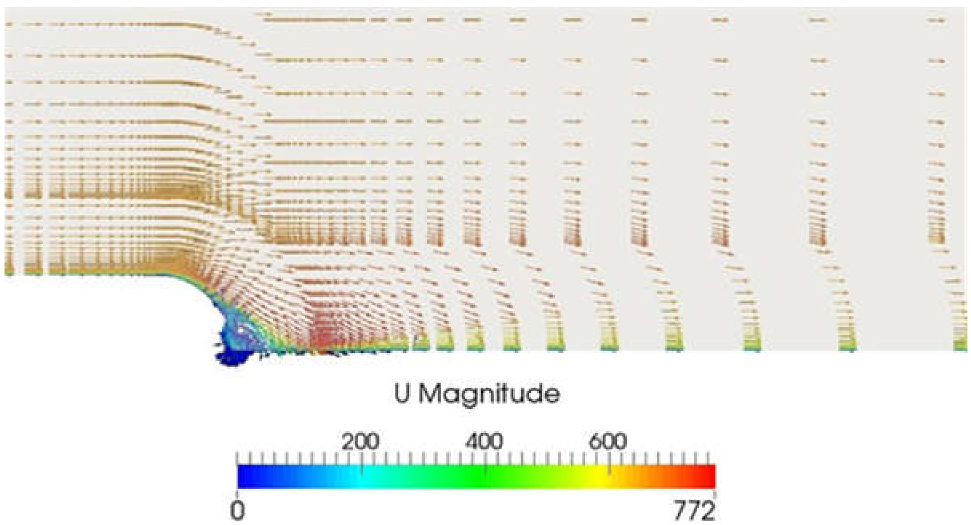


Fig 4. Velocity vector for flow past backward facing rounded step.

B. Velocity distribution

Figure 4 describes the velocity vector pertaining to the supersonic turbulent fluid flow over the backward facing rounded step. It is quite obvious that gradual expansion over the rounded step leads to delay in viscous layer separation resulting in the formation of relatively shorter shear layer and reattachment length over the bottom wall associated with the reattachment shock and redeveloping boundary layer. Besides, the flow around the shear layer approaches to the bottom wall which will follow along the initial direction. However, a part of the flow reverses to the dead air region which causes it as a recirculation region. However, the recirculation region gets reduced/minimized and the reattachment length becomes shorter with very less flow field losses leading to quite smooth and flawless flow near the recirculation vicinity. Furthermore, the coloured velocity vector together with the horizontal scale bar, within the fluid flow region as superbly illustrated in figure 4, also helps us for appropriately perfect understanding of the reattachment point flow physics proximate to the bottom wall region.

5. Conclusion

In the current investigation, a 2D numerical model is developed to study the fully supersonic turbulent flow characteristics over a backward facing rounded step. The model also take account of extra important issues like production, diffusion and destruction factors, in addition to the very normal features on the subject of the current study. The model is wonderfully tested for the thorough numerical studies on fluid flow characteristics using the compressible turbulent hybrid RANS-LES, which involves a viscosity-like working variable ($\tilde{\nu}$). The model includes the inflow free stream velocity and the corresponding Mach number as the important model parameters. Eventually, the model results relating to the stated vital model parameters are also along the expected lines. In addition, the model is observed to give fairly better and consistent results, and hence, it is chosen for the present research examinations. Besides, the simulation results show that the gradual expansion occurs over the rounded step giving rise to the delay in viscous layer separation. Definitely, it reasons the formation of quite shorter shear layer together with the equally shorter recirculation region, approaching towards the dead air region of the bottom wall. Moreover, it is quite obvious about the presence of very weak shock over the rounded step. Therefore, it is realized that there is diminishing of shocks due to the modeling practice with rounded step.

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