Numerical Simulationon Flow Behaviors over Backward Facing Rounded Step Applying Hybrid RANS-LES

Dr. Nirmal Kumar Kund
Associate Professor, Department of Production Engineering
Veer Surendra Sai University of Technology, Burla, Odisha, India

Received: April 29, 2018 Accepted: May 26, 2018

ABSTRACT *A 2D numerical model is developed to examine the fully supersonic fluid flow over the backward facing rounded step by using the hybrid RANS-LES/Spalart-Allmaras turbulence model, which encompasses a viscosity-like working variable ($\tilde{v}$). Furthermore, the stated numerical model also includes both compressibility and eddy viscous effects along with the relatively more vital issues like production, diffusion and destruction terms concerning the current investigations. The model parameters considered are the inflow free stream Mach number of 2.5 along with the free stream pressure and velocity of 15350 N/m² and 651.9 m/s², respectively. The simulation predictions with the stated hybrid RANS-LES turbulence model provides reasonably superior and accurate results all over the complete flow regime together with the wall vicinity regime as well, thus, the stated model is utilized throughout the complete examinations. The simulation results of pressure and velocity fields reveal that the gradual expansion occurs over the rounded step leading to the delay in viscous layer separation. Certainly, it results in the formation of relatively shorter shear layer together with the equally shorter recirculation region, approaching towards the dead air regime of the bottom wall. Additionally, it is quiteobvious from the present study that the presence of relatively weak shocks over the rounded step*

Keywords: *Supersonic Turbulent Flow; Backward Facing; Rounded Step; Hybrid RANS-LES; Flow Field.*

I. Introduction

Fluid flow over backward-facing step is havingnumerous industrial uses. 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 aforementioned studies, to the best of author' understanding, it is realistic that there is not a single full numerical study on supersonic turbulent flow over a backward facing rounded step by means of hybrid RANS-LES method. With this viewpoint, the current study exhibits the numerical studies on flow characteristics over a backward facing rounded step by considering the hybrid RANS-LES technique. Additionally, the numerical model also comprises additional significant factors like production, diffusion and destruction terms above and beyond the usual issues concerning the current research. Furthermore, the specified model also introduces both compressibility as well as eddy viscous effects. The model is fabulously demonstrated for the detailed numerical investigations on fluid flow characteristics relating to flow over a backward facing rounded step by involving the inflow free stream velocity along with the corresponding Mach number as the key model parameters. Ultimately, the model predictions in connection with the said important model parameters are along the expected lines. Finally, the current case of fully supersonic turbulent fluid flow over the backward facing rounded step with the hybrid RANS-LES/Spalart-Allmaras turbulence model involving the viscosity-like variable reveals that the growth/decay of shock is only on account of the geometric variations in the steps.

II. Description of Physical Problem

A. Geometric model

Figure 1 demonstrates the system structure for analyzing 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 tobe witnessed from the numerical simulation.

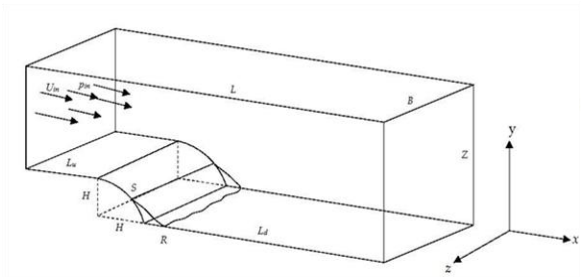


Fig 1. Flow specification of rounded step.

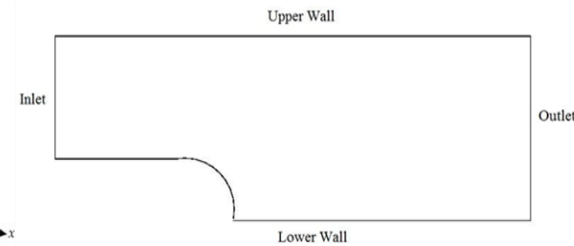


Fig 2. Boundary representation ofrounded step.

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

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: $\mu_t = \rho \tilde{\nu} f_{v1} = \rho \nu_t$ (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 175× 175 non-uniform grids for the final simulation. Corresponding time step taken in the simulation is 0.000001 seconds.

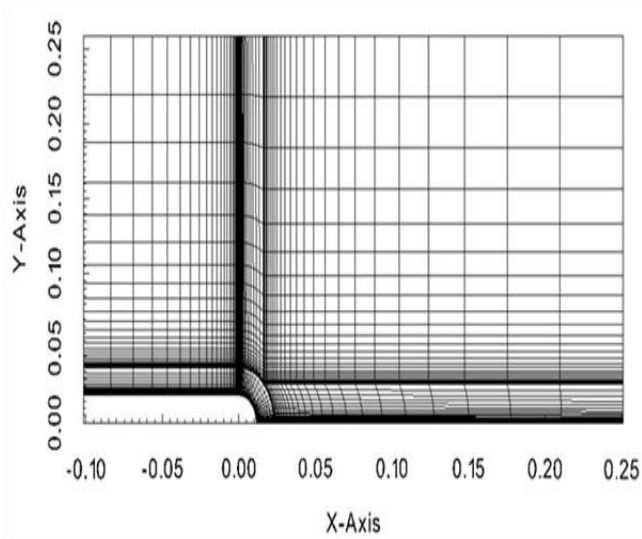


Fig 3. Mesh for backward facing rounded step.

IV. Results and Discussions

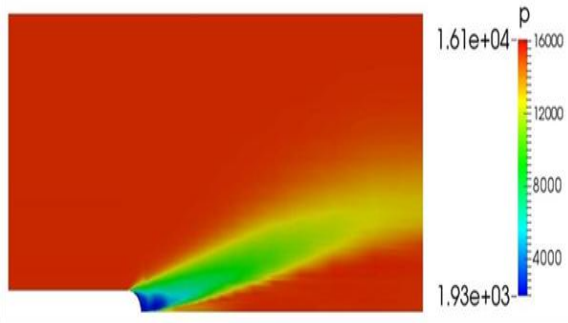
With the stated model conditions, the numerical simulations are performed for investigating the fluid flow behaviors of the associated flow variables pertaining to supersonic turbulent flow over a backward facing rounded step.

A. Pressure flow field for flow over rounded step

Figure 4illustrates the colored pressure field together with the vertical scale bar, illustrating the gradual decrease in pressure near the vicinity of the expansion fan region, whereas, the reattachment shock region has also witnessed gradual increase in pressure. Additionally, the recirculation vicinity i.e. dead air region has experienced the least pressure on account of non-viscous rotation. Besides, the supersonic turbulent flow over the backward facing rounded step has also felt gradual pressure fluctuations between expansion fan and reattachment shock wave regions. Furthermore, it is pretty obvious that because of the gradual expansion (owing to very less pressure gradient) over the rounded step there is effective and sound fluid flow. Specifically, the pressure gradient between the expansion fan and reattachment shock is very noticeably low. Therefore, the reasonably less pressure gradient results in the flow field to be favorable, smooth and efficient. Above and beyond, the physics behind the pressure gradient on account of two parallel weak shocks may certainly be understood from the present pressure field figure 4.

B.Velocity flow field for flow over rounded step

Figure 5demonstrates the colored velocity vector together with the horizontal scale bar within the fluid flow region relating to the supersonic turbulent fluid flow over the backward facing rounded step. It is pretty understandable 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. Furthermore, the flow around the shear layer approaches to the bottom wall which will follow the initial direction. Nevertheless, a part of the flow reverses to the dead air region which causes it as a recirculation region. And also, 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. In addition, the velocity vector inside the fluid flow regime also benefits in proper understanding of the reattachment point flow physics close to the bottom wall regime.



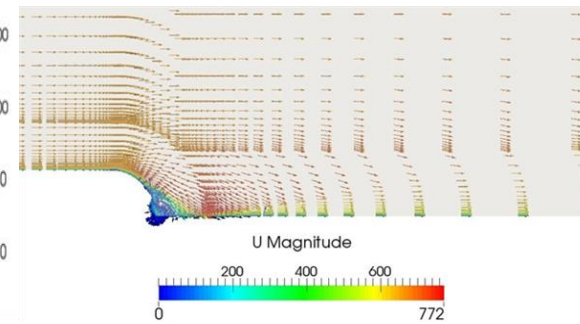


Fig 4. Pressure field for flow over rounded step. Fig 5. Velocity vector for flow over rounded step.

V. Conclusion

In the currentexamination, a 2Dcomputational model is established to study the supersonic turbulent flow over a backward facing rounded step by using the hybrid RANS-LES/Spalart-Allmaras turbulence model, encompassing a viscosity-like working variable ($\tilde{v}$). Furthermore, the said numerical model also includes both compressibility and eddy viscous terms accompanied by the comparatively more important issues like production, diffusion and destruction factors relating to the current studies. The model parameters taken into are the inflow free stream Mach number of 2.5 in conjunction with the free stream pressure and velocity of 15350 N/m^2 and 651.9 m/s^2, respectively. The simulations with the said hybrid RANS-LES turbulence model offerscredibly better and accurate predictions throughout the whole flow region alongside the wall vicinity region as well, therefore, the said model is used during the course of the entire investigations. The simulation predictions of both pressure and velocity fields unveil that the gradual expansion occurs over the rounded step leading to the delay in viscous layer separation. Undeniably, it brings about the formation of fairly shorter shear layer along with the equally shorter recirculation region, approaching towards the dead air region of the bottom wall. Furthermore, it is quite obvious from the currentstudy that the occurrence of reasonably weak shocks over the rounded step. Thus, it is observed that there is diminishing of shock owing to the modelling practice with rounded step.

References

[1] Smith, Howard E. “The flow field and heat transfer downstream of a rearward facing step in supersonic flow.” No. ARL-67-0056. Aerospace Research Labs, Wright Patterson AFB, Ohio, (1967).

[2] Launder, B. E., and B. I. Sharma. "Application of the energy-dissipation model of turbulence to the calculation of flow near a spinning disc." Letters in heat and mass transfer Vol. 1, Issue 2 (1974): 131-137.

[3] Armaly B. F., Durst F., Pereira J. C. F., and Schoenung B., “Experimental and theoretical investigation of backward facing step flow,” Journal of Fluid Mechanics, Vol. 127, pp. 473–496, (1983).

[4] Spalart, Phillipe R., and Steven R. Allmaras. "A one-equation turbulence model for aerodynamic flows." (1992).

[5] Anderson, John David, and J. F. Wendt. Computational fluid dynamics. Vol. 206. New York: McGraw-Hill, (1995).

[6] Neumann, Jens, and Hans Wengle. "DNS and LES of passively controlled turbulent backward-facing step flow." Flow, turbulence and Combustion 71.1-4 (2003): 297-310.

[7] Hamed, A., K. Das, and D. Basu. "Numerical simulations of fluidic control for transonic cavity flows." AIAA Paper 429, (2004).

[8] Chen, Zhi, et al. "An experimental study on fine structures of supersonic laminar/turbulent flow over a backward-facing step based on NPLS." Chinese Science Bulletin, Vol. 57, Issue 6, (2012): 584-590.

[9] Liu, Haixu, et al. "Effects of Inflow Mach Number and Step Height on Supersonic Flows over a Backward-Facing Step." Advances in Mechanical Engineering (2013).

[10] I. Terekhov, Ya. I. Smul’skii, and K. A. Sharov, *“Experimental study of the separated flow structure behind a backward-facing step and a passive disturbance,”*Journal of Applied Mechanics and Technical Physics, Volume 57, Issue 1, (2016)pp 180–187.