Numerical Investigations on Fluid Flow over Backward Facing Rounded Step Expending Hybrid RANS-LES

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Abstract- *A two dimensional numerical model is developed to examine the fully supersonic fluid flow over the backward facing rounded step by integrating the hybrid RANS-LES/Spalart-Allmaras turbulence model, which comprises a viscosity-like working variable (ṽ). 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 grid independence test is also performed to get optimal grid of (175×175). 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 divulge that the gradual expansion transpires over the rounded step giving rise to the delay in viscous layer separation. Indeed, it results in the formation of comparatively shorter shear layer accompanied by the equally shorter recirculation region, approaching towards the dead air regime of the bottom wall. Furthermore, it is pretty evident from the present investigation that the appearance of relatively weak shocks over the rounded step. In other words, it is understood that there is diminishing of shock on account of variations in backward step geometry through replacement of sharp edge step by the rounded step.*

Keywords- Supersonic Turbulent Flow, Backward Facing, Rounded Step, Hybrid RANS-LES, Grid Independence Test, Flow Field.

I. INTRODUCTION

The flow over backward-facing step is one of the very vital perspectives and has increased unambiguous focus owing to not just minimalism but for extensive industrial and scientific usages. Moreover, in applied aerodynamics, it is very extensively utilized to investigate so many complex structures together with separation and reattachment. In the arena of investigations on high Mach number flow, every time the backward facing step is rendered as a multifaceted system for ignition in a scramjet, where the recirculation zone has very important role in stabilizing the firing of the engine. The steps on the surfaces of hypersonic or supersonic flying machines (such as airplanes, aircrafts and spacecrafts, etc.) cause the flow pattern exceedingly complicated and therefore significant researches are desperately necessary for appropriate refining of the dynamic design of the flying machines.

II. LITERATURE REVIEW

The experimental studies on flow field along with the heat transfer, downstream of a rearward facing step in supersonic flow is performed 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 analyze 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 experimental investigations on the separated flow behavior behind a backward-facing step together with the passive disturbance are also conducted by Terekhov et al. [10].

III. OBJECTIVES OF PRESENT RESEARCH WORK

From the above-mentioned studies, to the best of author' understanding, it is pragmatic 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 unveils that the growth/decay of shock is only because of the geometric variations in the steps.

IV. DESCRIPTION OF PHYSICAL PROBLEM

Backward facing rounded step devising wide range of usages in applied aerodynamics is studied in the current investigation. The geometric configuration accompanied by initial and boundary conditions are just the modified form of the backward facing sharp edge step. The setup used for testing this intricate geometry involves the placing of a rounded step of radius dimension is same as that of height from the upstream.

A. Geometric model

Figure 1 illustrates 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 Ld = 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.

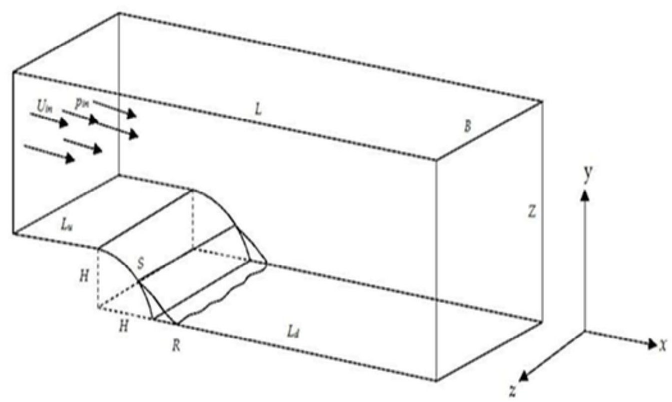

Figure 1. Flow specification of backward facing rounded step

B. Initial and boundary conditions

The inflow Mach number M_a = 2.5 Ma, which corresponds to the specified inflow static pressure of about p_{in} = 15350 N/m2 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 Spalart-Allmaras one-equation Detached Eddy Simulation, DES (also otherwise called as hybrid RANS-LES) model is introduced.

The boundary conditions associated with the geometry shown in figure 2 are as mentioned underneath:

- Wave transmissive outflow pressure at p = 15.35 kPa, everywhere else for pressure relating to the present hybrid RANS-LES model.
- Temperature T_{in} = 169.2 K, everywhere else for temperature pertaining to the current 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 the present hybrid RANS-LES model.

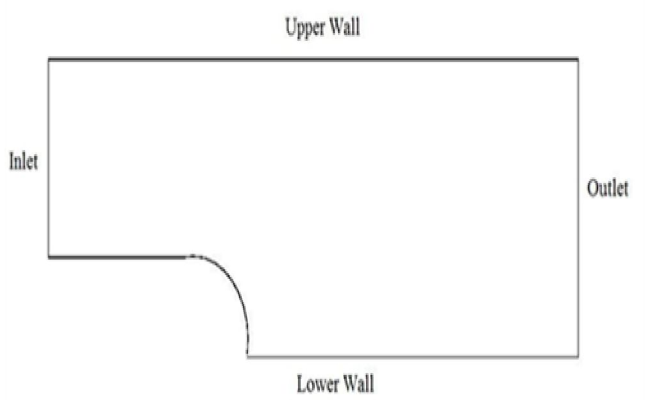

Figure 2. Backward facing rounded step boundary representation

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:

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

Momentum:

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

Energy:

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

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

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:

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

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

$$\mu_t = c_\mu f_\mu \rho k^2 / \varepsilon \tag{7}$$

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:

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

The eddy viscosity can be expressed as follows:

$$\mu_t = \rho \tilde{v} f_{v1} = \rho v_t \tag{9}$$

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.

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

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 depicts that the entire computational domain is divided into different non-uniform zones and also the grids are relatively finer within the proximate of wall likely to have high gradient. In the current research work, the simulation of the RANS-LES turbulence model is performed within the entire computational domain. A complete grid-independence test is conducted to develop an appropriate spatial discretization, and the levels of iteration convergence criteria to be expended. 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. Although, it is checked with smaller grids of 210 × 210 in numbers, it is pragmatic that a finer grid system does not modify the results very greatly.

Convergence in inner iterations is declared only when the condition $\left|\frac{\varphi-\varphi_{old}}{\varphi_{max}}\right| \le 10^{-4}$ 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.

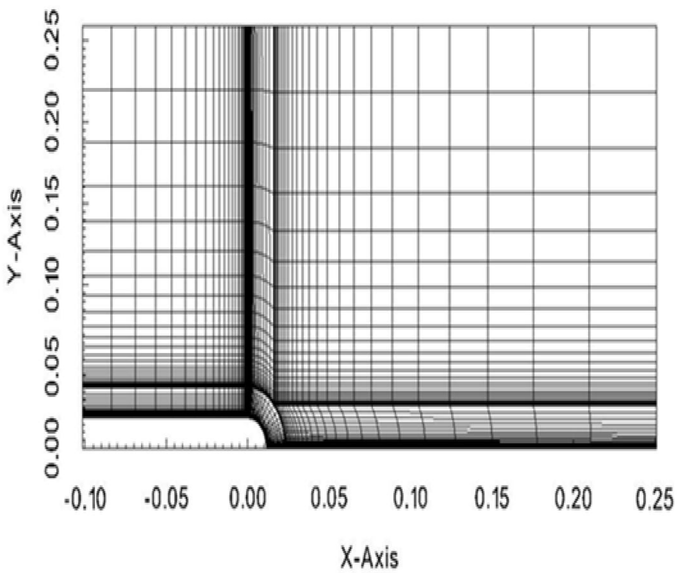

Figure 3. Mesh for backward facing rounded step

VII. RESULTS AND DISCUSSION

With the earlier demonstrated model conditions, the numerical simulations are performed for studying the fluid flow characteristics of the connected flow parameters in relation to fully supersonic turbulent flow over a backward facing rounded step. The turbulence model taken into account for the current investigational work is the hybrid RANS-LES/Spalart-Allmaras model involving a viscosity-like variable (ṽ). The hybrid RANS-LES turbulence model maintains the consistency in accuracy all over the entire flow field and therefore leads to comparatively better and accurate predictions. Hence, only the hybrid RANS-LES is selected for the current researches.

A. Grid independence test for flow over rounded step

The computational grid is non-uniform, with refinements in the vicinity of expected high gradients. In particular, the mesh refinement near the wall vicinity, allows for capturing sufficient shock resolution. Three different grids specifically (140×140), (175×175) and (210×210) named as Grid 1 of coarse type, Grid 2 of baseline/moderate type and Grid 3 of finer type, respectively, are summarized in Table 1 and are used in the calculation in order to check the dependence of the solutions on the grids. From the numerical simulations with the already described turbulence model along with the present grid types, it is observed that the results of the stated (three) grid types are very similar and comparable. However, the optimal grid type is found to be Grid 2 of baseline/moderate type, which is of (175×175). Hence, Grid 2 of baseline/moderate type is considered for all further investigations.

Table 1. Detailed grid specifications for flow over rounded step.

Name	Number of Points	Number of Cells	Number of Faces
Grid 1	5842	2800	11320
Grid 2	9052	4375	17650
Grid 3	12962	6300	25380

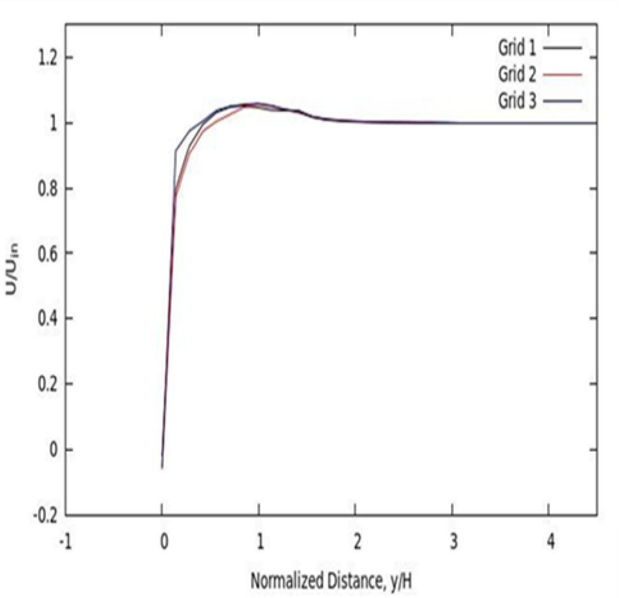

Figure 4. Grid independence test for flow over rounded step

B. Pressure flow field for flow over rounded step

Figure 5 demonstrates 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 5.

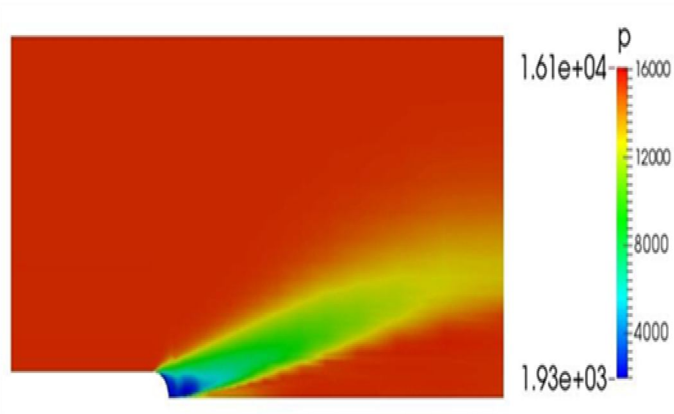

Figure 5. Pressure field for flow over rounded step

C. Velocity flow field for flow over rounded step

Figure 6 illustrates 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.

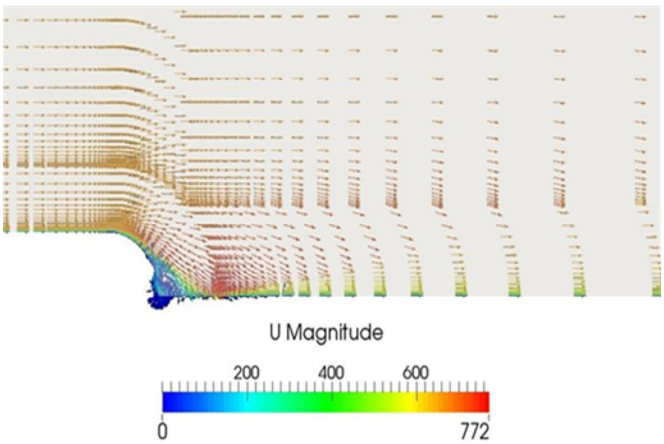

Figure 6. Velocity vector for flow over rounded step

VIII. CONCLUSION

In the present study, a two dimensional numerical model is established to examine the fully supersonic turbulent flow over a backward facing rounded step by considering the hybrid RANS-LES/Spalart-Allmaras turbulence model, containing a viscosity-like working variable ($\tilde{v}$). Additionally, the said numerical model also comprises 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 grid independence test is also conducted to find ideal grid of (175×175). The simulations with the said hybrid RANS-LES turbulence model gives realistically better and precise 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. Definitely, 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. Additionally, it is pretty obvious from the present examination that the presence of reasonably weak shocks over the rounded step. Therefore, it is realized that there is diminishing of shock as a result of the modelling exercise with rounded step instead of the sharp edge step.

IX. ACKNOWLEDGMENT

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