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Numerical Modelling for Investigations of Lip Shock Relating to Fluid Flow over a Backward Facing Rounded Step by Using Hybrid RANS-LES

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Abstract – A 2D numerical model is established to study the supersonic turbulent fluid flow over the backward facing rounded step by introducing the hybrid RANS-LES turbulence model, also otherwise termed as the Spalart-Allmaras turbulence model, which includes a viscosity-like working variable. In addition, the model comprises more significant challenges like production, diffusion and destruction terms apart from the very usual issues pertaining to the current investigations. The numerical simulations are conducted with the stated turbulence model with the inflow free stream Mach number of 2.5 accompanied by the free stream pressure and velocity of 15350 N/m^2 and 651.9 m/s^2, respectively. The simulation predictions with the hybrid RANS-LES model provides reasonably superior and accurate results all over the whole flow region including the wall vicinity region as well, therefore, the said model is used throughout the entire studies. The simulation predictions reveal that the gradual expansion takes place over the rounded step which leads to the delay in viscous layer separation. Certainly, it causes the formation of relatively shorter shear layer along with the fairly shorter recirculation region, approaching towards the dead air region of the bottom wall. In addition, it is quite apparent from the present research that the non-appearance of lip shock over the rounded step. In other words, it is realized that there is termination of lip shock owing to the use of rounded step in place of sharp edge step.

Index Terms – Supersonic, Turbulent Flow, Backward Facing, Rounded Step, Hybrid RANS-LES

1. INTRODUCTION

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 aeroplanes, 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.

2. 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 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 investigations on the separated flow behaviour behind a backward-facing step together with the passive disturbance are also conducted by Terekhov et al. [10].

From the above-mentioned 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 technique. 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 behaviours 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. Eventually, the current case of fully supersonic turbulent fluid flow over the backward facing rounded step simulated through the hybrid RANS-LES model also otherwise termed as Spalart-Allmaras model (accompanying the viscosity-like variable) reveals that the formation or termination of lip shock is only due to the geometric variations in the steps.

3. 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.

3.1. Geometric Model

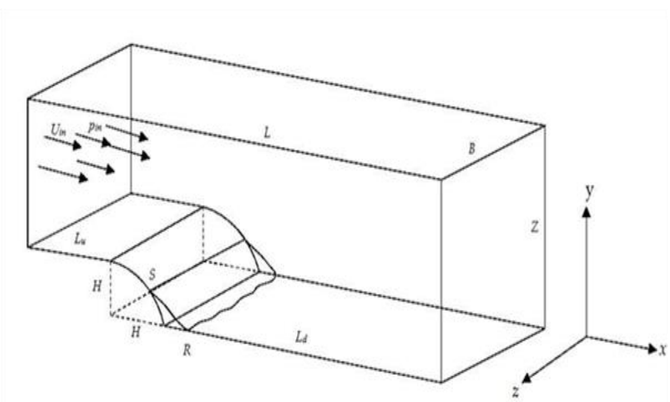

Fig 1. Flow specification of the backward facing rounded step

Figure 1 illustrates 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.

3.2. Initial and Boundary Conditions

The inflow Mach number Ma = 2.5 Ma, which corresponds to 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 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.

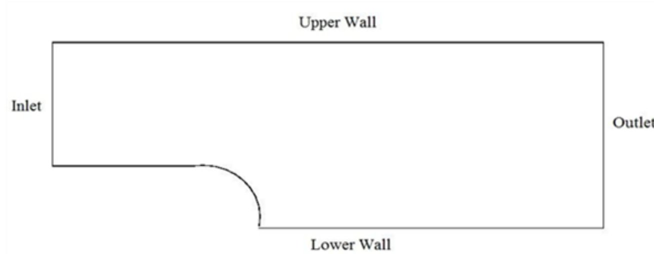

Fig 2. Backward facing rounded step boundary representation

4. MATHEMATICAL FORMULATION

4.1. Generalized governing transport equations

A set of appropriately generalized governing transport equations of mass, momentum and energy articulated in the conventional practice of Navier-Stokes equation for compressible flow concerning the effects of turbulence are described below.

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:

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

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,

$$E = e + k = h - \frac{p}{\rho} + \frac{v^2}{2} \tag{5}$$

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

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

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

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

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

4.2. Hybrid RANS-LES Turbulence Modelling

The Spalart–Allmaras turbulence model is a one-equation model for the eddy viscosity. And also, this model is otherwise termed as Hybrid RANS-LES model or Detached Eddy Simulation (DES) model. The differential equation has been derived with pragmatism and concepts of dimensional analysis, Galilean invariance and certain constraint of the molecular viscosity. Grid resolution does not require to be very finer for this model, but, one can really capture the flow field with the related algebraic models.

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

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

Where, the eddy viscosity is represented by:

$$\mu_t = \rho\tilde{\nu} f_{v1} = \rho \nu_t \tag{9}$$

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

5. NUMERICAL PROCEDURES

5.1. Numerical scheme and solution algorithm

The previously discussed governing transport equations are transformed into an appropriately generalised form as mentioned below.

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

The transformed governing transport equations are discretized by using a pressure based coupled framework pertaining to finite volume method (FVM) with the SIMPLER algorithm, where ϕ symbolises any conserved parameter and S is a source term. The developed pressure based, fully coupled solver is utilized to the predict flow characteristics of the associated flow parameters in relation to supersonic turbulent flow over a backward facing rounded step.

5.2. 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.

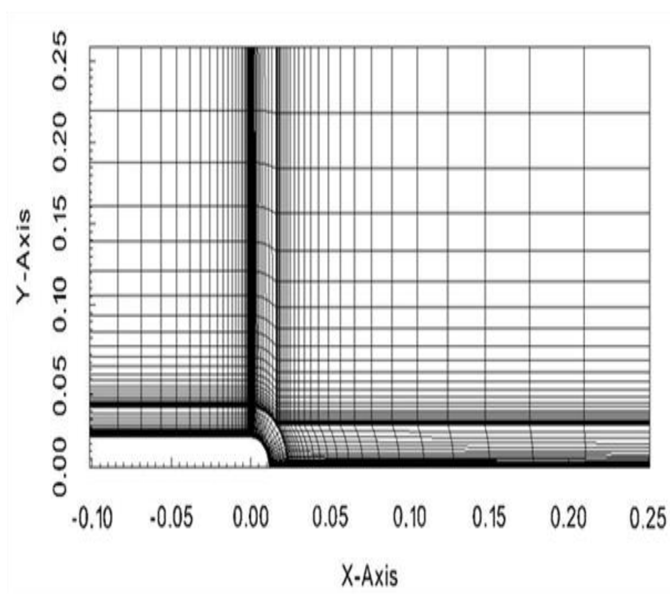

Fig 3. Mesh for backward facing rounded step

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.

The convergence in inner iterations is confirmed while the relation $\left|\frac{\varphi-\varphi_{old}}{\varphi_{max}}\right| \leq 10^{-4}$ is held good concurrently for all variables, where φ represents the field variable at a grid point at the present iteration level, φ_{old} represents the corresponding value at the previous iteration level, and φ_{max} is the maximum value of the variable at the current iteration level within the whole computational domain.

6. RESULTS AND DISCUSSIONS

With the previously demonstrated model conditions, the numerical simulations are carried out for studying the fluid flow characteristics of the related flow parameters on the subject of fully supersonic turbulent flow over a backward facing rounded step. The turbulence model taken into consideration for the present research work is the hybrid RANS-LES (very often otherwise termed as the Spalart-Allmaras model) which also involves the viscosity-like variable ($\tilde{\nu}$). The hybrid RANS-LES turbulence model keeps up the consistency in accuracy throughout the entire flow field and hence leads to relatively superior and precise predictions. Therefore, only the hybrid RANS-LES is chosen for the present investigations.

6.1. Pressure recovery distributions over sharp edge step with the presence of lip shock

The pressure recovery curve/profile plotted through the pressure ratio against the non-dimensional distance for the case of fully supersonic turbulent fluid flow over a backward facing sharp edge step is depicted in figure 4. It reveals a sudden pressure drop representing a hump like structure at the tip of separation which is due to sudden expansion of flow over the sharp edge step. The unexpected fluctuation in pressure is directly responsible for the presence of lip shock at the separated shear layer. In addition, the sudden fluctuation in pressure also indicates about the intensity of shock wave which is definitely very strong enough for high Mach flow. It may be ascertained that the reason behind this shock formation is due to viscous layer separation. Furthermore, this plot representing the presence of lip shock exactly near the lip of separation also epitomizes the pressure recovery taking place under the shock waves which includes several losses relating to the flow field as well. Besides, due to the emerging of lip shock the separated shear layer development is found to be more effective for the sharp edge step flow (which is also otherwise termed as corner/wedge flow) and can never be ignored.

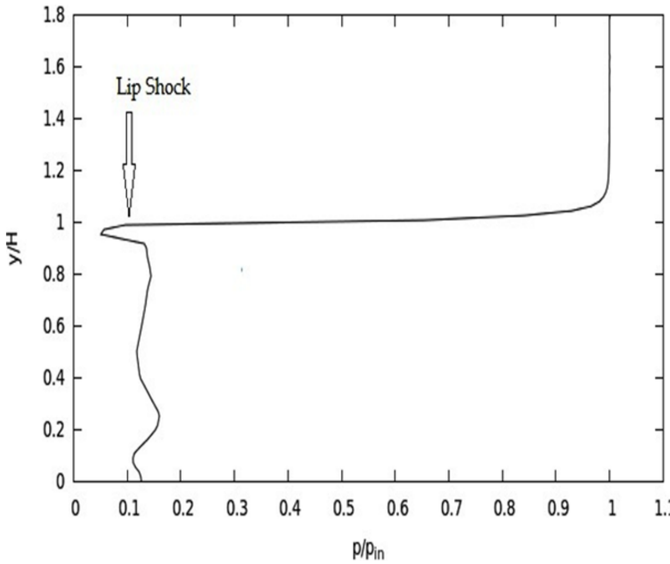

Fig 4. Presence of lip shock over sharp edge step

6.2. Pressure recovery distributions over rounded step with the absence the lip shock

Several numerical trials have been performed for the complete elimination of the lip shock to realize a very efficient and effective flow field. For this purpose, few numerical trials are also conducted by considering the geometric variations in steps, for overcoming or terminating the lip shock from the flow field. With the introduction of an arc like rounded step in place of the sharp edge step at the separation zone, it is observed that the intensity of the lip shock is diminished and has very minor effect on the flow field. That is why, in the present research, a rounded step is adopted with the step height equal to radius of the rounded step. This complex geometry is expected to allow the flow field to expand gradually (rather than suddenly) over the rounded step. Additionally, the stated rounded step complex geometry is tested against the corresponding sharp edge step under the same model conditions.

Figure 5 represents the pressure recovery distribution graph plotted with the pressure ratio against the non-dimensional distance for the case of fully supersonic turbulent fluid flow over a backward facing rounded step. With the inflow free stream pressure approaching the rounded step, the very gradual expansion over rounded step is experienced with the pressure expansion and pressure recovery in a smooth way. Due to the very gradual expansion, the intensity of expansion fan as well as reattachment shock is too less which can be observed from the graph where the recovery is in curved form. The rounded step possess more efficient and effective flow than the sharp edge step. There is no such shock present near the lip region due to the absence of viscous layer separation over the rounded step (very usually caused by the gradual expansion over the same), which is very clearly noticeable from the stated figure. As a consequence, it is quite obvious that the expansion fan together with the reattachment shock very negligibly affect the flow field behaviours of rounded step as compared to the influence of separation due to sharp edge step. In other words, the lip shock gets fully terminated with the introduction of rounded step in place of sharp edge step.

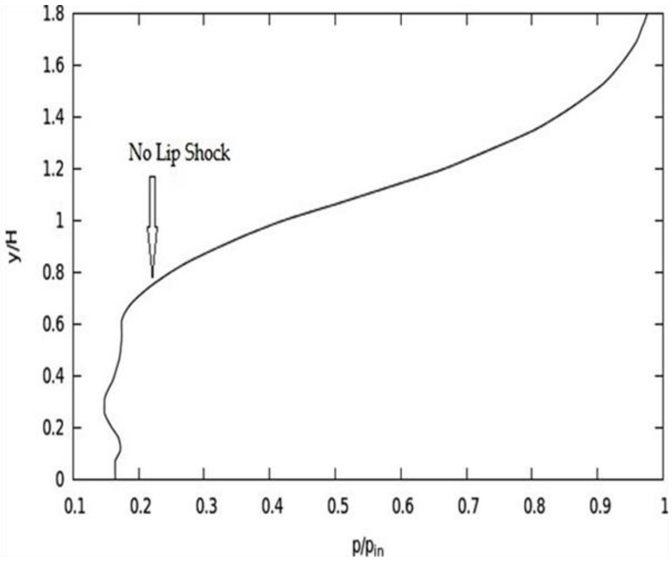

Fig 5. Absence of lip shock over rounded step

6.3. Flow field of pressure gradient over rounded step with the termination of lip shock

Figure 6 illustrates the enlarged view of coloured pressure gradient flow field (along with the horizontal scale bar) for the case of fully supersonic turbulent fluid flow over a backward facing rounded step. It depicts that the pressure gradient within the vicinity of the expansion wave is less than the pressure gradient nearby the reattachment shock. Within the vicinity of reattachment the maximum pressure gradient is experienced. The pressure gradient between the expansion fan and the reattachment shock is very much low. Less pressure gradient renders the flow field to be really efficient and effective. Near the step region, there is gradual expansion due to low pressure gradient. However, the dead air region experiences extremely low pressure gradient. There is no such shock present near the separation region which is very fairly observable from the magnitude of the pressure gradient. In other words, it is quite clear from the present illustration that the absence of lip shock at the rounded step. In addition, from this one may conclude that there is termination of lip shock which is achieved as a consequence of geometric variations in steps.

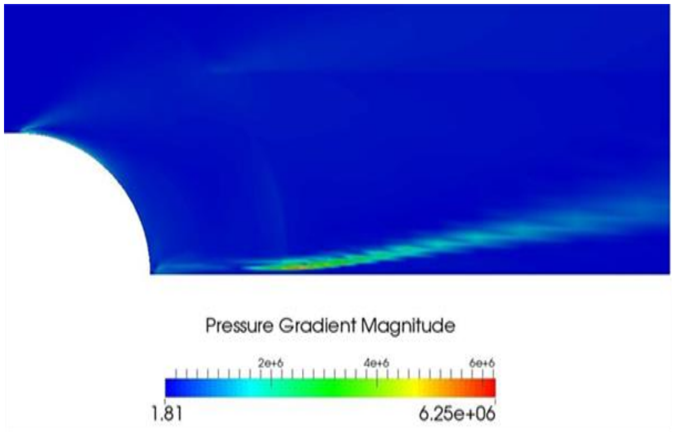

Fig 6. Termination of lip shock from pressure gradient flow field (enlarged view at separation)

6.4. Flow field of velocity distributions over rounded step with the termination of lip shock

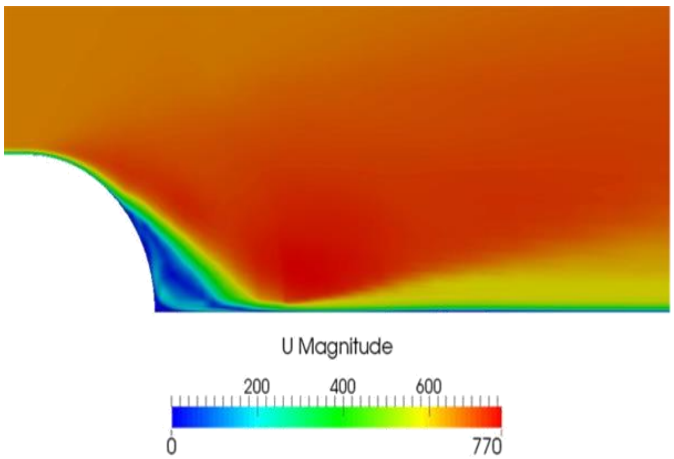

Fig 7. Velocity flow field (enlarged view at separation)

Figure 7 demonstrates the enlarged view of coloured velocity flow field (along with the horizontal scale bar) for the case of fully supersonic turbulent fluid flow over a backward facing rounded step. It shows that the gradual expansion takes place over the rounded step due to the geometric variation leading to the delay in viscous layer separation. Inevitably, it results in the formation of relatively shorter shear layer approaching towards the bottom wall leading to the development of boundary layer. In addition, the flow above the shear layer approaching the bottom wall will be along the initial direction and a part of the flow reverses to the dead air region which causes the formation of fairly shorter recirculation region. Furthermore, it is very evident from the current illustration that the non-appearance of lip shock at the rounded step. Besides, from this one may realize that there is termination of lip shock which is attained as a result of geometric variations in steps.

7. CONCLUSIONS

In the present investigation, a two dimensional numerical model is developed to examine the fully supersonic turbulent fluid flow behaviours over a backward facing rounded step. The model also includes 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 marvellously tested for the thorough numerical studies on fluid flow characteristics using the compressible turbulent hybrid RANS-LES fluid flow model, also otherwise called as Spalart-Allmaras model, which involves a viscosity-like working variable ($\tilde{v}$). The model includes the inflow free stream velocity and the associated Mach number as the important model parameters. Finally, the model predictions pertaining to the stated vital model parameters are also along the lines of expectations. In addition, the model is observed to provide fairly better and consistent results, and hence, it is chosen for the present research investigations. Furthermore, the simulation predictions show that the gradual expansion occurs over the rounded step causing the delay in viscous layer separation. Indeed, 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. Besides, it is also very evident about the absence of lip shock over the rounded step. Hence, it is understood that there is termination of lip shock because of the modelling practice with the rounded step rather than the sharp edge step.

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