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Numerical investigation of the recirculation zone formed downstream of a back ward facing step

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Abstract

A numerical investigation has been carried out on recirculation zone formed downstream of a compressible flow over a backward facing step. The study has been performed by solving Two-Dimensional Navier-Stokes equations. The system of governing equations has been solved, using an explicit Harten-Yee Non- MUSCL Modified flux type TVD scheme and a zero-equation algebraic turbulence model to calculate the eddy viscosity coefficient. The recirculation region dimensions are characterized over a range of Mach numbers of fixed step height 5mmThe detail of recirculation zone such as pressure, temperature, recirculation length, strength etc are reported. The variations of these characteristics due to change of Mach number are also presented.

Key words : Mach number, backward facing step, recirculation

1. Introduction:

The boundary layer separation of turbulent flow and its subsequent reattachment to a solid surface occurs in many engineering systems, and it has attracted many researchers due to its practical applications. Flows over air foils, in a channel with a sudden area increase, in gas turbines and many heat transfer devices are some of these applications. The combustor of a typical gas turbine represents some similarities with the turbulent flow over a backward facing step as the flame is stabilized by the recirculating area. Besides, due to the blockage, the sudden expansion also occurs; Regardless of whether these blockages are squares or cylinders, a wake-like flow behind the obstacle will be formed which is characterized by the recirculating area. The recirculation area also plays critical role to sustain the stable combustion. Since in many circumstances the occurrence of instability is related to the behavior of this recirculation zone.

A considerable number of researchers carried out their researches on flow over a flat plate. Chen et al. [1] and Scherberg [2] investigated the flow field for different Mach number with a fixed step height. Chen et al. showed the flow structures, including supersonic laminar boundary layer, separation, reattachment, redeveloping turbulent boundary layer, expansion wave fan and reattachment shock in the tran-

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Nomenclature

C_p	Specific heat at constant pressure	J/(kg.K)
E	Total energy	J/m^3
$\hat{F}$	Transform flux vector in ξ-direction	
G	Flux vector in y-direction	
P	Pressure	Pa
P_{in}	Inlet Pressure	Pa
R	Universal gas constant	J/(kg.mol.K)
T	Temperature	K
U	Vector in conservative variables	
$\hat{U}$	Transformed vector in conservative variables	
ρ	Mass density	kg/m^3
$\sigma_{x,y}$	Normal stress	Pa
τ	Shear stress	Pa
μ	Coefficient of dynamic viscosity	Kg/(m.s)
κ	Thermal conductivity	W/(m.K)
ν	Viscous term	

sient flow fields. Again Scherberg presented that the pressure changes from free stream pressure to base pressure were linear functions of free stream pressure for each Mach speed and step height. Popusco and Panait [3] conducted an experimental study to analyze the field velocity of a fully developed turbulent incompressible flow behind a backward facing step with a curve nose shape. Al-Maaitahet al. [4] investigated the effect of suction on the stability of compressible flow. Yang et al. [5] show the effect of the incoming boundary layer, step height and inlet free stream Mach number on the flow characteristics. Crouch et al. [6] reported on the boundary layer displacement thickness due to stepping. In this present work the detail of recirculation zone in case of high speed flow is addressed.

2. Mathematical Description:

The flow field is governed by the unsteady, two-dimensional full Navier-Stokes and species continuity equations. The body forces are neglected. With the conservation-law form, these equations can be expressed by

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=\frac{\partial F_v}{\partial x}+\frac{\partial G_v}{\partial y}$$ Where

$$U=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ E\end{pmatrix},\ F=\begin{pmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (E+p)u\end{pmatrix},\ G=\begin{pmatrix}\rho u\\ \rho uv\\ \rho u^2+p\\ (E+p)v\end{pmatrix},$$

$$F_v=\begin{pmatrix}0\\ \sigma_x\\ \tau_{xy}\\ \sigma_x u+\tau_{yx}v-q_x\end{pmatrix},\ G_v=\begin{pmatrix}0\\ \tau_{yx}\\ \sigma_y\\ \tau_{xy}u+\sigma_{yv}-q_y\end{pmatrix},$$

$$P=\sum_{i=1}^{ns}\rho_i R_i T=\sum_{i=1}^{ns}\rho_i\frac{R}{W_i}T$$

$$E=\sum_{i=1}^{ns}\rho_i h_i-\sum_{i=1}^{ns}\rho_i\frac{R}{W_i}T+\frac{\rho}{2}(u^2+v^2)$$

$$=\sum_{i=1}^{ns}\rho_i C_{pi}T-\sum_{i=1}^{ns}\rho_i\frac{R}{W_i}T+\frac{\rho}{2}\left(u^2+v^2\right)$$

$$\sigma_x=\lambda\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+2\mu\left(\frac{\partial u}{\partial x}\right),$$

$$\sigma_y=\lambda\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+2\mu\left(\frac{\partial v}{\partial y}\right),$$

$$\tau_{xy}=\tau_{xy}=\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right),\lambda=-\frac{2}{3}\mu$$

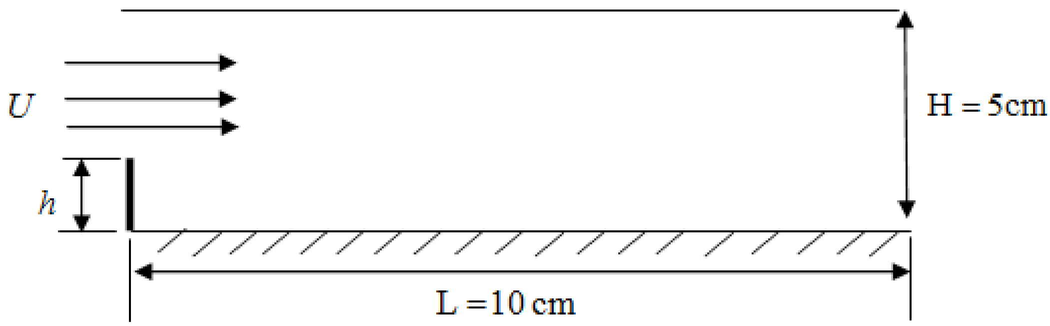

Fig. 1. Calculation domain

3. Flow Field Description and Numerical Parameters:

The numerical model is considered a two-dimensional airflow over a backward facing step. The geometrical configuration of calculation domain is shown in Fig. 1. The domain dimension in the stream wise horizontal and vertical directions are L= 10 cm and H= 5 cm, respectively. Facing step is located at the inlet (left) boundary of the calculation domain. Throughout the study, the grid system consists of 194 nodes in the longitudinal direction and 121 nodes in the transverse direction.

4. Results and Discussion:

The main objective of this study is to investigation the variation of different characteristics of recirculation zone of a flow having Mach no 0.8, 1.0 and 1.2 of step height 5.0 mm.The investigation has been done by varying the mach numbers at constant step height of 5.0 mm.

In velocity contour (in Fig.2), two shock regions are visible in the flow field, namely corner expansion shock and reattachment shock. Expansion shock appears to emanate from the vicinity of the top of the step and reattached shock appears at the reattachment region, which is located below the expansion shock region.

There is a sudden rise of velocity in the expansion shock region (in Fig.2) and it decreases at

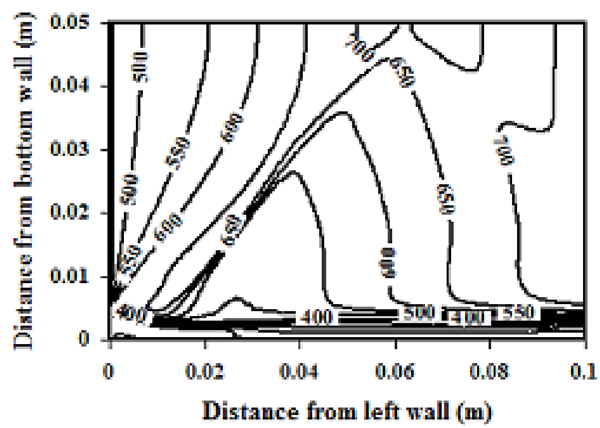

Fig. 2. Stream wise velocity contour for M=0.8

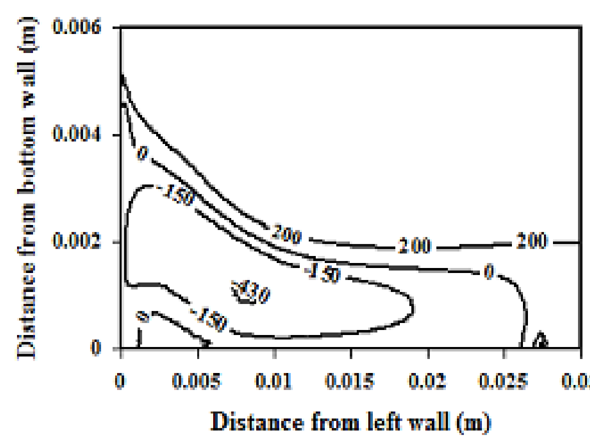

Fig. 3. Recirculation zone for M=0.8

reattachment shock region. In the flow field, it is found that after the interaction of two shocks a part of flow is reflected to the downward direction which exists up to the exit of the boundary (Fig. 2). At the left bottom corner of the velocity field recirculation

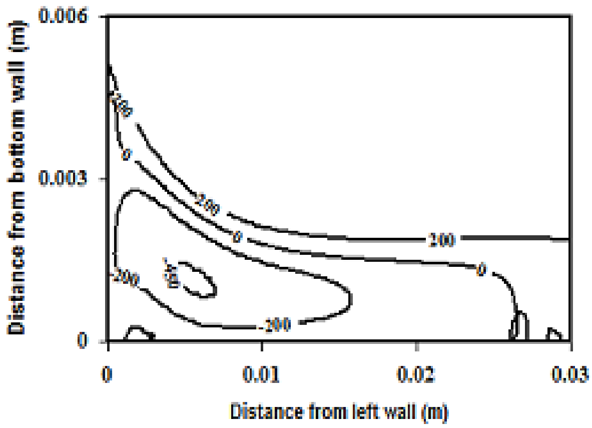

Fig. 4. Recirculation zone for M=1.0

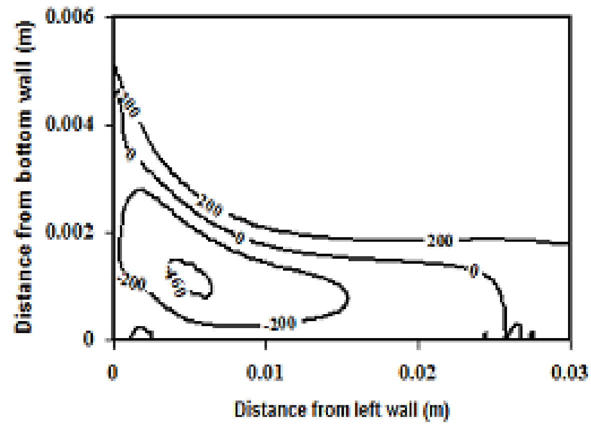

Fig. 5. Recirculation zone for M=1.2

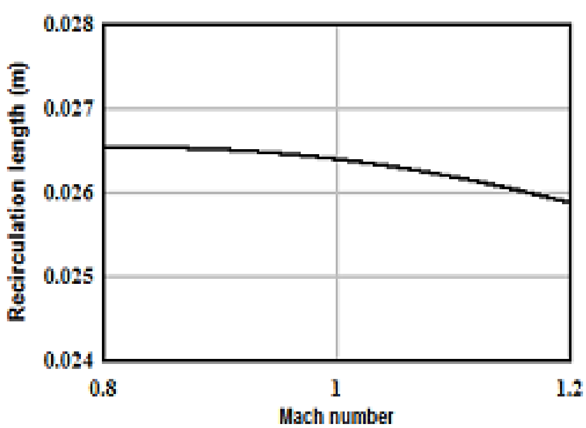

Fig. 6. Nature of recirculation length

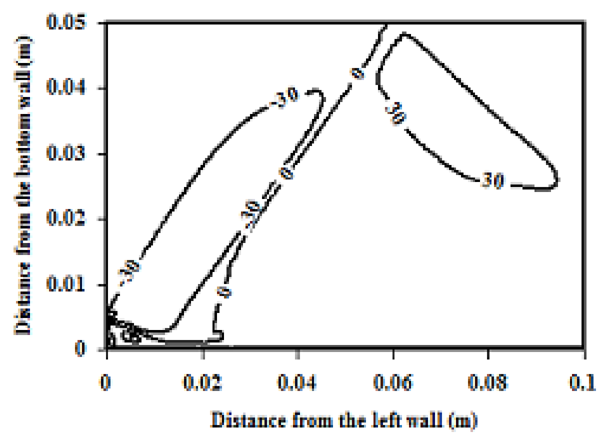

Fig. 7. Transverse velocity contour for M=0.8

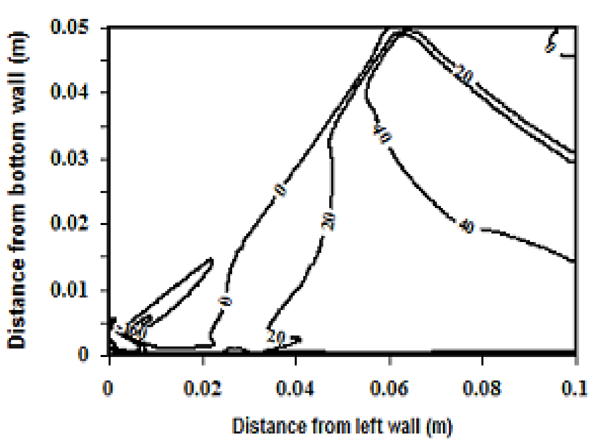

Fig. 8. Transverse velocity contour for M=1.0

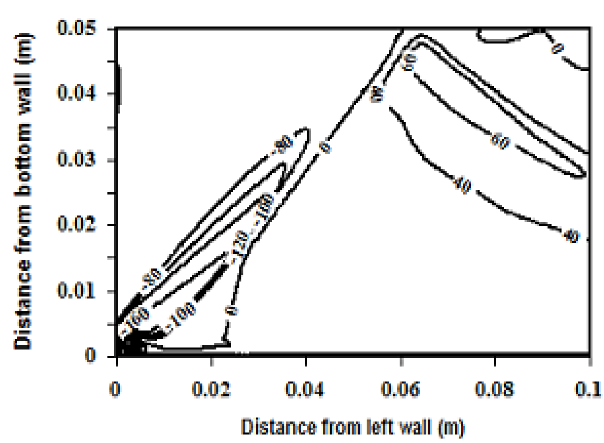

Fig. 9. Transverse velocity contour for M=1.2

appears and the zero value of the velocity contour is considered as recirculation zone. The length of this zone along the bottom wall is considered as recirculation length. Figures 3-5 show the recirculation zone for different Mach number. For close observation the figures are magnified and shown partly by height of 6.0 mm (from bottom wall) and length of 30 mm (from left boundary). With the increase of Mach number, the length of recirculation decreases, which is found, 0.0265, 0.0265 and 0.0258m respectively. From fig. 6 it is found that, for all cases, recirculation length decreases gradually and the rate of decrement increases with the increase of Mach number. This is caused by the high compression of inlet flow for higher Mach number. But the strength of recirculation i.e the turbulence excited in this case becomes stronger, as the change of Mach number. The stream wise vorticity is stronger near the step and reduces in strength further downstream. The maximum strength of recirculation is found at about one-fourth of the recirculation length.

Figures 7-9 show the transverse velocity contours. Apart from the inlet, the minimum value of transverse wise velocity is located immediately after the tips of the step. The minimum value of the transverse velocity immediately after the tip physically demands that the flow needs some stream wise distance to adjust and become fully developed. Due to the change of Mach number, there occurs a little increase in area of realm where minimum cross-stream velocity demanding to get fully developed.

In this analysis minimum pressure is found in the recirculation zone. Actually this low pressure zone triggers the flow to generate recirculation. A little increase of pressure is in the recirculation zone as the Mach number increases.

The maximum temperature of the flow field is found in recirculation zone, which is around 3 times greater than the initial temperature. There is no remarkable change of temperature in the flow field, as the change of Mach number.

5. Conclusion:

The effects of Mach number on the characteristic of recirculation zone have been reported. Length, strength, pressure and temperature of recirculation zone are the major findings of the flow field addressed herein. With the increase of Mach number, the length of recirculation decreases, but the strength increases. Maximum temperature and minimum pressure of the flow field are found in recirculation zone, which is almost same for different Mach number.

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