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Effect of side confining walls on the growth rate of compressible mixing layers

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ABSTRACT

Model free simulations are performed to study the effect of the presence of side wall in compressible mixing of two parallel dissimilar gaseous streams with significant temperature difference. The turbulence statistics shows the three dimensional nature of the flow with and without the presence of side walls. The presence of side wall neither makes the flow field two dimensional, nor suppresses three dimensional disturbances. However, the comparison of shear layer growth rate and wall pressures reveal a better match with the two dimensional simulation results. This better match is explained on the basis of formation of oblique structures due to the presence of side walls which also suppress the distribution of momentum in third direction making the pressures to be higher as compared with the case without side walls.

1. Introduction

In a hypersonic air breathing vehicle, scramjet engine remains only option for propulsion system. The better understanding of mixing and combustion process in the scramjet combustor is one of the critical areas for its development. One of the main technological challenges in the development of scramjet engines is the effective mixing of air and fuel in the combustor at compressible (supersonic) conditions. The combination of very short residence times and poor mixing caused due to compressibility makes the problem difficult to solve. ‘Planar confined compressible shear layer’ is considered as a canonical problem to study the parallel injection in the scramjet combustor.

Most of the studies related to mixing layers have been carried out on free mixing layers which do not have any wall interaction. In practical scramjet combustors with rectangular cross sections, the fuel and oxidiser (air) mixing streams are confined in the top and bottom direction as well as in the sides. The effects of these walls have been studied using stability analysis and numerical simulations. For a shear layer inside a rectangular channel, Tam and Hu [1] showed that the coupling between the motion of the shear layer and the acoustic modes of the channel produces new instability mechanism called as ‘supersonic instability’ different form Kelvin–Helmholtz instability for the spatially growing mixing layers. Greenough et al. [2] have also shown two general types of instabilities: confined Kelvin–Helmholtz mode and supersonic wall modes, by analysing the effect of wall on a confined compressible temporal mixing layer. Zhuang et al. [3] carried out instability analysis for confined mixing layer and they argued that the increased instability of the confined mixing layer was due to the feedback mechanism between the growing supersonic shear layer and the wave system (wall reflections) that makes the shear layer more unstable, than the corresponding free supersonic shear layer, which loses energy to acoustic radiation to the far field. The amplification rates of the two-dimensional (bounded) and three-dimensional (free) supersonic instability modes were also compared with the experimental data by Zhuang et al. [3], and it was observed that the two dimensional results are in much better agreement with the experimental data. Morris et al. [4] further showed that the choice of width-to-height ratio of the confining duct may determine whether the two- or three-dimensional mode has a greater growth rate. The effect of lateral confining walls is studied by Chakraborty [5], a comparison of the mixing layer thickness for both laterally confined and free mixing layer are made. The thicknesses are found to be more for the confined case than those for free cases. The shock reflections from these top and bottom confining walls make the laterally confined shear layer more unstable and thus the growth starts earlier than the free counterpart, resulting in higher thickness at the same streamwise location with the growth rate remaining almost the same. Recently, Javed et al. [6] carried out both two and three-dimensional spatiotemporal simulations employing higher order finite difference scheme as well as finite volume scheme based on open source software (OpenFOAM) to understand the effect of three-dimensionality on the development of mixing layer. It is observed that although the instantaneous structures exhibit

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three-dimensional features, the average pressure and velocities are predominantly two-dimensional. This study shows a higher growth rate for three-dimensional mixing layer simulations in comparison with that evaluated from two-dimensional simulation results. However, a number of two dimensional numerical studies [7–10] have shown a good match with the experimentally observed growth rate, velocity and pressure data, indicating that the flow field for the mixing layer experiments carried out in a confined environment may be two-dimensional in nature. Two dimensional simulations were carried out by Lu and Wu [7] for convective Mach numbers ranging from 1.05 to 1.77. The growth rates observed numerically was compared with experimental results and found in good match. Two dimensional simulations carried out by Liou et al. [8] for convective Mach numbers ranging from 0.14 to 1.28 show a good match for the normalised growth rate with the experimental curve. Normalised growth rate is also captured nicely in the 2D simulations for $M_c = 0.2–1.0$ by Li and Fu [10] using Bhatnagar–Gross–Krook (BGK) scheme [11,12]. They have concluded that although the mean velocity field and the thickness growth rates for 2D mixing layers agreed generally well with the experimental results even though the real flow is three-dimensional, velocity fluctuation intensities and shear stresses are over predicted compared with the experimental data. Chakraborty et al. [9] have carried out a 2D model free simulations of a supersonic confined mixing layer of dissimilar gases with significant temperature differences and showed a good match of wall surface pressures with experimental results, indicating the ability of 2D simulations to predict the wall pressure of a 3D experimental flow field. For these 2D numerical studies the good comparison of growth rate at higher convective Mach numbers ($M_c > 0.6$) with the experimental results give an indication that the experimental flow field may be 2D in nature in presence of confining side walls. According to Lu and Wu [7] the side walls act as suppressors for three-dimensionality and the flow is dominated by two-dimensional disturbances and structures. This suppression of three-dimensionality by side walls could explain the better match of experimental pressures data with two-dimensional simulations data.

The experimental results for growth rates and mean quantities, which are from actual 3-dimensional flows, could be well predicted using 2D simulations, when they are conducted in the presence of confining walls. It has been argued that these side walls make the flow field more two dimensional, and due to this two dimensionality of the flow field the 2D simulations are in better agreement with the experimental results. In most of the experimental studies there is little or no information available for the two or three dimensionality of the flow field. And thus the reason for the good match of the two dimensional numerical results for mixing layer growth rate, with that with the experimental data remains debatable. In order to resolve the issues concerned with the effect of side wall on the flow field, a simulation is carried out using actual duct geometry of the experimental case studied by Erdos et al. [13] as considered in Ref. [6]. Three dimensional model free simulations are carried out for exact Erdos experimental geometry in the presence of side wall for two dissimilar gases with significant temperature differences. The flow structure for three dimensionality is examined along with the turbulence statistics, and compared with the three dimensional case without any side walls and two-dimensional simulations. The growth rates of shear layer, and wall pressures are evaluated and analysed to explain the possible effects of the presence of side wall.

2. Geometry, grids, and boundary conditions for simulations

The mixing duct for Erdos' [13] experimental study is 50.8 mm wide with a height of 25.4 mm. The duct height to width ratio comes out to be 0.5. The length of duct is 535 mm. A sketch of the experimental geometry is shown in Fig. 1 with a side view showing the duct cross section, and relevant coordinate axis convention. For numerical simulations the middle plane in z-direction is considered as symmetry plane. This results in geometry with a width of 25.4 mm, with one side in the width direction as wall and the other side as symmetry. The position $z = 0$ mm represent symmetry plane, while $z = 25.4$ mm is the location of side wall.

For the present simulations a case with the nitrogen stream as the primary flow at the lower part of the duct and the hydrogen stream as secondary flow at the upper part of the duct separated by a splitter plate are considered. The details of the flow parameters are presented in Table 1. The convective Mach number $M_c = (U_1 - U_2)/(a_1 + a_2)$, comes out to be 0.80 for this mixing layer.

A detailed study of the grid independence is presented in Ref. [6] with a 2D domain. The grid independence of the solution is demonstrated by not only comparing the average results with different grids but also comparing the spectral content of the fluctuation with different grids. The grid is stretched exponentially in the axial and lateral directions with minimum grid spacing at the inflow boundary and at the interface of the two streams to capture the initial development of the mixing layer. The wall boundary layer is resolved by taking very fine mesh near the solid wall and the grid is again stretched exponentially in the region away from the wall. The grid structure employed in the simulations has 1000 points in the axial direction with minimum grid size of 0.3 mm near the inflow boundary plane and the maximum size of 0.8 mm near the outflow boundary. In the lateral direction, 101 grid points are used with a minimum grid spacing of 0.09 mm near the interface and wall, and the maximum grid spacing is of the order of 0.5 mm in the region away from interface and wall. The ratio of this minimum grid spacing in y-direction (0.09 mm) with mixing layer width in the upstream direction ($\approx$2.0 mm) comes out to be 0.045, which according to Oh and Loth [14] was adequate to give grid independent results even with second order spatial scheme as this ratio is less than 0.05. It is to be noted that the present simulations employ a fourth order spatially accurate scheme. For 3D calculation without considering side walls, a three-dimensional computation mesh with 41 planes is formed by spanning the two-dimensional grids with an equal distance in the z-direction. The distance between two planes is kept to be 0.3 mm. For the simulations considering side walls, the computational grid in the x and y direction is kept same as that used in 3D simulations without side wall, while in the z-direction 101 grid points are used. The minimum distance is near the side wall with a value of 0.01 mm. The grid is stretched towards the symmetry plane with a maximum width of 0.3 mm. The total grid size comes out to be around 10.2 million.

The velocities at the walls and splitter plate are kept zero, and constancy of wall temperatures are employed for heat transfer. A parabolic boundary layer profile is given near the walls and the splitter plate. The boundary conditions at the sides are set as periodic boundary condition for without side wall simulations. For the case considering effect of side wall, adiabatic wall with no slip velocity boundary condition is given for side wall while the other side is made a symmetry boundary. Both the streams are given equal pressure of 27,580 Pa. Nitrogen mass fraction is set to unity for primary stream, while hydrogen mass fraction is unity for the secondary stream. The exit boundary condition is obtained by second order extrapolation and is considered satisfactory for this problem dominated by supersonic flow. A purging time of 515 μs is used in the simulation as explained in Ref [6].

3. Numerical simulation

In the present study, OpenFOAM open source software [15] is used to carry out model free simulation. Unlike Direct Numerical