Manuscript Details

Manuscript number	AESCTE_2016_58
Title	Large Eddy Simulation of Supersonic, Compressible, Turbulent Mixing Layers
Article type	Full length article

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Keywords	Large Eddy Simulation;mixing layer; SLAU2; turbulence; self similarity
Taxonomy	Fluid Dynamics, Aerospace Propulsion, Aerospace Engineering, Aerodynamics
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Large Eddy Simulation of Supersonic, Compressible, Turbulent Mixing Layers

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Abstract: Two and three dimensional large eddy simulations of a supersonic mixing layer are performed using an in-house hybrid finite volume code. This code combines a fourth order non-dissipative MacCormack scheme for capturing turbulence and a second order SLAU2 upwind scheme for capturing shocks and other discontinuities in the flow. Predictions of growth rates and statistical moments in the self similar regime are consistent with past experimental and direct numerical simulation studies. The peak values of the transverse turbulence stresses are over predicted in two dimensional simulations. This may be attributed to the lack of vortex stretching and the lack of significant energy transfer to the smaller scales.

Key Words: Large Eddy Simulation, mixing layer, SLAU2, turbulence, self similarity

1. Introduction

Increasing interest in scramjet engines development for hypersonic airbreathing vehicles has made supersonic mixing layers an important subject for both engineering and fundamental flow physics research. Although geometrical complexities are not present, supersonic mixing layers possess all physical characteristics of scramjet combustor flow field. In a spatially evolving mixing layer, the two streams flowing on either side of a splitter plate come into contact at the edge of the plate. The resultant shear layer leads to the generation of large scale flow structures which convect with the flow. In initial region, Kelvin Helmholtz instability results in the formation of well separated vortical structures. In the second region, the adjacent vortices pair up causing the thickness of the mixing layer to increase. The structures break down as the turbulent energy cascade develops, generating fine scale turbulence characterized by a self similar state.

Earlier studies [1-6] mostly focused on explaining the reduced growth rate of the mixing layers with increasing convective Mach number. Linear stability analysis, Direct Numerical Simulation (DNS) and experimental studies discussed at length the role of production term [7,8], dilatation dissipation [9] in the reduction of growth rate of mixing layers. The linear stability analysis [10-13] showed that the maximum growth rate of disturbances for a wide range of values of free stream temperature and density fall on essentially a single curve that is a function of convective Mach number. Although, similarity exists between linear stability analysis and experimental observation, it is not quite clear why and how a simple linear theory can explain the evolution of a fully turbulent mixing layer. Hussaini [14] offered a possible explanation of the growth rate reduction by studying numerically the behavior of an eddy convecting subsonically, relative to a locally supersonic flow with a convective Mach number greater than 1.0. As the eddy accelerates in the supersonic flow, eddy shocklet is formed that tends to distort the eddy. In the process, eddy bifurcation occurs resulting in the formation of a vortex of opposite circulation. Additionally, the length scale of the original vortex is reduced. Hence the presence of the eddy shocklet can cause the production of the counter fluctuating vorticity and reduction of turbulence scale and thus reducing the growth rate. Review papers [15-18] on supersonic mixing layer elaborated greatly on this growth rate reduction aspects.

Turbulent statistics in a compressible mixing layer have been obtained experimentally by Goebel and Dutton [19,20], Barre *et al.* [21] Grubber et al [22] and Saminy and Elliott [5]. Goebel and Dutton [19] conducted experiments on compressible turbulent mixing layers which become fully developed for a Reynolds number of 100000 (based on free stream velocity difference and local mixing layer thickness). Different free stream conditions are considered to achieve convective Mach number (M_c) of 0.2 and 0.99 and these experimental results are very useful to validate computational models. Both streamwise and transverse turbulence intensities are found to reduce with increasing M_c. Although the kinematic Reynolds stress profiles decrease with increasing M_c, the correlation coefficient remains relatively constant in the mixing layer region. The data on anisotropy shows almost similar trend for both the cases. These observations suggest that compressibility reduces both the small scale and large scale fluctuation as the convective Mach number increases.

Two dimensional and three dimensional supersonic mixing layers are explored numerically through DNS [23-30], Large Eddy Simulation (LES) [31-37] methods employing different higher order numerical schemes like Compact, WENO, Discontinuous Galerkin (GK), Gas Kinetic BGK etc. Most of the simulations preferred temporally developing mixing layers to reduce computational load. In temporally developed mixing layer, the computational domain is kept fixed in a reference frame which moves with the flow structures enabling the mixing layer develops in time, rather than in space, from specified initial conditions. Periodic boundary conditions are employed in the streamwise direction and no inflow/outflow boundary conditions are necessary. Such temporally developing mixing layer cannot properly account the effects of divergent streamlines and asymmetric entrainments [25]. Proper modelling of shocklets along with vortex structures in supersonic mixing layers warrants an effective and efficient numerical scheme to capture discontinuities and have good resolution in the smooth regions.

Chakraborty et al [24] presented 2D DNS of spatially developing supersonic confined mixing layer for convective mach number of 0.86 using a fourth order accurate compact finite difference scheme. The instantaneous flow structure and mean flow profiles indicate that the growth of the mixing layer is towards high speed side. Turbulent statistics decreased with increasing convective Mach number. Liu & Lele [25] conducted DNS studies of 3D spatially developed mixing layer with 6th order accurate finite difference scheme for two different convective Mach numbers of 0.6 and 0.4. Although the turbulent statistics were described qualitatively, the simulation depicted fundamentally different flow structures for different compressibility conditions; span-wise roller like structure for $M_c = 0.4$ and elongated stream-wise streaky structures for $M_c=0.6$. Li & Fu [26, 27] applied gas kinetic BGK scheme to simulate 2D and 3D supersonic mixing layer in the convective Mach number range of 0.2 to 1.0. Although 2D simulations [26] show over prediction of turbulent statistics, 3D simulations [27] matched the experimental result reasonably well. It is noticed that similar to supersonic flow around a bluff body, the shocklets are formed when the lumps of low speed fluids enter the high speed flow. The magnitudes of most of the contributing terms in the kinetic energy budget reduce with increased compressibility. Shi et al [28] used DG method to simulate both temporal developing and spatial developing supersonic mixing layer in the convective Mach number range of 0.2 to 0.8. The vortex pairing is found to be different for higher convective Mach number [$M_c>0.6$] compared to lower M_c. Large scale ordered structure like Brown – Roshko structures, shocklets and multi-vortices merging were observed for high convective Mach number.

Zhou *et al.* [29] simulated spatially developed mixing layer with $M_c = 0.7$ using 8th order spatially accurate finite difference scheme. The full evolution process of instability including the formation of Λ vortices, hair pin vortices, breakdown of large scale structures and establishment of self similar turbulence is explained. Hair pin vortices are found to play an important role in the flow breakdown. The evolution of mean streamwise velocity and Reynolds stress are found to depend on large vortex structures. The streamwise velocity profile has triple inflection point near the inlet and quickly changed to quintriple inflection point. The growth rate in the transition region is higher (roughly 4 times) than that in final self similar region. Javed et al [30] presents a model free simulation with open source software to study the effect of side confining wall on the growth rate of confined compressible mixing layer of dissimilar gases in hypervelocity condition. Although increased three dimensionality is observed in turbulence statistics, the shear layer growth rate and wall pressure show a better match with 2D simulation compared to 3D simulation. The presence of oblique structures due to the side wall suppresses the distribution of momentum in third direction.

Full three dimensional DNS of mixing layer is computationally expensive even if at moderate Reynolds number. The spatial mixing layer DNS study with a zero thickness splitter plate by Sandham & Sandberg [38] required close to 500 million mesh points. LES can be used as a viable design tool for quantitative prediction of flow parameters of turbulent mixing layers at realistic Reynolds numbers. Foysi and Sarkar [31] and Hadjadj [32] has performed LES for temporal mixing layers with different Reynolds numbers and convective Mach numbers using higher order discritization schemes. Nelson and Menon [33] reported good qualitative and reasonable quantitative results from his LES study of spatially developed mixing layers at convective Mach number of 0.51 and 0.86 using a fifth order accurate AUSM scheme with localized dynamic model of subgrid kinetic energy. Sharma et al. [35] carried out LES of spatially developed mixing layer at convective Mach number of 0.5 with a sixth order compact finite difference scheme and dynamic model for subgrid fluxes. The effect of different inflow conditions on the growth and evolution of mixing layer was systematically studied. The distance to achieve self-similarity of mean velocity profile is shortest for case isothermal streams with velocity ratio 0.17. It is observed that vortex pairing and breakdown to turbulence contribute significantly to radiated sound. Iyer and Rajan [36] presented two dimensional LES with fourth order accurate PISO algorithm and one equation eddy viscosity model for sub grid scale stress using open source openFOAM frame work. Experimental conditions of Goebel and Dutton [20] and Papamoschou and Roshko [39] were simulated and the computations were shown to match the experimental data reasonably well. Iyer et al. [37] further used the LES data to develop a model for shear stress for a compressible mixing layer with M_c as a parameter. It is noticed that the shear stress to strain rate relation is remarkably linear in the self similar region of the mixing layer. The model predicts the growth rate of the mixing layer reasonably well even at high M_c.

The boundary layers at the walls are generally considered to be inconsequential in LES studies [26,27,36,42] of Goebel and Dutton's experimental case. Without these boundary layers, the pressure would nearly be uniform along the axial direction and the walls could be kept parallel. The Schlieren images of the experiments [19,20] clearly shown multiple reflections of waves from the lateral boundaries. If non-reflecting boundaries are used, these reflections cannot be captured at all [26,27,28] while use of symmetric/slip boundary conditions [36,42] would lead to perfect reflections with no loss of strength. With such simplifications, lateral profiles of the first and second order statistics in the self-similar region would likely remain unaffected, but the growth of the mixing layer may depend on the wall effects.

It is clear from the above discussion that the role of two dimensional and three dimensional simulations in resolving features of spatially developing supersonic mixing layers need further investigations. In the present study, both two dimensional and three dimensional LES of a spatially developing supersonic mixing layer are performed using an in-house developed hybrid finite volume code [40, 41]. This code uses a fourth order central MacCormack scheme for capturing turbulence and a second order SLAU2 upwind scheme for capturing shocks and discontinuities in the flow. The Goebel and Dutton experimental condition [19, 20] is taken as the test case of validation. The divergence angle of the wall is estimated for ensuring zero pressure gradient along the center line. The growth rate, profiles of different flow parameters and turbulence statistics are compared between 2D and 3D simulations as well as the experimental data.

2.0 LES Solver

A hybrid solver [40,41] based on a combination of MacCormack and shock capturing SLAU2 schemes is used for integrating the filtered governing equations for compressible flows. These non-dissipative MacCormack scheme is spatially fourth order accurate while the baseline SLAU2 is extended to second order accuracy using MUSCL approach. The blending of the non-dissipative and dissipative (upwind) schemes is usually done by relying on discontinuity sensors. However, unphysical numerical oscillations tend to persist even far away from discontinuities in solutions obtained using hybrid solvers. So, an additional unphysical oscillation sensor is also used in the present hybrid method to suppress such oscillations. The overall inviscid fluxes are computed as weighted averages of the fluxes computed using the two schemes. The weight of the upwind scheme is highest near discontinuities and almost negligible in smooth regions of the flow. The weight of the upwind scheme, in addition, also increases monotonically with the amplitude of unphysical two-point oscillations in the density field. The numerical dissipation of the upwind scheme keeps the numerical oscillations under check even away from the discontinuities. The effectiveness of the blending technique based on this additional sensor in eliminating unphysical and undesirable oscillations while ensuring accurate capturing of physical oscillations has been tested by simulating various prototype problems for compressible turbulence and documented in Ref. 40, 41.

3.0 Test condition for which simulations are carried out

The schematic of the experimental setup [20,21] for which the simulations are carried out is shown in Fig.1. Two supersonic streams (Mach numbers of about 2.0 and 1.4) are brought together at an angle of 2.5^0 across a thin splitter plate with a tip height of approximately 0.5 mm. Each stream has an exit height of 23.75 mm and a width of 95 mm and has uniform flow at their exit. The length of the test section is 500 mm and the divergence angle of the upper and lower walls of the test section is adjusted to control the streamwise pressure gradient. The facility is capable of heating each streams independently (maximum temperature ~ 900 K), thereby allowing variation of the velocity ratio, density ratio and convective Mach number of the mixing layer.

The wind-tunnel has a run time of approximately six minutes. A two-color, two-component, dual-beam LDV system was employed to measure the mixing layer velocity field. The growth rates, mean and turbulent velocity fields of seven mixing layer cases are studied from static pressures, schlieren photographs and flowfield velocity measurements. To examine the isolated effects of freestream disturbances, velocity ratio, relative Mach number etc, wide variety of conditions are investigated with freestream velocity ratios (0.16 - 0.79), freestream density ratios (0.57 - 1.55), and convective Mach numbers ranging from 0.2 to 0.99. The splitter plate boundary-layer velocity profiles were also measured using a one-component LDV setup. From the level of measured turbulence intensities, the boundary layers were found to be turbulent for all of the cases.

4.0 The Computational Details

The code is setup to simulate the Goebel and Dutton experiment for convective Mach number case of 0.2. The inflow parameters for this flow are shown in Table 1. The Mach numbers of the two streams are 2.04 and 1.4 respectively and the temperatures of both the streams are maintained at 295 K. The velocity ratio and density ratios of the two streams are 0.79 and 0.76 respectively.

The computational domain used in numerical simulation is shown in Fig. 1. The lengths of the domain in the axial, transverse and directions are 0.5 m, 0.048 and 0.008 m respectively. The thickness of the splitter plate is 0.5 mm and protrudes 0.02 m inside the computational domain from the inflow boundary. Various boundary conditions in the computational domain are shown in Fig. 1. A 600x150 mesh is used to two-dimensional simulation while a 600x150x64 mesh that is uniform in the spanwise direction is used for three-dimensional simulations. The 0.5mm thickness of the splitter plate is resolved using 6 grid points. Geometric stretching factor of 1.0082 is used for the grid in axial direction while hyperbolic tangent function is used for clustering around solid walls in wall normal direction. The grid is also clustered near the top and bottom walls that confine the mixing layer. The minimum grid spacing is 0.08 mm in both axial and transverse direction while it is 0.125 mm in the spanwise direction

As boundary layers grow along these solid walls, the flow encounters an adverse pressure gradient if the walls are parallel. To maintain the flow pressure gradient-free in the experiment, the walls were slightly diverged starting at an axial location where the boundary layers on either side start to compress the flow and create an axial pressure gradient. The same is done here. The axial distribution of the centerline pressures for 2D simulations are plotted in Fig.2 for different divergence angles. The precise divergence angle required to achieve pressure gradient-free flow is determined by running simulation for couple of divergence angles and making iterative adjustment using linear interpolation/extrapolation. It is found that wall divergence angle of 0.36^0 for 2D case and 0.18^0 for 3D case provide gradient free centerline pressure.

Random noise is added to the boundary layer profile to trigger the instability. Boundary layer profiles for velocity and temperature corresponding to required momentum thickness are used to specify inlet boundary conditions on either sides of the splitter plate. Adiabatic, no-slip conditions are used at all walls (splitter plate and top and bottom wall) and non-reflecting boundary conditions are used at outflow boundary. The amplitudes are adjusted so that the root-mean-squares values equal turbulent fluctuation intensities within the boundary layer. Predictions of the three-dimensional simulation for the self-similar region change minimally if digital filtering approach [42] is used to specify the inlet turbulence. However, in case of digital filtering approach, self similar behavior starts little upstream.

5.0 Results and discussion

5.1 Simulation of 2D mixing layer

Although, the experimental investigations of seven supersonic mixing layer cases are reported in Goebel and Dutton experiment [19,20], present simulation consider the case of the mixing layer of convective Mach number of 0.2. Instantaneous density contours for 2D case (Fig. 3) show shock reflection from the edge of the splitter plate, development of mixing layer, rolling up and pairing up of vortices. Velocity profiles for different axial locations are compared with Goebel-Dutton experimental results in Fig.4. Velocity is nondimensionalised with velocity difference (Δu) of the two streams and the radial distance is nondimensionalised with mixing layer width (b). The velocity profiles collapsed into single curve indicating the attainment of self similarity before x=0. 32 m.

Table 1: Flow parameters for the simulation

Mach numbers : M_1, M_2	2.01, 1.38
Total Temperature : T_{t1}, T_{t2} (K)	295, 295
Stream Velocity : U_1, U_2 (m/s)	515, 404
Boundary layer thickness : δ_1, δ_2 (mm)	2.5, 2.6
Boundary layer momentum thickness : θ_1, θ_2 (mm)	0.20, 0.20
Free stream velocity ratio : $r = U_2/U_1$	0.78
Velocity parameter : $\lambda = (1-r)/(1+r)$	0.12
Free stream density ratio : $s = \rho_2 / \rho_1$	0.76
Velocity density parameter : $\lambda_s = [(1-r)(1+s^{1/2})]/[2(1+rs^{1/2})$	0.12
Relative Mach number : $M_r = \Delta U / a$	0.40
Convective Mach number : M_c	0.20
Static pressure : P (KPa)	46

*Subscripts 1,2 refer to primary and secondary stream conditions.

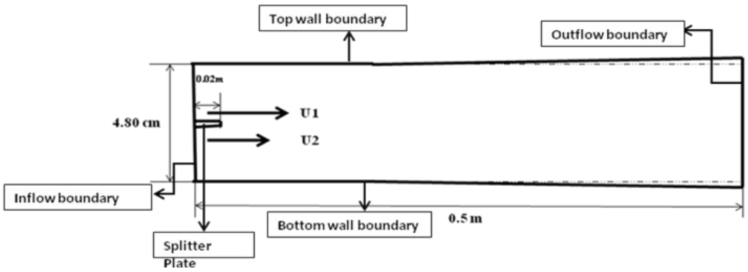

Fig.1 Computational domain in 2D

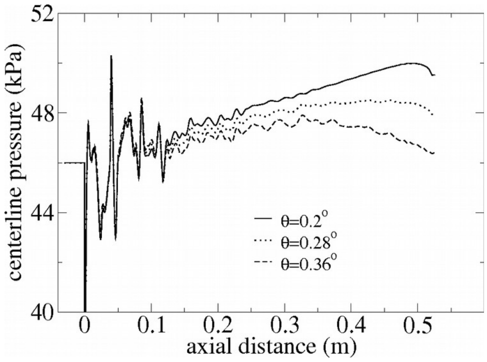

Fig. 2: Axial distribution of centerline pressure for different wall divergence angles

The streamwise and transverse velocity fluctuations profiles at different cross sections are compared with experimental results alongwith the spatial developing mixing layer simulations of Li and Fu [26], Shi et al [29], Bodi [43]. Computed peak streamwise velocity fluctuations matches well with experimental results. The computed profiles of the present computations as well as other numerical simulations are much boarder compared to experimental profile. The peak streamwise velocity fluctuation of Bodi [43] is lower than the experimental data also the profile is narrower in the upper side and boarder in the lowerside of the mixing layer. The profiles of transverse velocity fluctuation of present computations (Fig. 5(b)) as well as the other computations show much larger peak and broader characteristics than experimental data. The peak fluctuation in transverse direction is found to be higher than that of streamwise direction which is consistent with other 2D simulations [44,45,46] reported in the literature.

The computed Reynolds stress profiles ($u'v'/\Delta u^2$)) at different axial locations are compared in Fig. 6 with the experimental values of Goebel & Dutton [19,20] and the simulations of Li and Fu [26], Shi et al [29], Bodi [43]. It is observed that Reynolds stress attained self-similarity and peak value is accurately predicted by 2D simulation. Reynolds stress profile of 2D LES calculation of Li and FU [26] at x=0.40 m show difference from other simulation results and experimental values.

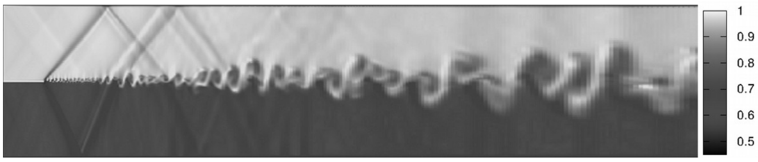

Fig. 3 Density contours showing the roll up of vortices in 2D simulation

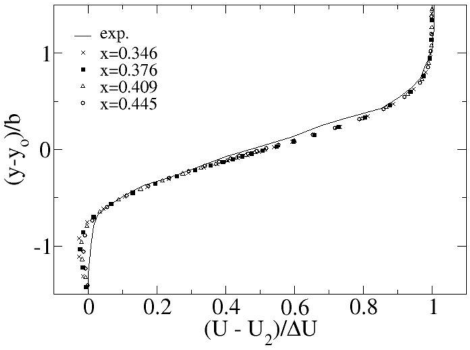

Figure 4: Comparison of velocity profiles with experimental data for 2D mixing layer case

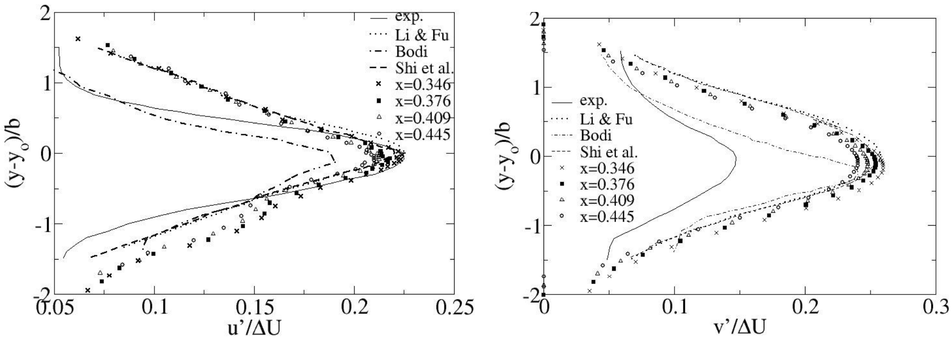

Figure 5: Comparison of (a) streamwise and (b) transverse velocity fluctuations with experimental data for 2D mixing layer

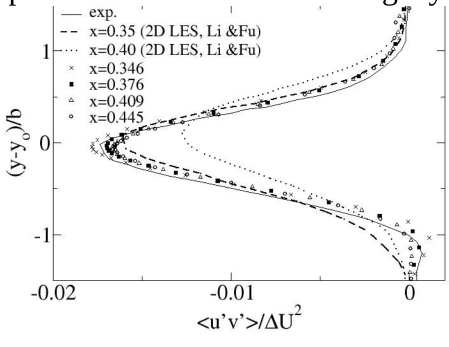

Fig 6. Comparison of Reylonds stresses with experimental data for 2D mixing Layer

5.2 Simulation of 3D mixing layer:

Instantaneous density contours of 3D simulation in Fig.7 show development of mixing layer, rolling up and pairing up of vortices. Comparison of 2D and 3D density reveals that the coherent structures in 3D case is smaller as compared to that obtained in the 2D simulation resulting in lesser growth rate in the former. The growth rate of the mixing layer (db/dx) predicted by 3D simulation is 0.022, which is in good agreement with experimental growth rate (0.02-0.022) [20,21]. The computed growth rate obtained from 2D simulation is 0.0266 which is about 20% more than 3D growth rate. The comparison of axial variations of the mixing layer width for the two cases in Fig. 8 also confirm that the width of the mixing layer obtained by 3D simulation is less than that obtained from 2D simulation. The incompressible mixing layer studies using 2D and 3D codes by McMullan et al. [45] reported a faster growth rate from 3D simulation showing an opposite trend of the present simulation of compressible mixing layer. It was stressed that the initial conditions of the flow must be matched as closely as possible to that of the experiment to obtain accurate results. The 2D Mixing layer growth predicted by Stanley and Sarkar [46] is much higher compared to experiment just as observed in the current 2D simulation. The velocity fluctuations also extend significantly outside the mixing region due to transverse transport of turbulent eddies.

The nondimensionalised velocity profiles for 3D simulation case at various axial locations are compared with experimental data in Fig.9. Like in 2D case, the velocity profiles attained self similarity at about x= 0.31 m and the computed results compare extremely well with experimental results. The computed 3D profiles of the streamwise and transverse velocity fluctuations are compared with experimental results in Fig.10. Both velocity fluctuations match better with experimental results compared to 2D simulations, the improvement of the transverse fluctuation is more remarkable. The computed Reynolds stress profiles at different axial stations are compared with experimental data in Figure 11. Although there is broad match in profiles, the computed peak is smaller than the experimental data. Comparison of experimental [47] and computational work in this area [8,26,27,32] presented in Fig.12 shows that the experiments of Goebel and Dutton [19] produced higher fluctuations than expected. For example, the peak value of streamwise velocity fluctuation levels is about 0.16 for a convective Mach of 0.0. As the convective Mach number increases, the peak value decreases. However the compressibility effects are generally low below Mc=0.4 and so the peak values including one from current LES are generally in 0.16 ± 0.01 range. The peak value in case of Goebel and Dutton (0.22), on the other hand, is noticeably higher than other cases.

6 Summary

2D and 3D simulations of a supersonic mixing layer are performed using an in-house hybrid LES code. This code uses a specially designed switch to change from the 4th order central MacCormack scheme in the smooth regions of the flows to a second order low dissipation SLAU2 scheme in the vicinity of the discontinuities like shocks. The results of 2D and 3D simulations of supersonic mixing layers are compared with the experimental results of Goebel & Dutton and the simulation (DNS and LES) results of other researchers. The profiles of mean velocity and streamwise velocity fluctuations match nicely with both 2D and 3D simulation. For transverse velocity fluctuation, the agreement of computation and experimental data is much better in 3D simulation than in 2D simulation. Although, the peak values of the Reynolds stress obtained using 2D simulation show a good match with the experimental results, the profiles are much boarder. For 3D simulation, computed peak Reynolds stress is much lower than the experimental data. Comparing the computed turbulent statistics from both 2D and 3D results, we can observe that 2D profiles are much intense and boarder than that of 3D simulation. This is in accordance with the hypothesis that there is a lack of significant energy transfer to the small scales in 2D as compared to 3D due to a vast difference between the 2D and 3D flows. For future mixing layer studies focusing on high compressibility (i.e. high Mc) effects, a study with self similar states more consistent with the expected trends will be considered instead of the high Mc data from Goebel and Dutton work.

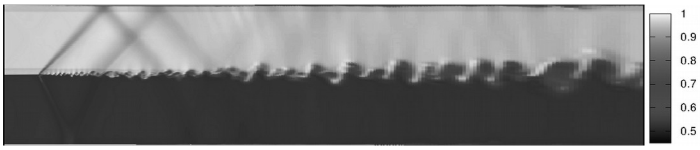

Fig. 7 Density contours for 3D simulation

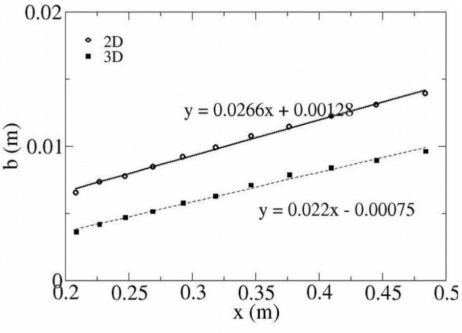

Fig.8 Comparison of mixing layer growth predicted by 2D and 3D simulations

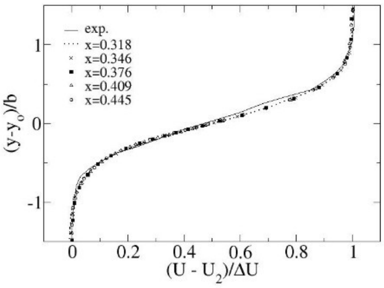

Figure 9: Comparison of nondimensionalised velocity profiles with experimental data for 3D mixing layer case

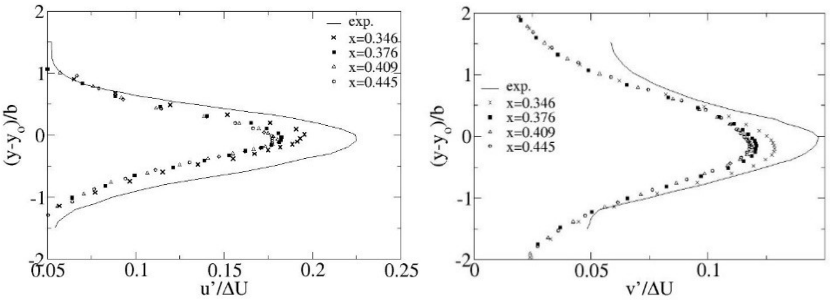

Figure 10: Comparison of (a) streamwise and (b) transverse velocity fluctuations with experimental data for 3D mixing layer

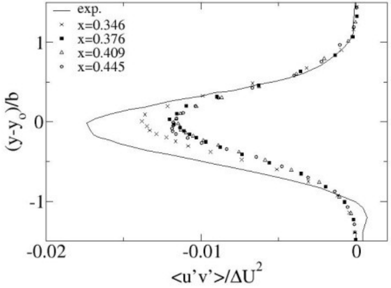

Figure 11: Comparison of Reynolds stress profiles with experimental data for 3D mixing layer case

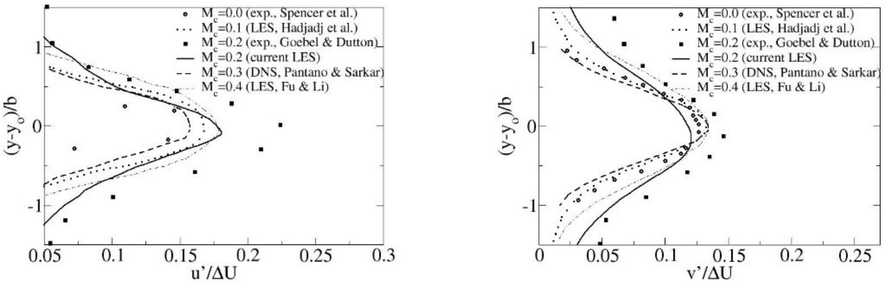

Figure 12 Comparison of (a) streamwise and (b) transverse velocity fluctuations between various LES calculations

REFERENCES

[1] G. Brown and A. Roshko (1974): ``On density effects and large structure in turbulent mixing layers'', Journal of Fluid Mechanics, Vol. 64 pp 775 - 816.

[2] D. W. Bogdanoff (1983): ``Compressibility effects in turbulent shear layers'' AIAA Journal, Vol. 21, No. 6, pp 926 - 927,

[3] D. Papamschou and A. Roshko (1988): ``The compressible turbulent shear layer: an experimental study'', Journal of Fluid Mechanics, Vol. 197, pp 453 - 457.

[4] N. Chinzei, G. Masuya, T. Komoru, A. Murakami, K. Kudou (1986): ``Spreading of two stream supersonic turbulent mixing layers'', Physics of Fluids, Vol. 29, pp 1345- 1347.

[5] M. Saminy and G. S. Elliot (1990): ``Effect of compressibility on the characteristics of free shear layers'', AIAA Journal, Vol. 28, pp 439-445.

[6] S. Barre and J.P. Bonnet (2015): “Detailed experimental study of a highly compressible supersonic turbulent plane mixing layer and comparison with most recent DNS results: Towards an accurate description of compressibility effects in supersonic free shear flows’’, International Journal of Heat Fluid Flow, Vol 51, pp 324-334.

[7] S. Sarkar (1995): ``The stabilizing effect of compressibility in turbulent shear flow'', Journal of Fluid Mechanics, Vol. 282, pp 163 - 186.

[8] C. Pantano and S. Sarkar (2002): “A study of compressibility effects in the high-speed turbulent shear layer using direct simulation”, Journal of Fluid Mechanics, vol. 451, pp. 329-371.

[9] O. Zeman (1990): ``Dilatation dissipation - the concept and application in modeling compressible mixing layer'', Physics of Fluids, A2, pp 178 - 188.

[10] N. D. Sandham and W. C. Reynolds(1991): `` Three dimensional simulation of large eddies in the compressible mixing layer'', Journal of Fluid Mechanics,Vol. 224, pp 133 - 158.

[11] P. J. Morris, M. G. Giridharan and G. M. Lilley (1990): ``On the turbulent mixing of compressible free shear layer'', Proceedings of Royal Society of London, A, Vol. 431, pp 219 - 243.

[12]S. A. Ragab and J. L. Wu (1989): ``Linear instabilities in two dimensional compressible mixing layer'', Physics of Fluids, A1, pp 957 - 966.

[13] T. L. Jackson and C. E. Grosch (1990): ``Absolute/convective instabilities and the convective Mach number in a compressible mixing layer'', Physics of Fluids, A2, pp 949 - 954.

[14] M. Y. Hussaini, F. Collier and D. M. Bushnell (1986): ``Turbulence altercation due to shock motion'', in Turbulent shear-layer/shock wave Interaction Edited by J.Delry, Springer Verlag, New York, pp 371 - 381.

[15] S. K. Lele (1994): ``Compressibility effect on turbulence'', Annual Review of Fluid Mechanics'', Vol 26, pp 211 - 254.

[16]W. Shyy and V. S. Krishnamurty (1997): “Compressibility effects in modelling complex turbulent flows”, Progress in Aerospace Sciences, Vol. 33, pp. 587-645.

[17] Smits, A., Dussauge, J.P. (1996): Turbulent Shear Layers in Supersonic Flow. Springler Verlag, Berlin.

[18] Gatski, T.B. and Bonnet, J.P. (2013): Compressibility, Turbulence and High Speed Flow. Academic Press.

[19] S.G. Goebel, J.C. Dutton, H. Krier and J.P. Renie, “Mean and turbulent velocity measurements of supersonic mixing layers”, Experiments in Fluids 8, 263-272 (1990).

[20] S. G. Goebel and J. C. Dutton (1991): ``Experimental study of compressible turbulent mixing layers", AIAA Journal, Vol. 29, pp 538 - 546

[21] M. R. Grubber, N. L. Messersmith and J. C. Dutton (1993): ``Three dimensional velocity field in a compressible mixing layer", AIAA Journal, Vol. 31, pp 2061 - 2067.

[22] S. Barre, C. Quine and J. P. Dussauge (1994): ``Compressibility effect on the structure of supersonic mixing layers", Journal of Fluid Mechanics, Vol. 259, pp 47 - 78.

[23] A. W. Vreman, N. D. Sandham and K. H. Luo (1996): “Compressible mixing layer growth rate and turbulence characteristics”, Journal of Fluid Mechanics, Vol 320, *pp.* 235-258.

[24] Chakraborty, D.,Paul P. J. and Mukunda H. S. (2000): “Two Dimensional Direct Numerical Simulation of Non-Reacting Supersonic Confined Mixing Layer”,The Aeronautical Journal, Vol 104(1036), pp 291 - 296.

[25] Liu,C. and Lele, S. K. (2001):”Direct numerical simulation of Spatially developing, compressible,Turbulent mixing layers” AIAA Paper 2001-0291.

[26] Li, Q.B., Fu, S (2003): “Numerical simulation of high-speed planar mixing layer”. Computers and Fluids Vol 32, pp 1357–1377 (2003)

[27] Fu, S and Li,Q.B (2006): “Numerical simulation of compressible mixing layers”,International Journal of Heat and Fluid Flow, Vol 27, pp 895-901.

[28] Shi, X., Chen, J., Bi, W., Shu C. and She, Z. (2011):”Numerical simulations of compressible mixing layers with a Discontinuous Galerkin method”, Acta Mechanica, Vol 27(3), pp318-329. DOI 10.1007/s10409-011-0433-0

[29] Zhou, Q., He, F. and Shen M. Y. (2012): “Direct numerical simulation of a spatially developing compressible plane mixing layer: flow structures and mean flow properties”
Journal of Fluid Mechanics, Volume 711, pp 437 468, DOI: 10.1017/jfm.2012.400.

[30] Afroz Javed, NKS Rajan, and Debasis Chakraborty: “Effect of Side Confining Walls on the Growth Rate of Compressible Mixing Layers”, Computers and Fluids, Vol 86, pp 500-509, 2013

[31] Foysi, H. and Sarkar S. (2010):” The compressible mixing layer: an LES study”, Theoretical and Computational Fluid Dynamics, Vol 24, pp 565–588, DOI 10.1007/s00162-009-0176-8

[32] Hadjadj, A., Helen C. Y. and Sjögreen, B. (2012): “LES of temporally evolving mixing layers by an eighth-order filter scheme”, International Journal for Numerical Methods in Fluids, Vol 70, pp1405–1427, DOI: 10.1002/fld.2753

[33] Nelson, C. and Menon, S. (1998): Unsteady simulations of compressible spatial mixing layer. Paper No. *AIAA* 98–786.

[34] Sankaran,V. and Menon, S. (2005): “LES of scalar mixing in supersonic mixing layers”, Proceedings of the Combustion Institute, Vol 30 , pp 2835–2842.

[35] Sharma, A., Bhaskaran, R. and Lele, S.K. (2011): “Large-eddy simulation of supersonic, turbulent mixing layers downstream of a splitter plate”, AIAA paper 2011-208.

[36] Iyer, A. and Rajan, N.K.S (2015): “Simulation of spatial high speed mixing layers using LES”, Computers & Fluids, Vol 109, pp113–122

[37] Iyer, A. Rajan N.K.S. and Chakraborty, D (2015): “Evolution of RANS Model of High Speed Mixing Layers using LES”, pp 137-145, IUTAM Symposium on Advances in

Computation, Modeling and Control of transitional and Turbulent Flows, World Scientific Publishing Company

[38] Sandham, N. D. and. Sandberg, R. D (2009): “Direct numerical simulation of the early development of a turbulent mixing layer downstream of a splitter plate. *Journal of Turbulence*, Vol 10, pp1–17, DOI: 10.1080/14865240802698774.

[39] D. Papamschou and A. Roshko (1988): ``The compressible turbulent shear layer: an experimental study", Journal of Fluid Mechanics, Vol. 197, pp 453 - 457.

[40] Chakravarthy, V.K. and Chakraborty, D (2014): “Modified SLAU2 scheme with advanced shock stability”, Computers and Fluids, Volume 100, pp 176-184.

[41] Chakravarthy, V.K., Arora, K. and Chakraborty, D (2015):”A simple hybrid finite volume solver for compressible turbulence”, International Journal of Numerical Methods in Fluids, Vol 77, pp 707-731.

[42] Touber , E. & Sandham , N. D. (2009): “Large-eddy simulation of low-frequency unsteadiness in a turbulent shock-induced separation bubble. Theoretical and Computational Fluid Dynamics, Vol 23, pp79-107.

[43] Kowsik V R Bodi (2005): “Large Eddy Simulation of Compressible Mixing Layers”, MSc Thesis, Department of Aerospace Engineering, Indian Institute of Science, Bangalore.

[44] Wang J. K. and Milane R. E. (2006): “Large eddy simulation (2D) of spatially developing mixing layer using vortex-in-cell for flow field and filtered probability density function for scalar field, International Journal for Numerical methods in Fluids, Vol 50, pp 27-61.

[45] McMullan, W. A., Gao, S. and Coats,C. M.(2007): “A comparative study of inflow conditions for two- and three-dimensional spatially developing mixing layers using large eddy simulation”, International Journal for Numerical methods in Fluids, Vol 55, pp 589-610.

[46] Stanley, S. and Sarkar, S. (1997): “Simulations of spatially developing Two-Dimensional Shear Layers and Jets, Theoretical and Computational Fluid Dynamics, Vol 9, pp121-147.

[47] B.W. Spencer and B.G. Jones, “Statistical Investigation of Pressure and Velocity Fields in the Turbulent Two-Stream Mixing Layer”, AIAA Paper No. 71-613.

Highlights

- 2D and 3D LES of supersonic Mixing Layer is performed using indigenous CFD code.
- 4th order central & 2nd upwind schemes are combined to capture shock and viscous flows.
- Mean velocity and velocity fluctuation profiles match nicely with both 2D and 3D simulation.
- 3D simulation matches the transverse velocity fluctuation better with experimental data.
- 2D profiles are much intense and boarder than that of 3D simulation.

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NO.DRDL/5060/1/DOCD Dated : 20th July, 2016

Dear Sir,

Please find enclosed the manuscript entitled, **“**Large Eddy Simulation of Supersonic, Compressible, Turbulent Mixing Layers” by Konark Arora, Kalyana Chakravarthy, Debasis Chakraborty for review and publication in the Aerospace Sciences and Technologies Journal The research presented here is the bonafide work of the authors and not under consideration of publication anywhere else. Please feel free to contact me for any further clarifications.

With warm regards,

Yours sincerely,

(Dr.DEBASIS CHAKRABORTY)

To:
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