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Exploration of supersonic confined mixing layer: Effect of dissimilar gases at different temperatures

Afroz Javed[1], PJ Paul[2], NKS Rajan[2] and Debasis Chakraborty[1]

Abstract

The growth rate of high-speed mixing layer between two dissimilar gases is explored through the model free simulation results. To analyse the cause for the higher mixing layer growth rate in comparison to the existing values reported in literature, the results were compared with the model free simulations of mixing of two high-speed streams of nitrogen (similar gas) at matched temperature and density. The analysis indicates that pressure and density fluctuations no longer remain correlated completely for the mixing layer formed between two dissimilar gases at different temperatures in contrast to the complete pressure density correlation for similar gases. It has been observed that the correlation between temperature and density fluctuations is near −1.0 for dissimilar gases in the mixing layer region and is much higher than for similar gases. It is concluded that mixing layer of similar gases shows a decrease in growth rate due to compressibility effect, while that of dissimilar gases shows a decrease due to dominant temperature effect on density.

Keywords

Compressible mixing layer, model free simulation, pressure density correlation

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Introduction

Extensive studies on compressibility effect on supersonic mixing layers are reported in literature where both the streams have same chemical composition, temperature, and density. But, in a scramjet engine combustor, dissimilar gases (fuel and oxidiser) at different temperatures mix with each other. A number of experimental studies involving the mixing of similar and dissimilar gases, at same or different temperatures, with matched static pressures of both the streams have been carried out to understand the mixing behaviour of two parallel streams of gases under compressible conditions. Wantuck et al.[1] have reported a good match of growth rate reduction with Messersmith[2] empirical curve. For the experimental studies carried out by Hall et al.,[3] some of the experimental points do not follow the available experimental trend, this is attributed to very high-density ratios in the subsonic convective Mach number range and use of different gases. The data for growth rate by Papamoschou and Roshko[4] also show some variations with the empirical curve. However, the normalised growth rates for similar gases show a much better match with the empirical curve. Lu and Lele[5] have made an attempt to explain the variations in the mixing layer growth rate data based on density ratio effect. They could match the normalised growth rates of similar gases with the empirical curves taking the effect of very high-density ratios, and the lack of good match for some of the experimental data was attributed to the effect of dissimilar gases. The salient features of the experimental studies are given in Table 1. It can be observed that most of the experimental conditions do not tackle the simultaneous effect of dissimilar gases and large temperature difference. The first four experimental conditions use dissimilar gases with considerable molecular weight difference, but the temperature difference between the two streams is not large. The stability analysis studies of mixing of dissimilar gases (Kozusko et al.[6] and Fedioun and Lardjane[7]) is shown to be quantitatively different from the corresponding mixing layer formed between the same composition gases with similar flow parameters, but the qualitative trend of decreasing growth rate with increasing convective Mach

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Table 1. Salient parameters for experiments for mixing layers of dissimilar gases.

S. No.	Experiment	Speeds of the streams	Convective Mach number	Gases used	Temperature
1	Wantuck et al.[1]	Supersonic/supersonic	1.23	Ar/He	100 K/100 K
2	Hall et al.[3]	Supersonic/subsonic	0.1–1.0	Ar/He/N_2 in different combinations	Same total temperatures
3	Papamoschou and Roshko[4]	Supersonic/supersonic and supersonic/subsonic	0.07–1.81	He/Ar/N_2 in different combinations	Same total temperatures
4	Rossmann et al.[12]	Supersonic/very low speed	0.01, 1.21, 2.33	Air/He, Ar/He, Ar/CO_2	Temperature ratios 1.0 to 0.4
5	Erdos et al.[9]	Supersonic/supersonic	2.8, 0.8	N_2/N_2, H_2/N_2	102 K/2436 K, 103 K/2436 K
6	Urban et al.[13]	Supersonic/subsonic	0.24, 0.63, 0.79	Air/air and air/Ar	Temperature difference within 100 K

number is followed for both the mixing of similar and dissimilar gases. The number of numerical simulations carried out for non-reacting simulations of dissimilar gases mixing under compressible conditions remain small in the published literature. One of the important studies has been made by Chakraborty et al.[8] where an analysis of Erdos et al.[9] non-reacting experimental case has been made. In this study, a series of model free simulations have been carried out for both non-reacting and reacting cases. The wall pressure data computed using model free simulations from SPARK 2D code show a good match with the experimental results. The turbulence statistics like turbulence intensity and anisotropy have been compared with Goebel and Dutton[10] free shear layer results and a qualitatively consistent trend is observed. Recently, Javed et al.[11] 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 three-dimensional features, the average pressure and velocities are predominantly two-dimensional. Although the mixing layer thicknesses differ among different simulations, their growth rate is nearly the same.

In the present work, two-dimensional model free simulations to study the development of mixing layer between two dissimilar gases under compressible condition are presented. The possible causes of the differences of mixing of similar and dissimilar gases are analysed for different temperatures and convective Mach numbers.

Consideration for simulation

The parameters for the mixing layer simulations in the present work are taken from the experimental study carried out by Erdos et al.[9] In one of the experimental cases of their study, hydrogen and nitrogen at Mach numbers of 3.09 and 3.99, respectively, flow in the upper and lower parts of a rectangular duct, forming a mixing layer. A schematic of the experiment along with the flow parameters is shown in Figure 1. The cross section after the splitter plate is 25.4 mm high and 50.8 mm wide.

In this simulation, the nitrogen stream is taken as the primary flow at the lower part of the duct and the hydrogen stream is taken as secondary flow at the upper part of the duct separated by a splitter plate. The details of the flow parameters are presented in Table 1. The convective Mach number is 0.80 for this mixing layer. To understand the effect of convective Mach number on the growth rate, two more simulations are carried out at $M_c = 0.4$ and 0.6 while keeping the temperature of the gases same as that in $M_c = 0.8$ case. Simulations are also carried out for the

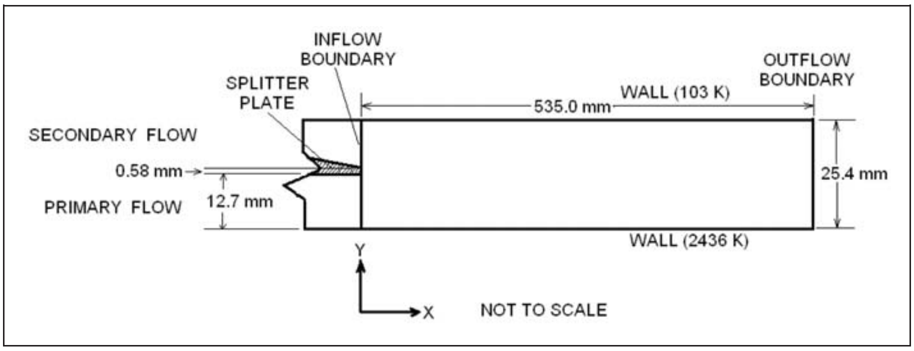

Figure 1. Schematic of experimental condition of Erdos et al.[9] for which simulation is carried out.

Table 2. Simulation matrix of high-speed confined mixing layer.

No.	Location	Species	Velocity (m/s)	Temperature (K)	Pressure (Pa)	Mach No.	M_c	Remarks
1	Primary	N_2	3807	2436	27,580	3.99	0.8	Erdos experiment
	Secondary	H_2	2389	103	27,580	3.09		
2	Primary	N_2	2887	2436	27,580	2.99	0.6	Dissimilar gases at various M_cs and temperatures
	Secondary	H_2	1819	103	27,580	2.35		
3	Primary	N_2	1925	2436	27,580	1.99	0.4	
	Secondary	H_2	1230	103	27,580	1.59		
4	Primary	N_2	1527	300	27,580	4.32	0.8	Similar gases with same temperature at different M_c
	Secondary	N_2	962	300	27,580	2.72		
5	Primary	N_2	1145	300	27,580	3.24	0.6	
	Secondary	N_2	721	300	27,580	2.04		
6	Primary	N_2	763	300	27,580	2.16	0.4	
	Secondary	N_2	481	300	27,580	1.36		

mixing of two streams of nitrogen gas at a temperature of 300 K. The details of the inflow parameters considered in the study are tabulated in Table 2.

The code and the computational details

The details of the numerical simulation and computational grid are the same as described in Ref. 11. A fourth-order compact scheme is used in SPARK 2D software, developed at NASA LaRC by Drummond[14] and Carpenter.[15] The flow domain is of size $535\,\text{mm} \times 25.4\,\text{mm}$. The two streams are separated by a splitter plate at a height of 12.7 mm, before the start of mixing. 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 (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[16] 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. 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 velocities at the walls and splitter plate are kept zero, and constancy of wall temperatures are employed for heat transfer. Laminar boundary layer thickness is taken for both the streams, as experimental[9] wall heat transfer data are consistent with the laminar conditions at the inlet. In this thickness, a parabolic velocity profile is given for each stream, both at splitter plate as well as at duct walls. In the present study, no fluctuations in the velocity fields at the inlet are introduced. The instability develops due to the intrinsic behaviour of the governing equations. The issues related with the growth rate and initial disturbances are presented in detail in Ref. 11. Both the streams are given equal pressure of 27.58 kPa. 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 for the purging of initial conditions, as explained in Ref. 11.

Results and discussions

Growth rate for all the model free simulations have been normalised by incompressible growth rate given by Dimotakis'[17] correlation (equation (1)) and shown in Figure 2.

$$\left(\frac{\mathrm{d}\delta_{\omega}}{dx}\right)_{inc} = C_{\delta 0}\,\frac{(1-r)\left(1+\sqrt{s}\right)}{2\left(1+r\sqrt{s}\right)}\left[1-\frac{\left(1-\sqrt{s}\right)/\left(1+\sqrt{s}\right)}{1+2.9(1+r)/(1-r)}\right] \tag{1}$$

It can be seen that the growth rate ratios evaluated for the mixing of similar gases at the same temperature and density matches very well with the values predicted using Dimotakis'[17] correlation. However, the growth rate ratios for dissimilar gases, although decreasing with increasing M_c, show higher values than those predicted for the mixing of similar gases. The differences in the growth rate between the similar and dissimilar gases increases with increase in convective Mach number.

It has been observed from the experimental studies that the growth rate of mixing layers formed between dissimilar gases[1–4] and similar gases,[10,13,18–20] with low temperature difference under compressible conditions follow Dimotakis'[21] curve. Some of these experimental results are also shown in Figure 2. In the experiments of Goebel and Dutton,[10] the velocities varied between 800 and 100 m/s and the static temperatures of the streams varied from 150 to 300 K in various combinations. In case of the dissimilar gases experiments carried out by Hall et al.[3] and Papamoschou and Roshko,[4] the velocities of mixing streams are of the order of 1000 m/s, while the maximum molecular weight ratios studied are 10 (Ar and He). While in case of the Erdos[9] experiments (for which the present dissimilar gases simulations carried out), the velocities of two mixing layers are quite high (of the order of 2000–4000 m/s), with a static temperature ratio of around 23.6. It is clear that in the present case that the mixing of dissimilar gases is combined with very high temperature difference. Unfortunately, no experimental mixing layer growth data are available from Erdos' study. However, the stability analysis carried out by Kozusko et al.,[6] as discussed earlier, has predicted higher growth rate for the combination of dissimilar gases with high temperature difference (temperature ratio = 0.5). Similar kind of higher growth rate for dissimilar gases is observed in the present study also. The growth rate of dissimilar gases is higher by 8–34% with increasing M_c. The difference in the temperature ratio for the dissimilar

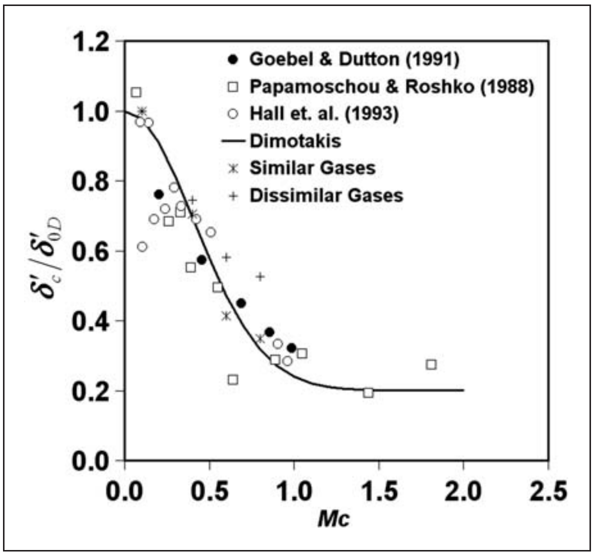

Figure 2. Normalised growth rate from different simulations compared with 'Dimotakis curve' and experimental data.

gases has caused the correlation between pressure and density fluctuations to deviate from unity which is conjectured to be the cause of higher growth rate.

In the mixing of similar gases at the same temperature, density is an explicit function of pressure. When there are dissimilar gases in the mixing streams, the density is a function of pressure as well as that of the molecular weights of the gases. When the two streams are at the same pressure, the difference in the molecular weights is taken care of by density ratio. Similarly, for the mixing of similar gases at the same pressure but different temperatures, the effect of temperature difference is manifested in the density ratio and is catered for in the growth rate formula. However, when both the temperature and species are different, the density difference issue is not as simple to be addressed. In the present dissimilar gases case, hydrogen stream with very low temperature and high specific heat mixes with a very high temperature nitrogen stream with low specific heat. Due to its temperature (103 K), hydrogen stream is the stream with higher density and nitrogen stream is the stream with lower density. A small amount of hydrogen mixed in nitrogen stream could decrease the temperature drastically increasing the density of the fluid element, despite having a lower molecular weight. Therefore, in this scenario, density changes are no longer an explicit function of pressure changes. The density and pressure variations within the mixing layers formed between two dissimilar gases at different temperatures are different from that for a mixing layer formed between two similar gases at same temperature. The profiles of the temperature, density, and pressure fluctuations in the form of the ratio of root mean square value of the fluctuation to the average value of the parameter, at 400 mm axial location, are compared between dissimilar and similar gases in Figures 3 to 5, for different M_c values. It can be seen from Figure 3 that the magnitude of temperature fluctuations is quite small for similar gases in comparison with that observed for dissimilar gases. The difference between the two normalised density fluctuations for similar and dissimilar gases is not as high as it exists for the normalised temperature fluctuations due to a very large difference between the molecular weights of the two mixing gases. The root mean square pressure fluctuations normalised by average pressures are slightly lower in case of dissimilar gases mixing, except in $M_c = 0.6$ case where it is around 18% lower, as shown in Figure 5. It can be seen that despite comparable (and lower in one case) pressure fluctuations, the density fluctuations are more in case of dissimilar gases mixing. It appears from the foregoing discussion that although mixing of both the similar and dissimilar gases streams show considerable amount of density fluctuations, the underlying mechanisms of these density changes is different. In order to explain the cause for increased growth rate, with the effect of density fluctuations in case of dissimilar gases, the correlations of pressure and temperature fluctuations with density fluctuation are studied further.

Pantano and Sarkar[22] used the pressure fluctuation equation to explain the cause of reduction of pressure strain term which in turn is responsible for the reduction of the growth rate of the compressible mixing layer. This evolution equation for the pressure fluctuation is given as

$$\frac{1}{c_0^2}\frac{\partial^2 p'}{\partial t^2} - \frac{\partial^2 p'}{\partial x_i\,\partial x_i} = \frac{\partial^2}{\partial x_i\,\partial x_j}\left(\rho u_i u_j\right)' \qquad (2)$$

Equation (2) is an inhomogeneous wave equation with c_0 as wave speed. This equation is derived by taking the divergence of the momentum equation and subtracting the average momentum equation from it. It has been assumed that viscous terms are negligible and isentropic relationship for single specie, $\partial p/\partial t = c_0^2 \partial\rho/\partial t$ applies. Away from shocks and solid boundaries, such assumptions are reasonable for

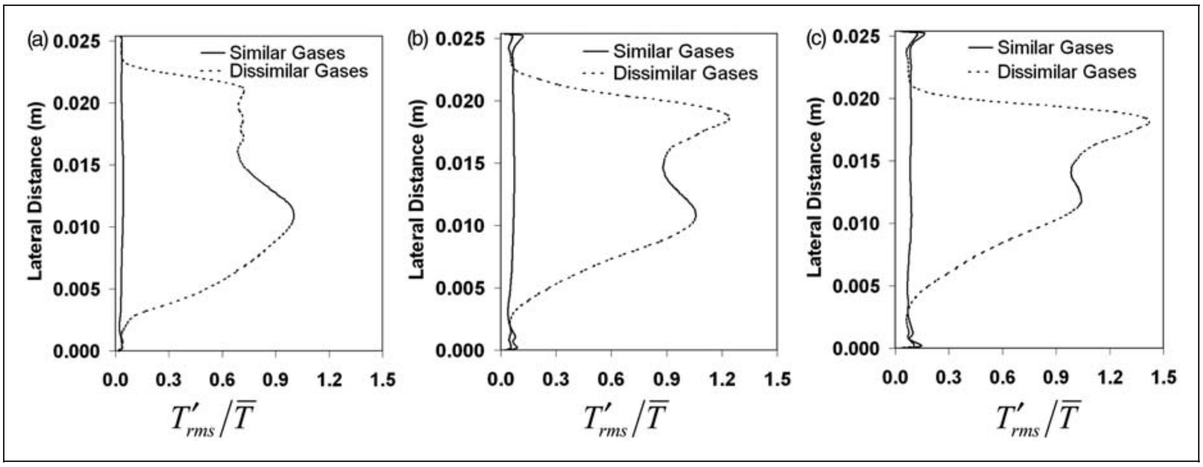

Figure 3. Temperature fluctuations for similar and dissimilar gases at an axial location of 400 mm: (a) $Mc = 0.4$, (b) $Mc = 0.6$ and (c) $Mc = 0.8$.

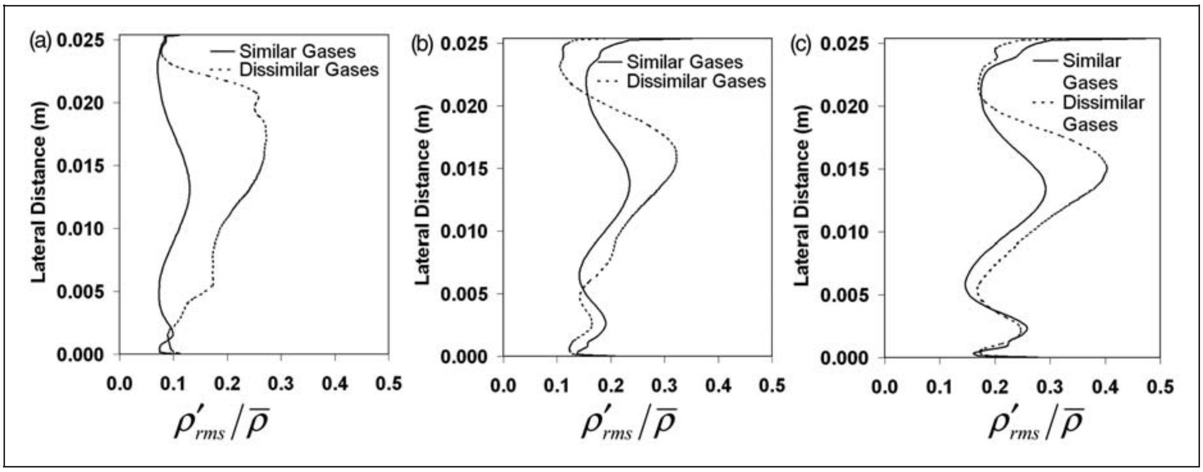

Figure 4. Density fluctuations for similar and dissimilar gases at an axial location of 400 mm: (a) $Mc = 0.4$, (b) $Mc = 0.6$ and (c) $Mc = 0.8$.

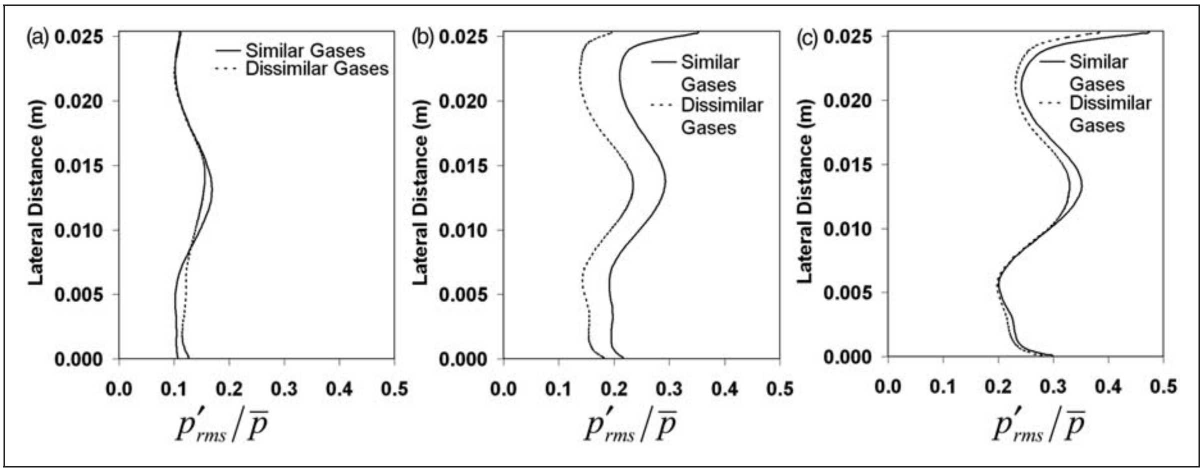

Figure 5. Pressure fluctuations for similar and dissimilar gases at an axial location of 400 mm: (a) $Mc = 0.4$, (b) $Mc = 0.6$ and (c) $Mc = 0.8$.

high-Reynolds number flows. One of the consequences of the isentropic assumption is that the pressure and density fluctuations are completely correlated, and the correlation coefficient defined as $\overline{\rho' p'}/\rho_{rms} \cdot p_{rms}$ is unity.

This equation is analysed in Fourier space by Pantano and Sarkar,[22] and it has been shown that for convective Mach numbers near to unity, the ratio of compressible to incompressible pressure strain terms can be given as

$$\frac{\Pi_{ij}}{\Pi_{ij}^{I}} = \frac{1}{K_\infty M_c^2} \tag{3}$$

where the constant K_∞ must be calculated from experimental data, and pressure strain correlation tensor is defined as

$$\Pi_{ij} = \overline{p'\left(\frac{\partial u_i''}{\partial x_j} + \frac{\partial u_j''}{\partial x_i}\right)} \tag{4}$$

When the assumption of pressure and density being exclusive functions of each other does not hold good, the first term on the left hand side of the wave equation cannot be cast in the terms of pressure and would constitute of a density term. And the resulting pressure equation would be a Poisson's equation as given by equation (5). Also, the value of pressure density correlation coefficient will show a departure from unity.

$$\frac{\partial^2 p'}{\partial x_i\, \partial x_i} = \left(\frac{\partial^2 \rho'}{\partial t^2} - \frac{\partial^2}{\partial x_i\, \partial x_j}\left(\rho u_i u_j\right)'\right) \tag{5}$$

In Figure 6, the values of pressure density fluctuation correlation coefficients are shown for different convective Mach numbers, for both similar and dissimilar gases mixing. The values of the correlation coefficients are evaluated after the self-similar state has reached for all the mixing layers which occur at around 300 mm of axial distance. Two axial locations of 400 mm and 500 mm are chosen as sampling

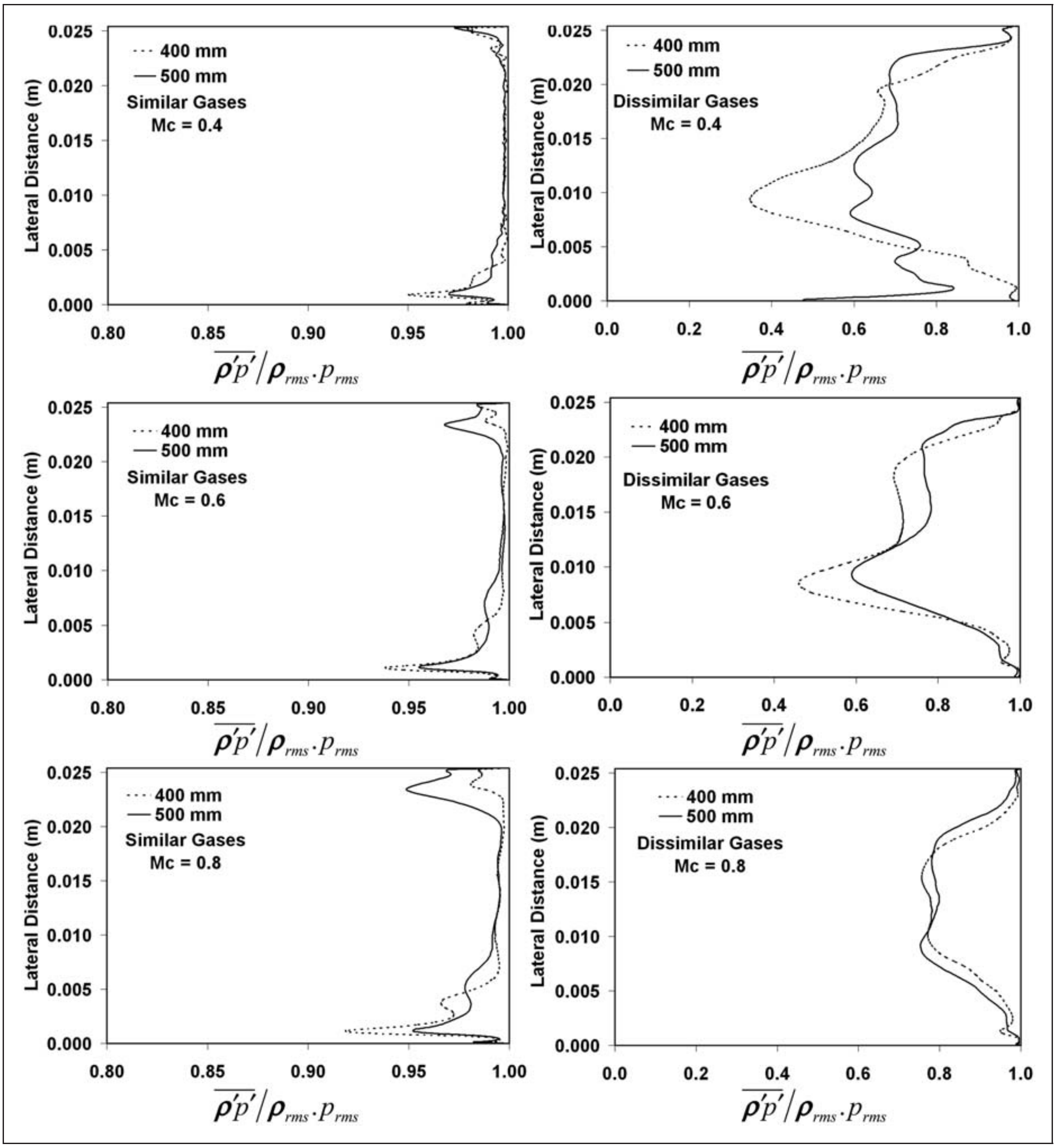

Figure 6. Variation of pressure density fluctuation correlation coefficient within the mixing layer at different convective Mach numbers for both similar and dissimilar gases mixing cases.

locations in the self-similar regime of the mixing layers for the evaluation of the correlation coefficients. It can be clearly observed that the correlation coefficient is near unity within the mixing layer region for the mixing of similar gases at all the convective Mach number values, while a significant departure from unity can be observed for the dissimilar gases cases. In the dissimilar gases, the pressure density fluctuation correlation coefficient shows variations at different axial locations. This deviation from unity is maximum at $M_c = 0.4$ and is lower for increased M_c. This departure from unity for the pressure density fluctuation coefficient shows that the isentropic assumptions does not hold good for the case of mixing of dissimilar gases at different temperature, and the pressure fluctuations occurring in the mixing layers cannot be explicitly defined using the wave equation (equation (2)).

A complete lack of correlation would make the pressure fluctuations to be governed by a Poisson's equation as would happen in case of an incompressible mixing layer, instead of by a wave equation as occurs in case of the compressible mixing layers. However, the pressure fluctuations are not completely decorrelated from the density fluctuations in the case of the dissimilar gases, and the correlation coefficient is between 0.6 and 0.8 for all the convective Mach number cases considered in the present study. This partial decorrelation would make the pressure fluctuations to be governed by the Poisson's equation only partially. A drop in the normalised growth rate is observed for dissimilar gases at increasing convective Mach number due to the pressure fluctuations being governed by the wave equation. However, the lack of correlation between pressure and density fluctuations causes the pressure fluctuations to be governed by the Poisson's equation depending on the extent of decorrelation. This makes the pressure-strain terms higher than that could be attained for the case of a completely correlated pressure and density fluctuation as happens in the case of mixing of similar gases at the same temperature. This study indicates that the growth rate pattern for dissimilar gases at different temperatures follows a trend which is nearer to the incompressible limit.

A departure from unity for the pressure density fluctuation correlation indicates a reduction in contribution of compressibility itself, i.e., the density of the fluid is affected by changes in temperature and species mass fraction also, in addition to being affected by pressure changes alone. Stated differently, the effect of compressibility does not remain the dominating cause for change in density. In a compressible mixing layer with mixing of similar gases at the same temperature, the fluctuations in density and pressure are a result of change of velocity from one stream to the other stream due to momentum mixing. The fluctuations in temperature are caused by the fluctuations in pressure and velocity; in other words, the temperature changes are caused due to the change in pressure and velocity. However, in case of mixing of two dissimilar gases at a large temperatures difference, the temperature fluctuations cause density fluctuations and corresponding pressure fluctuations.

The increase in temperature in case of similar gases is caused by an increase in pressure and density and vice versa. An examination of the thermodynamic fluctuations equation to the first order, and isentropic relation given by

$$\frac{\rho'}{\bar{\rho}} = \frac{p'}{\bar{p}} - \frac{T'}{\bar{T}} + \frac{W'}{\bar{W}} \tag{6}$$

$$\frac{T'}{\bar{T}} = \frac{\gamma - 1}{\gamma}\frac{p'}{\bar{p}} \tag{7}$$

where ρ, p, T, W and γ are density, pressure, temperature, molecular weight and ratio of specific heats, respectively. These equations (equations (6) and (7)) clearly show that the temperature fluctuations are caused by the fluctuations in pressure and density, in case of mixing of similar gases. Noting that in case of similar gases the last term in equation (6) vanishes, and combining both equations (6) and (7) the temperature fluctuations can be expressed as following.

$$\frac{T'}{\bar{T}} = \gamma\frac{\rho'}{\bar{\rho}} \tag{8}$$

From the above equation, it is obvious that the density fluctuations and temperature fluctuations would be in phase giving a unity correlation coefficient.

However, in case of mixing of two dissimilar gases at different temperatures, the change in density occurs due to molecular mixing and thermal mixing in addition to the pressure changes. When heat and mass (species) are transferred from one stream to another in non-negligible amount, the isentropic assumption does not hold good. Again, examining the thermodynamic fluctuation equation without the combination of isentropic relation, it is clear that in the presence of substantial temperature fluctuations, the density fluctuations would be of the opposite sign. Further to elaborate, it is like heating a mass of gas at constant pressure, the density decreases while the temperature increases due to heat addition. This situation is expected to results in a -1 correlation between the density and temperature fluctuation. In this situation, the temperature changes are *cause* for the density changes. The temperature density correlation coefficient is analysed for both the similar and dissimilar gases cases in the following section.

The correlations of density and temperature are shown in Figure 7 for both similar and dissimilar gases at different M_c. For similar gases, it can be observed that the correlation coefficient is nearly unity in the mixing layer region, indicating an in-phase fluctuation of both density and temperature, which means an increase in density coincides with an increase in temperature. It is evident from the near unity correlation of density and temperature fluctuation that the temperature fluctuations are caused by the density fluctuations.

In case of dissimilar gases, negative correlation is observed between density and temperature fluctuations, indicating density and temperature fluctuations to be out of phase. The time variation of density would show a valley for a peak in temperature. The fluctuation in temperature due to mixing of highly different temperature gases causes an opposite fluctuation in the density, i.e., an increase in temperature causes a decrease in density and vice versa. For sufficiently high temperature fluctuations introduced due to high temperature difference, the density fluctuations caused due to pressure fluctuations from velocity are dominated by those caused by temperature fluctuations, showing an almost -1.0 correlation coefficient. The decorrelation of pressure and density has already been observed from Figure 6, for dissimilar gases.

In case of dissimilar gases, the density fluctuations are also a function of species mass fraction.

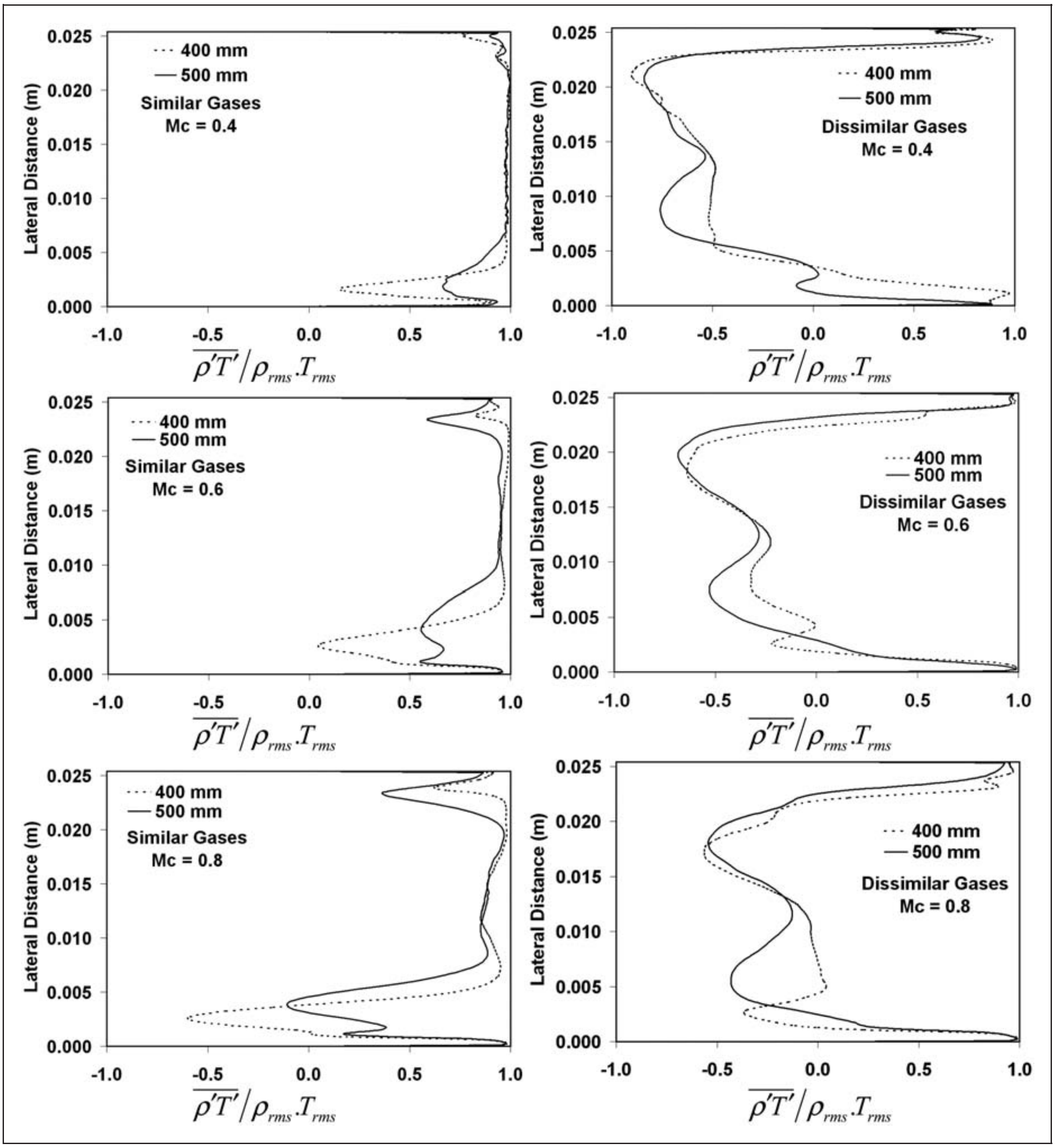

Figure 7. Variation of temperature density fluctuation correlation coefficient within the mixing layer at different M_c for both similar and dissimilar gases.

The correlation coefficients of density fluctuations with molecular weight fluctuations are plotted in Figure 8. The correlation coefficient comes to be negative with values above −0.5, indicating a relatively small effect of molecular weight on the density variations. Again an inspection of equation (7) shows only source of negative correlation could be a high temperature fluctuation, which could dominate both the effects of pressure and molecular weight fluctuation. When nitrogen mixes with hydrogen, the molecular weight increases with respect to pure hydrogen, at the same time the high temperature associated with nitrogen reduces the density and as a result of the mixing although the molecular weight increases, density decreases. It can be concluded that the density fluctuations in case of compressible mixing of gases at different temperatures are dominated by the temperature fluctuations, instead of pressure fluctuations as in case of similar gases.

In a numerical study carried out by Mahle et al.[23] for reacting and non-reacting compressible temporal mixing layers, decorrelation of pressure and density fluctuations has been observed for reacting case. Also the value of correlation coefficient between density and temperature fluctuations has been shown to be near −1.0. The reason for the behaviour of the correlation coefficients is explained to be due to heat addition from chemical reaction and consequent increase

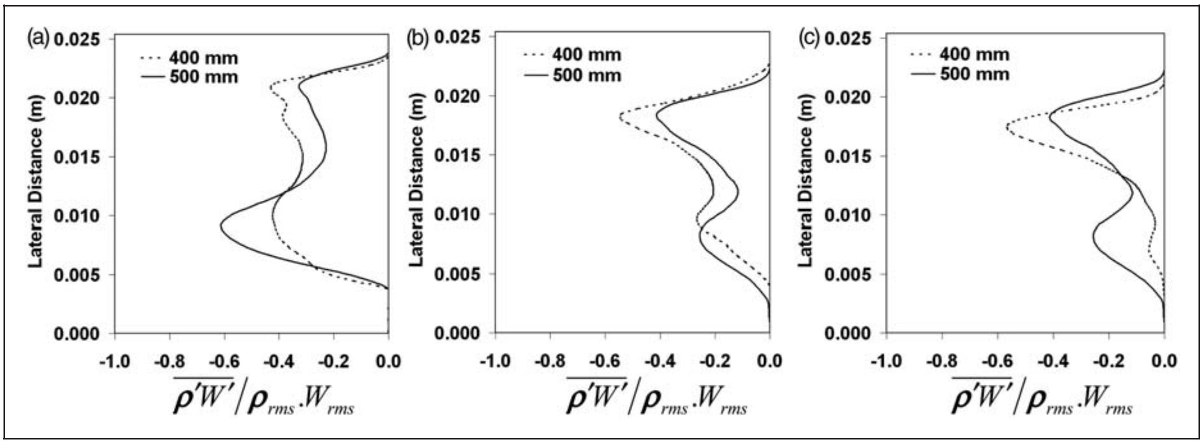

Figure 8. Variation of molecular weight density fluctuation correlation coefficient within the mixing layer at (a) $Mc = 0.4$, (b) $Mc = 0.6$ and (c) $Mc = 0.8$.

in temperature. It has been explained in their work that the reduction in pressure strain correlation tensor becomes predominantly a mean density effect due to temperature changes in reacting case; while this reduction remains a compressibility effect in non-reacting case. However, in the study carried out by Mahle et al.,[23] no comment is made on the growth rates of the reacting and non-reacting mixing layers. In the present study dealing with the mixing of two streams with very high temperature difference, the effect of high temperature difference causes the density effect to be predominant than the compressibility effects. This effect of high temperature difference is manifested in the form of decorrelation of pressure and density fluctuation and near −1.0 correlation of temperature and density similar to the observations made from the numerical simulations of Mahle et al.[23] It appears that the reduction in the growth rate of the compressible mixing layer formed between similar gases at the same temperature occurs due to predominant compressibility effects, while that formed between two dissimilar gases with large temperature difference the growth rate reduction occurs due to dominant heat transfer effects from one stream to another.

Concluding remarks

Model free simulations have been carried out for a compressible mixing layer formed by two different gases namely hydrogen and nitrogen, at two different temperatures and densities. It is observed that for similar gases, the growth rate follow the Dimotakis'[21] curve, whereas for dissimilar gases the growth rate is higher. The differences in the growth rate between the similar and dissimilar gases increases with increase in convective Mach number. The reduction of growth rate occurs due to reduction in the pressure–strain term. The present analysis indicates that the pressure and density fluctuations no longer remain correlated completely for the mixing layer formed between two dissimilar gases at different temperatures in contrast to the complete pressure density correlation for similar gases. This partial correlation makes the pressure fluctuations to be controlled by the Poisson's equation, as happens for incompressible flow, resulting in less reduction of the normalised growth rate with the increase in convective Mach number. It has been observed that the correlation between temperature fluctuation and density fluctuation is near −1.0 for dissimilar gases in the mixing layer region and are much higher than those observed for similar gases. It has been concluded that mixing layer of similar gases (with same temperatures and densities) shows a decrease in growth rate due to compressibility effect, while that of dissimilar gases (with different temperatures and densities) shows a decrease due to dominant temperature effect on the density.

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References

1. Wantuck PJ, Tennant RA, Rothstein AD, et al. *An experimental investigation of the properties of a non-reacting, supersonic shear layer*. In: *29th AIAA aerospace sciences conference*, Reno, NV, USA, 7–10 January 1991. AIAA Paper No. 91-0628. Reston, VA: AIAA.
2. Messersmith NL, Goebel SG, Frantz WH, et al. *Experimental and analytical; investigations of supersonic mixing layers*. In: *26th Aerospace sciences meeting*, Reno, NV, USA, 11–14 January 1998. AIAA Paper No. 1988-0702. Reston, VA: AIAA.
3. Hall JL, Dimotakis PE and Rosemann H. *Experiments in non-reacting compressible shear layers*. In: *29th Aerospace sciences meeting*, Reno, NV, USA, 7–10 January 1991. AIAA Paper No. 91-0629. Reston, VA: AIAA.
4. Papamoschou D and Roshko A. The compressible turbulent shear layer: an experimental study. *J Fluid Mech* 1988; 197: 453–477.

5. Lu G and Lele SK. On the density ratio effect on the growth rate of a compressible mixing layer. *Phys Fluids* 1994; 6: 1073–1075.
6. Kozusko F, Lassaigne DG, Grosch CE, et al. The stability of compressible mixing layers in binary gases. *Phys Fluids* 1996; 8: 1954–1963.
7. Fedioun I and Lardjane N. Temporal linear stability analysis of three-dimensional compressible binary shear layers. *AIAA J* 2005; 43: 111–123.
8. Chakraborty D, Mukunda HS and Paul PJ. Two dimensional direct numerical simulation of nonreacting confined supersonic mixing layer. *Aeronaut J* 2000; 104: 291–296.
9. Erdos J, Tamagno J, Bakos R, et al. *Experiments on shear layer mixing at hypervelocity conditions*. In: *30th Aerospace sciences meeting and exhibit*, Reno, NV, USA, 6–9 January1992. AIAA Paper No. 92-0628. Reston, VA: AIAA.
10. Goebel SG and Dutton JC. Velocity measurements of compressible turbulent mixing layers. *AIAA J* 1991; 29: 538–546.
11. Javed A, Chakraborty D and Paul PJ. Model-free simulations for compressible mixing layer. *J Aerospace Eng* 2013; 227: 977–991.
12. Rossmann T, Mungal MG and Hanson RK. *An experimental investigation of high compressibility non-reacting mixing layers*. In: *38th AIAA Aerospace sciences meeting and exhibit*, Reno, NV, USA, 10–13 January 2000. AIAA Paper No. 2000-0663. Reston, VA: AIAA.
13. Urban WD, Watanbe S and Mungal MG. Velocity fields of the planar shear layer: compressibility effects. In: *36th AIAA Aerospace sciences meeting and exhibit*, Reno, NV, USA, 12–15 January 1998. AIAA Paper No. 98-0697. Reston, VA: AIAA.
14. Drummond JP. Supersonic reacting internal flow field, in numerical approaches in combustion modeling. In: ES Oran and JP Borris (eds) *Progress in aeronautics and astronautics*. vol. 135, Reston, VA: AIAA, 1991, pp.365–420.
15. Carpenter MH. *A generalized chemistry version of SPARK*. NASA-CR-4196. Hampton, VA: NASA, 1998.
16. Oh CK and Loth E. A numerical investigation of supersonic turbulent shear layers: compressibility effect. In: *25th AlAA Fluia Dynamics Conference*, Colorado Springs, CO, USA, 20–23 June 1994. AIAA Paper No. 94-2244. Reston, VA: AIAA.
17. Dimotakis PE. Two-dimensional shear-layer entrainment. *AIAA J* 1986; 24: 1791–1796.
18. Gruber MR, Messersmith NL and Dutton JC. Three-dimensional velocity measurements is a turbulent, compressible mixing layer. In: *AIAA/SAE/ASME/ASEE 28th joint propulsion conference and exhibit*, Nashville, TN, USA, 6–8 July 1992. AIAA Paper No. 92-3544. Reston, VA: AIAA.
19. Elliott G and Samimy M. Compressibility effects in free shear layers. In: *28th Aerospace sciences meeting*, Reno, NV, USA, 9–11 January 1990. AIAA Paper No. 90-0705. Reston, VA: AIAA.
20. Clemens NT, Mungal MG, Berger TE, et al. Visualisations of the structure of the turbulent mixing layer under compressible conditions. In: *28th Aerospace sciences meeting*, Reno, NV, USA, 9–11 January 1990. AIAA Paper No. 90-500. Reston, VA: AIAA.
21. Dimotakis PE. Turbulent free shear layer mixing and combustion, high speed flight propulsion system. In: SNB Murthy and ET Curran (eds) *Progress in aeronautics and astronautics*. vol. 137, Reston, VA: AIAA, 1991, pp.265–340.
22. Pantano C and Sarkar S. A study of compressibility effects in the high-speed turbulent shear layer using direct simulation. *J Fluid Mech* 2002; 451: 329–371.
23. Mahle I, Foysi H, Sarkar S, et al. On the turbulence structure in inert and reacting compressible mixing layers. *J Fluid Mech* 2007; 593: 171–180.

Appendix

Notation

a	speed of sound
p	pressure
r	ratio of velocities of the two mixing streams
s	ratio of densities of the two mixing streams
t	time
u	velocity
x	axial distance
M_c	convective Mach number $\Delta U/(a_1 + a_2)$
$C_{\delta 0}$	mixing layer growth rate coefficient ($=0.37$)
T	temperature
W	Molecular weight
δ_ω	mixing layer thickness
γ	ratio of specific heats
P	density
ΔU	difference in speeds of the two mixing streams