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EXPERIMENTAL STUDY OF A SCALAR MIXING LAYER USING REACTIVE AND PASSIVE SCALARS

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Abstract

The reactive scalar mixing layer in grid generated turbulence similar to that of Bilger et. al. (1991) has been repeated after a modification to the experiment set-up. The various statistics of the mixture fraction (a conserved scalar) deduced from reacting and nonreacting measurements of concentration are presented. The data do not show the uncharacteristic behaviour in the centre of the mixing layer any more and agree well with the data obtained from the thermal mixing layer of the other sources.

1 Introduction

Many people have studied the scalar mixing layer experimentally in grid turbulence. Keffer, Olsen & Kawall (1977), LaRue & Libby (1981), LaRue, Libby and Seshadri (1981) and Ma & Warhaft (1986) have studied the thermal mixing layer in grid turbulence. They all used temperature as the passive scalar to investigate the effect of turbulence on the thermal mixing layer. Saetran et. al. (1989), Bilger, Krishnamoorthy & Saetran (1989) and Bilger, Saetran & Krishnamoorthy (1991) studied the scalar mixing layer in grid turbulence using diluted nitric oxide (NO) and ozone (O_3) as reactive species. The reactants are separated before entering the grid generated turbulence and the mixture fraction, a conserved scalar which characterizes the local mixedness of the two species, can be defined as

$$F = \frac{\Gamma_A - \Gamma_B + \Gamma_{B2}}{\Gamma_{A1} + \Gamma_{B2}}. \qquad (1)$$

Here, Γ_A is the NO concentration, Γ_B the O_3 concentration, Γ_{A1} the NO concentration in stream 1 and Γ_{B2} the O_3 concentration in stream 2. In Bilger et. al. (1991), both the conserved scalar theory and the various statistical data of the mixture fraction measured in the scalar mixing layer have been given in detail. They have also studied the effect of relative rates of chemical reaction and mixing on the reactive species statistics, the mean chemical reaction rate and the modelling of scalar transport.

While the various statistics of the mixture fraction presented in Bilger et. al. (1991) generally agree with that of Keffer et. al. (1977), LaRue & Libby (1981) and Ma & Warhaft (1986) from thermal mixing layers, they show some uncharacteristic behaviour in the centre of the mixing layer at high Reynolds numbers, which appears to be bi-stable flapping. Since both the temperature and the mixture fraction are conserved scalars and their governing equations are the same, both sets of data should have the same behaviour. Many possibilities which may cause this uncharacteristic behaviour have been checked, and it was found that using two small fans for each stream caused the instability. The two pairs of fans have been replaced by two larger fans and new experimental data are given in this paper. Also we have done some experiments using NO alone as a passive scalar. The various statistics of the mixture fraction obtained from the reactive scalar and from the passive scalar have been compared with that of Bilger et. al. (1991) and that of Keffer et. al. (1977), LaRue & Libby (1981) and Ma & Warhaft (1986) in the thermal mixing layer and good agreement has been found.

The velocity results in Bilger et. al. (1991) should be reduced by a factor of $\sqrt{2}$ arising from an error in the computer code used to process the hot wire results. Consequently a corresponding increase of $\sqrt{2}$ should be made to the reported Damköhler numbers.

2 Experimental Set-Up

The experimental results presented in this paper are measured in the Turbulent Smog Chamber (TSC) at the University of Sydney. The schematic diagram of the present experimental set-up is shown in figure 1 and has been thoroughly described by Saetran et.al.(1989) and Bilger et. al. (1991). The only difference between the present experiment set-up and that of the previous one is that the four small fans have been replaced with two of a larger capacity. The flows are doped with ozone and nitric oxide respectively at the inlet of the fans and are separated by a splitter plate before entering the working section of the TSC. The reactant gases are well mixed in the two air streams through three right-angle bends following each fan. The two flows with the same mean velocity and two constant reactant concentrations are introduced into the working section respectively. The turbulence is generated by a grid which is mounted at the beginning of the working section. The grid is made from 63 × 63 mm hollow square-section aluminium on a $M = 320$ mm square pitch giving an open area of 65%. The cylindrical working section is 8 m long and 2.8 m in diameter. The mean velocity of this experiment is $0.5 m/s$, giving the Reynolds number $Re = \frac{UM}{\nu} = 10700$. Here U is the streamwise mean velocity and ν is the kinematic viscosity. The present experimental set-up is a compromise between the need for having a known turbulence field at a reasonably high Reynolds number and for achieving enough spatial and temporal resolution for the analysers to measure the species concentrations.

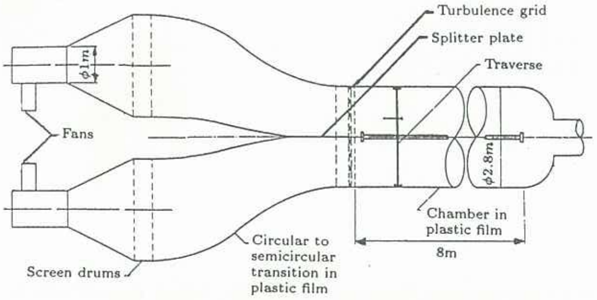

Figure 1 Schematic diagram of experimental facility.

The nitric oxide and ozone used as chemical reactants have very close diffusion coefficients at room temperature (Bilger et. al. 1991) and in the absence of significant ultra violet radiation to drive the back reaction, they undergo the irreversible reaction

$$NO + O_3 \rightarrow NO_2 + O_2 + 200kJ/mol \qquad (2)$$

with a reaction constant k of 0.37 p.p.m.$^{-1}s^{-1}$ at 20^0C (Chameides & Stedman 1977). One of the parameters which characterizes the time scales of both turbulence and chemical reaction is the Damköhler number. In this paper, it is defined as $N_D = \tau_{turb}/\tau_{chem} = kM(\Gamma_{A_1} + \Gamma_{B_2})/U$. Here τ_{turb} and τ_{chem} are the turbulent and chemical time scales respectively. The experimental results given in this paper are measured at the Damköhler number of about 1.6.

In order to resolve the high frequency fluctuations of the two chemical concentrations, a Chemiluminescent Gas Analyser (CLA) with 12 Hz frequency response has been developed by Mudford & Bilger (1983). The frequency response of the CLA has been improved up to 23 Hz by Bilger et. al. (1991) through increasing the capacity of the vacuum pump. In this experiment, it was found that the frequency response of the CLA has been pushed up to its limit with the present design and special care needs to be taken during the experiment. We found that the following factors can all alter the frequency response of the CLA: a) sample and reactant-in-excess flow rates; b) reactant-in-excess concentration; c) reaction chamber design; d) reaction chamber pressure; e) length and diameter of the sample tube and f) the high-tension voltage applied to the Photo-Multiplier tube. The frequency response is currently limited by high frequency noise, the mixing-chamber volume of the CLA and the length of the sample tube.

The NO calibration is done using a gas cylinder of known concentration diluted with precision flow metres. The O_3 calibration is determined indirectly by the titration method of Post & Kewley(1978). A cross-wire probe with a constant temperature hot-wire anemometer was used to measure the two velocity components. The wires were calibrated statically against a TSI 1125 calibrator and a third order fitting procedure is used to fit the calibration data.

Simultaneous point measurements of two components of velocity and two reactants are taken across the flow field at different stations downstream of the grid (range x/M: 4-21). The sampling tube is located 18 mm above the hot-wire probe and it has been found that with this separation, the measured flow field is not interfered by the tube. The CLA samples gas at 140 std. cm^3/s through a 3.1 m teflon tube of diameter 2.8 mm with a sonic nozzle at the inlet. The delay time in the tube is approximately 63 ms.

The signals of the four channels (two CLA, two hot-wire) are sampled at 128 Hz using a 12 bit A/D converter. The total number of samples is 32768, giving the sampling time of 256 seconds. All data processing is done on a high speed PC486.

3 Results

3.1 *The Velocity Field*

Batchelor and Townsend (1948) identified three periods in the decay of homogeneous grid-generated turbulence: initial, transitional, and final. They suggested that it will take $x/M = 100$ for the flow to finish the initial period. The measurements from the TSC are confined to the region $4 \leq x/M \leq 21$ which puts them well within the initial period.

In order to adjust the flow condition to achieve uniform flow in the working section, two butterfly valves have been put at the inlet of the fans. The mean velocity and the rms of the velocity fluctuations across the flow have been checked. The profiles are fairly flat except at the edges of the flow where a boundary layer is developing. The data show that the flow field is a normal grid flow, i.e. the statistics of the velocity varies only in the streamwise direction. Figure 2 shows the streamwise profile of turbulent kinetic energy along the centre line of the working section. The energy decays slowly from the grid to $x/M = 4$, this might be due to the fact that the flow is still undergoing an instability process. From $x/M = 4$ to $x/M \leq 8$ the energy decays very quickly and it follows a -1 law in the region $8 \leq x/M \leq 18$. In the region be-

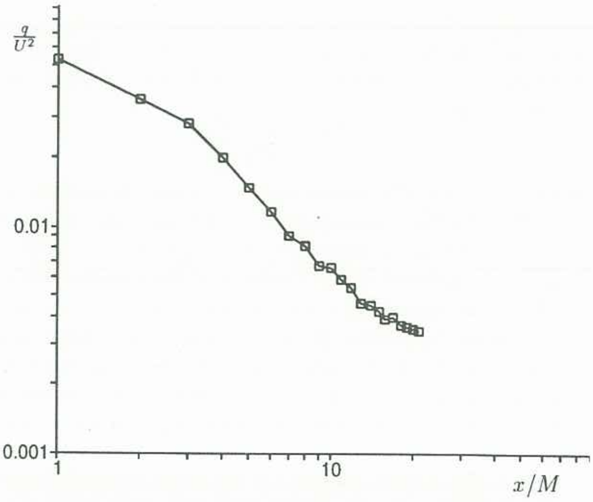

Figure 2 Energy decay in the streamwise direction. Here $q = \frac{1}{2}(\overline{u^2} + \overline{v^2} + \overline{w^2})$.

yond $x/M = 18$, the energy decay is slower. But this may be due to the end effect of the TSC. The flow is quite anisotropic with $u'/v' = 2.03$ constant in the test section and has not shown any tendency towards an isotropic condition yet.

3.2 *Statistics of Mixture Fraction*

Figure 3 shows the mean mixture fraction profiles obtained from the present work. The y distance from the centre has been normalized by the mixing layer thickness δ. Here δ has been defined as the distance from the point where the mean mixture fraction equals to 0.1 to where it equals to 0.9. As suggested by Libby (1975), the profile follows an error function. Also shown in the figure are the data from LaRue & Libby (1981) and it can be seen that our results agree very well with theirs. Figure 4 shows the evolution of the mixing layer thickness with the distance from the grid. Libby (1975) suggested that $\delta \propto x^{1/2}$. On the other hand, using the idea that the mixing layer thickness should be proportional to the length scale of the energy containing eddy, Ma & Warhaft (1986) derived that $\delta \propto x^{1-m/2}$ where m is the exponent of the energy decay law. The mixing layer thickness in the present experiment increases almost linearly from $x/M = 4$ to $x/M = 12$ and has a slower growth rate after $x/M = 12$. The slower increase of δ after $x/M = 12$ can be explained using the idea of Libby (1975) or that of Ma & Warhaft (1986). Before $x/M = 12$, both the theory of Libby (1975) and that of Ma & Warhaft (1986) can not be applied but this might be due to the fact that the mixing layer is still in its very early stage.

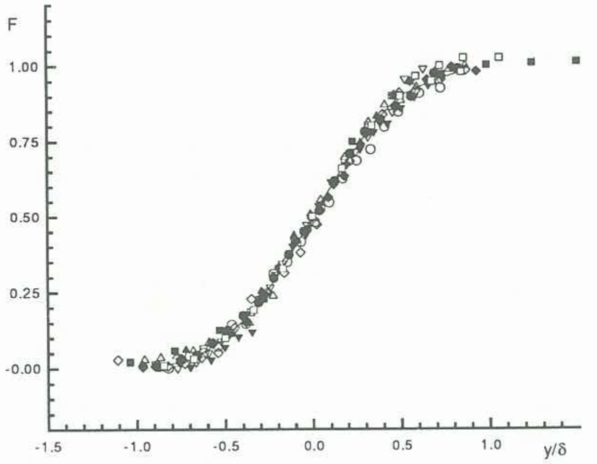

Figure 3 Profiles of mean mixture fraction. Symbols as in table 1.

Symbols	x/M	N_D	Symbols	x/M	Comments
■	4	1.54	◇	15	NO alone
□	8	1.54	●	19	NO alone
▲	12	1.6	○	21	NO alone
△	15	1.54	—■—	30	LaRue & Libby (1981)
▼	19	1.6	—□—	100	Ma & Warhaft (1986)
▽	21	1.6	—▲—	21	Bilger et. al. (1991)
◆	12	NO alone	—△—	41	Keffer et. al. (1977)

Table 1 List of symbols used in figures 3, 5, 6 and. 7

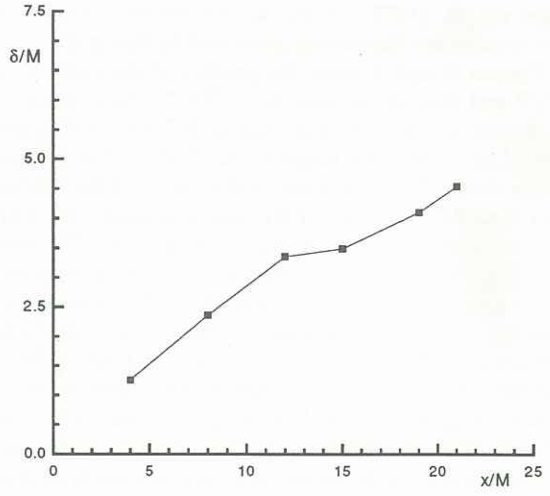

Figure 4 Mixing layer thickness as a function of downstream distance.

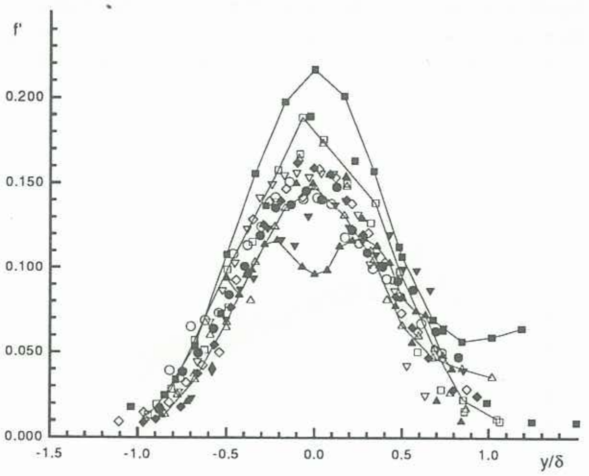

Figure 5 Profiles of r.m.s. of mixture fraction. Symbols as in table 1.

Figure 5 shows the rms values of the mixture fraction (f') from the present experiment. Also shown in the figure are the data from Bilger et. al. (1991), Keffer et. al. (1977), LaRue & Libby (1981) and Ma & Warhaft (1986). For the data of Ma & Warhaft (1986), only those obtained using the toaster to produce the temperature step are used. It can be seen that the present results do not show the dip in the centre of the mixing layer as that of Bilger et. al. (1991) did. Generally speaking, the f'_{max} of the present experiment is close to that of Keffer et. al. (1977) and is smaller than both that of LaRue & Libby (1981) and Ma & Warhaft (1986). Interestingly the f'_{max} ≈ 0.160 of the present data is close to the theoretical prediction of Lumley (1986), $f'_{max} = 0.159$. It can be seen from the figure that on the positive y/δ side, our results agree with that of Ma & Warhaft (1986) as they should since the present experiment and that of Ma & Warhaft (1986) are both from an ideally generated scalar mixing layer. The higher value of LaRue & Libby (1981) and

Keffer et. al. (1977) are due to the residual variance of the temperature fluctuation generated by the grid.

Figures 6 and 7 show the profiles of skewness $S = \overline{f^3}/f'^3$ and that of kurtosis, $K = \overline{f^4}/f'^4$. Also shown in the figures are the data from LaRue & Libby (1981), Ma & Warhaft (1986) and Bilger et. al. (1991). The present results do not have the kinks in the centre of the mixing layer that Bilger et. al. (1991) has and agree well with that measured from the thermal mixing layer. The data have large scatter near the edge of the mixing layer but this is due to the rare occurence of the fluctuation. As expected, the present data agree better with that of Ma & Warhaft (1986) than that of LaRue & Libby (1981). The data of LaRue & Libby (1981) show larger S and K on the negative y/δ side than the present data and that of Ma & Warhaft (1986). Again this might be due to the residual variance of the temperature fluctuation generated by the grid on their hot side.

The various statistics of the mixture fraction strongly support the conserved scalar theory of Bilger et. al. (1991). Apart from some scatter in f', the present experimental data using reactive scalars at $N_D \approx 1.6$, the passive scalar of NO alone, the reactive scalar of Bilger et. al. (1991) at $N_D = 0.42$ and that from thermal mixing layer all agree. The small difference in diffusivity of the scalars used has not had much effect on the statistics of the conserved scalar and it seems that the Reynolds number effect is weak if there is any since the Reynolds number of the present experiment and that of LaRue & Libby (1981) are quite different (their $Re = \frac{UM}{\nu}$ is about 3390).

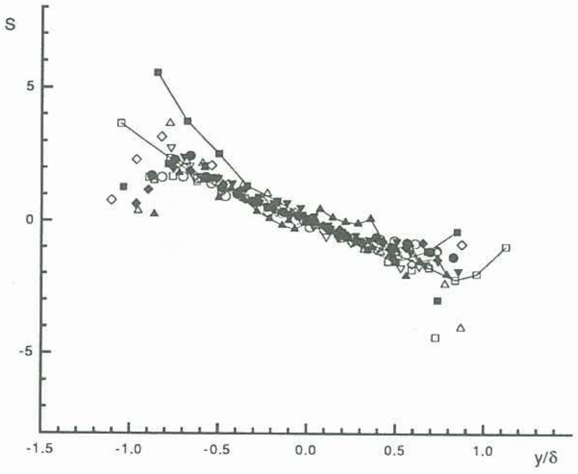

Figure 6 Profiles of skewness of mixture fraction across mixing layer. Symbols as in table 1.

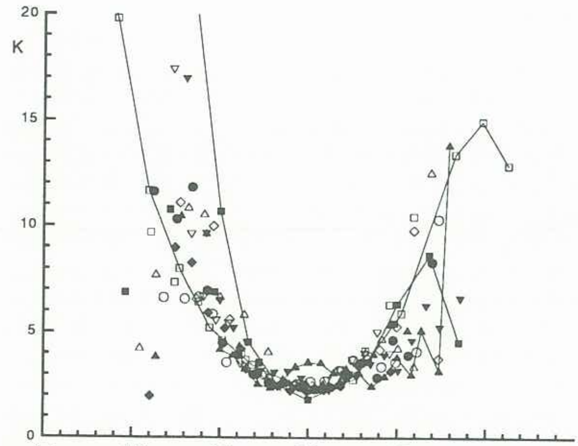

Figure 7 Profiles of kurtosis of mixture fraction across mixing layer. Symbols as in table 1.

4 Conclusion

A conserved scalar deduced from reactive scalars and a nonreactive scalar has been used to investigate the scalar mixing layer in grid turbulence. It is found that the uncharacteristic behaviour of Bilger et. al. (1991) in the centre of the reactive scalar mixing layer is due to the smaller capacity of the fans used. After installing fans of a larger capacity, the new results presented here agree well with those from the thermal mixing layer of the other sources. The results give strong support to the conserved scalar theory of Bilger et. al. (1991) and the results of different Damköhler number show the same mixing characteristics.

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