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NUMERICAL SIMULATION OF HEAT TRANSFER IN TURBULENT MIXING LAYERS

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ABSTRACT

The AGE method is used to simulate turbulent mixing layers with heat transfer for two types of initial conditions. Asymmetrical fluctuation distributions and p.d.f.s are correctly reproduced for the usual case. When the flow is heated some way downstream from the inlet, the initial asymmetry disappears, but the usual types of scalar fluctuations quickly develop with only small residual differences.

INTRODUCTION

Turbulent shear flows are very interesting, both academically and practically, for their ability to transport and mix passive scalars such as temperature or species concentration. The planar mixing layer is conceptually one of the simplest flows in which to study such processes. The processes themselves are not necessarily simple, however; the "almost conclusive evidence that the concept of gradient diffusion is inapplicable ..." is reviewed by Broadwell & Breidenthal (1982), for example. Also, it seems that mixing layers that are self-preserving in terms of mean velocity and Reynolds stress profiles may be far from self-preserving for passive scalar properties. Flow conditions including Reynolds number, velocity ratio, splitter plate boundary layers, free stream turbulence, disturbances such as periodic noise, and the Prandtl or Schmidt number (relative molecular diffusion coefficient of the scalar) may influence results. If chemical reactions occur, the Damkohler number is important.

The general picture that can be drawn from published results, drawing also from discussion by Rogers & Moser (1994), is that transport and mixing of passive scalars falls into three overlapping stages:

(i) If the initial rollup is fairly laminar and 2D, then scalars are transported across the mixing layer in large unmixed volumes of fluid [e.g. Masutani & Bowman (1986), Koochesfahani & Dimotakis (1986)].

(ii) With increasing three-dimensionality and vortex amalgamation, the flow passes the 'mixing transition', and regions of well-mixed scalar can be found interspersed with unmixed lumps. The temperature or concentration ratio in the well-mixed parts is independent of transverse position, i.e. probability density functions of the scalar are 'non-marching' [e.g. Koochesfahani & Dimotaki (1986), Mungal & Dimotakis (1984), Rogers & Moser (1994)].

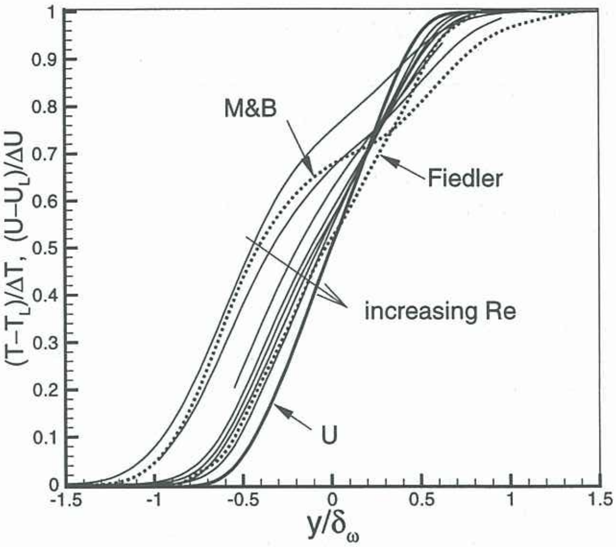

Figure 1: Mean temperature, $1700 < Re < 18,100$ (thin lines); Masutani & Bowman (1986, $Re \approx 2100$), Fiedler (1974, $Re \approx 50,000$). U is a representative mean velocity profile.

(iii) At high enough Reynolds number (where "high enough" is a strong function of other flow conditions), turbulent mixing through a range of scales occurs faster than wholesale transport across the flow, and the composition of the well-mixed parts depends on transverse position (hence 'marching' p.d.f.s) [e.g. Batt (1977), Rogers & Moser (1994); Fiedler (1974) may be part way between stages (ii) and (iii)].

Presumably there could be an overlapping fourth stage in cases where the Prandtl or Schmidt number is large: a kind of 'mixing crisis' in which there are many small (Kolmogorov viscous scale) lumps of fluid that are not fully mixed and are only undergoing slow viscous straining motions [e.g. Dimotakis (1986)].

The broad **aim** of the present work is to inves-

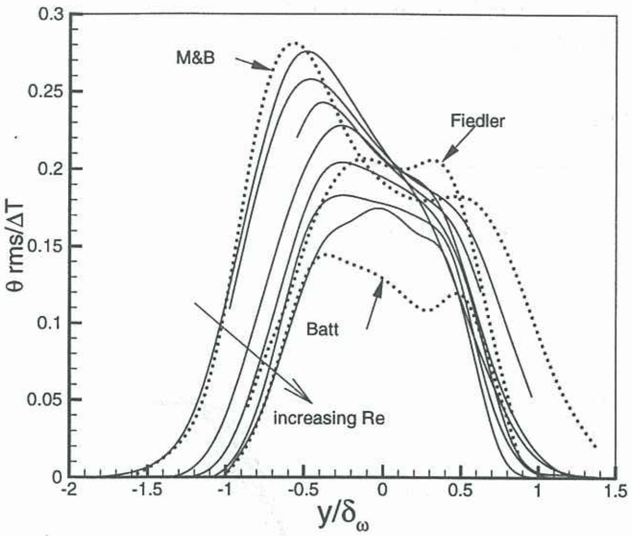

Figure 2: Root-mean-square temperature fluctuations for $1700 < Re < 18,100$ (thin lines) and three experiments.

tigate the above processes for a range of flow conditions by means of numerical simulations using the Advected Grid Explicit (AGE) method. Another aim is to demonstrate that the AGE method is both versatile and efficient, and able to produce very realistic spatial simulations of shear flows, including their scalar transport properties. The AGE method was successfully used for mixing layers (without scalar transport) by Bisset (1998a,b) and for plane jets by Bisset (1998b) and Bisset & Antonia (1998). In the present work, temperature as a passive scalar with a Prandtl number of 1.0 is simulated in a mixing layer at a velocity ratio $r = 0.4$ and vorticity thickness Reynolds number exceeding $Re = 19,000$. Two cases are considered: flow heated for $y > 0$ at the inlet, as usual, and flow heated 300 mm downstream, after the initial rollup of the layer.

Previous mixing layer simulations with passive scalars include Comte, Lesieur & Lamballais (1992) and Rogers & Moser (1994). These were temporal simulations ($r = -1.0$), which did not achieve the real, asymmetric entrainment. The former simulation passed mixing transition in a fairly small calculation domain. The latter convincingly reached the stage of marching p.d.f.s by starting from a very 3D turbulent state, i.e. back-to-back fields from a previous boundary layer simulation, though the final Reynolds number (10,800) was not as high.

SIMULATION DETAILS

A computational domain of 900 × 201 × 161 points was used, periodic in z, and including damping layers at the top face, bottom face and outlet. Grid spacings were $\Delta x = 1.0$ mm, $\Delta z = 1.5$ mm (both constant), and $\Delta y = 1.0$ mm at the centreplane with a gradual increase above and below. Inlet boundary layers (4 mm thick) from the splitter plate were modelled with a velocity defect and superimposed random noise. Data from 16 spanwise positions were averaged at each streamwise station, the last station being $x = 800$ mm ($Re = 18,100$). The corresponding Taylor microscale Reynolds number was $R_\lambda = 275$. CPU time for 16,384 steps on the Fujitsu VPP300 at ANU was 26 hours.

Diffusion terms were modelled with second-order central differences, and second-order differences with dynamic derivative offset (DDO) were used for momentum advection terms (Bisset 1998b). Results for second-order scalar advection were highly unsatisfactory because of the Gibbs phenomenon at sharp interfaces, and therefore first-order upwind differences were used in spite of their well-known tendency to cause unwanted numerical diffusion, affecting small

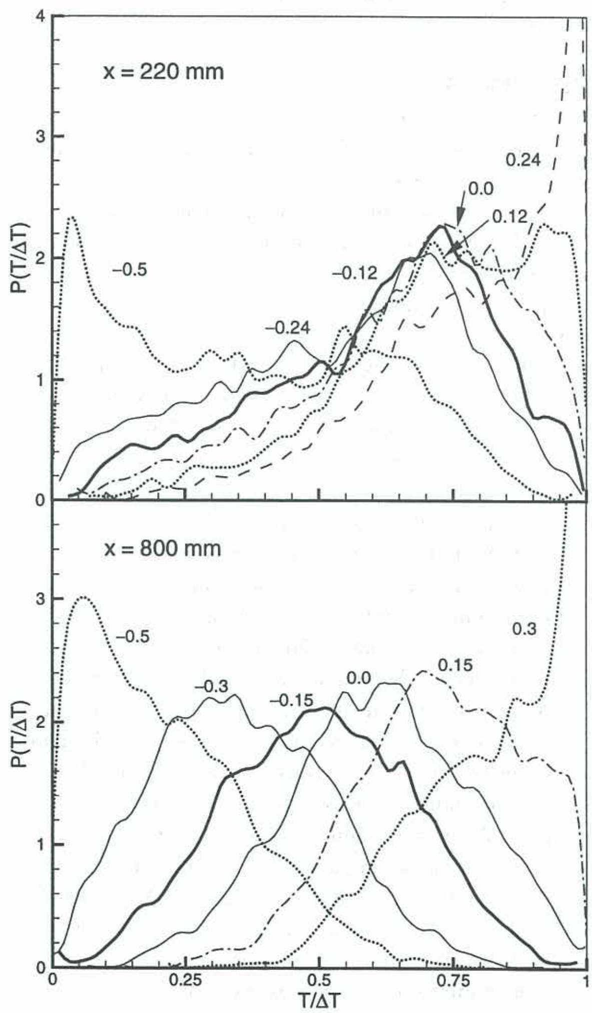

Figure 3: Probability densities for two streamwise stations showing non-marching (x = 220 mm) and marching (x = 800 mm) behaviours. Labels on curves indicate approximate y/δ_ω positions.

scale scalar fluctuations to an unknown extent.

RESULTS

Profiles of normalized mean temperature at seven streamwise stations are shown in Figure 1, along with a mean velocity profile. At every station including those in Figure 6, and for every experimental result, the data have been normalized by vorticity thickness and offset so that the mean velocity profiles pass through the point (0,0.5). The collapse of velocity profiles was good to excellent, but Figure 1 shows that mean temperature, unlike velocity, is not self-preserving. The experiment profiles are from Masutani & Bowman (1986), $r = 0.5$ and $Re = 2100$, and Fiedler (1974), $r = 0$ and $Re \approx 50,000$. The former is straddled by the present results at $Re = 1700$ and 2900, while the latter is close to the final profile from the simulation.

Fiedler (1974) remarks that the two additional inflection points in the mean temperature profiles correspond to bimodal temperature fluctuation profiles, as demonstrated in Figure 2. For the rms profile from Batt (1977), Re is about 125,000. Profiles of rms velocity fluctuations (not shown) are highly symmetrical in contrast to the profiles of Figure 2.

Strong scalar asymmetry in the early stages of mixing layer development is caused by the asymmetrical velocity profile following the splitter plate boundary layers: the initial rollup occurs mainly within the high speed stream (the warm side in this case). The early vortex-like structures seem to mix and redistribute the fluid in their cores very effectively, but that fluid is warmer than average. This situation is reflected by non-marching p.d.f.s in Figure 3, which peak around $T = 0.7\Delta T$. Further downstream, the development of very 3D structures at a large range of scales leads to the rapid mixing of newly entrained fluid, and therefore the average composition of a fluid region depends on its proximity to the warm or cool streams, as shown by marching p.d.f.s in Figure 3.

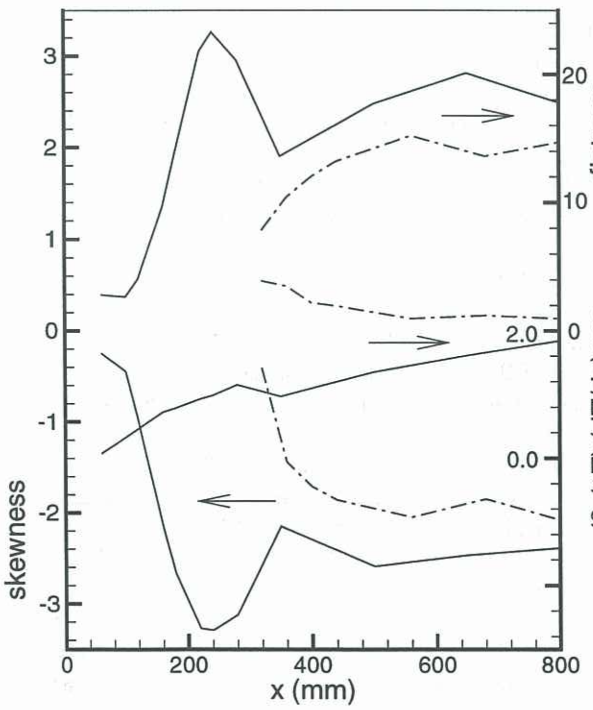

Figure 4: Skewness, flatness factor and normalized rms of the streamwise temperature derivative. (—) normal; (- - -) heated x = 300 mm.

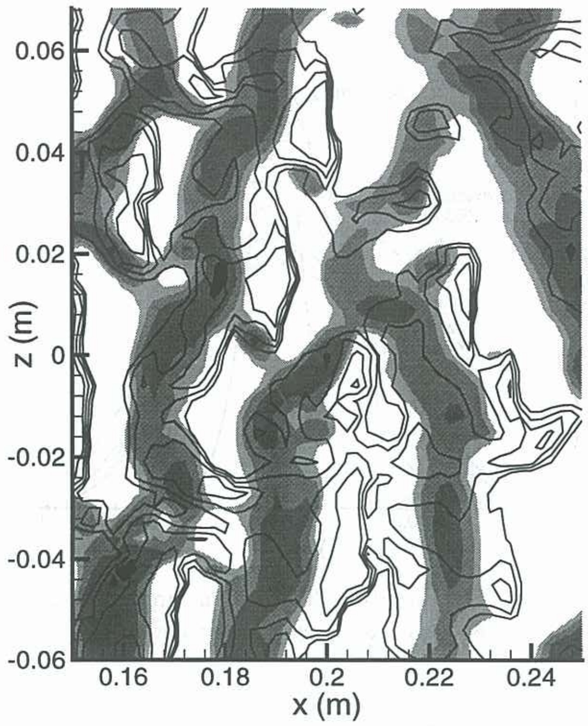

Figure 5: A small part of the spanwise centreplane; shading indicates low pressure regions, and contours outline warmer-than-average regions.

Efficient mixing can only occur if warm and cool fluid are moved into close proximity. Inspection of instantaneous temperature distributions shows one of the mechanisms through which this is achieved. Thin layers of high temperature gradient often form in the regions between adjacent vortex-like structures, usually oriented such that $\partial T/\partial x$ is negative. Statistics of $\partial T/\partial x$ along the centreplane (Figure 4) confirm the significance of such layers. It is interesting that both skewness and flatness build up quickly during initial rollup, but fall away somewhat before recovering in the later stages. The rms of $\partial T/\partial x$ fluctuations generally increases when normalized by the outer lengthscale δ_ω, showing that internal layers of high gradient are always significant.

Figure 5 is an example of the distribution of temperature relative to the low pressure cores of vortex-

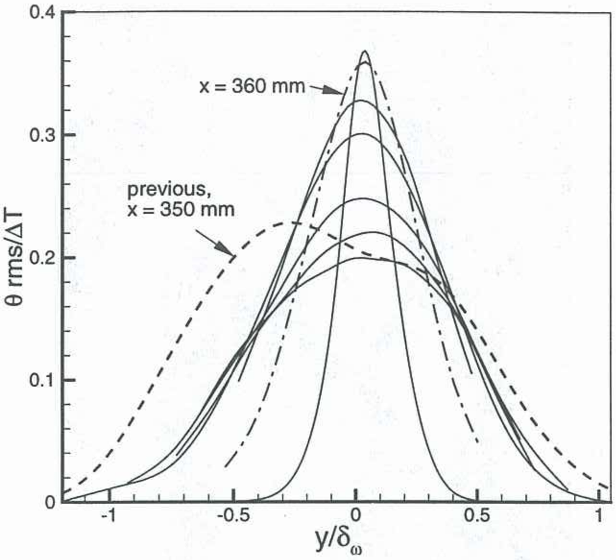

Figure 6: Temperature fluctuation rms values, $320 \le x \le 800$ mm, flow heated x = 300 mm

like structures. Rotation about the roughly spanwise axes of these structures tends to engulf fluid and carry it down into the mixing layer; thus regions of warmest fluid tend to be found on the downstream sides of the structures. The strongest gradients (close-packed contours) occur on the downstream edges of these regions, where warm fluid collides with cold fluid engulfed from the low speed side (blank areas in this figure). Further downstream (not shown) the picture looks more complex because of motions at a range of scales acting simultaneously, but the overall effect is the same.

Flow heated downstream from inlet

A further simulation was run with fluid heated only for $x = 300$ mm, $y > 0$. At this point the turbulence is fully 3D and on the way towards self-preservation (for velocities). Figure 6 shows how rms fluctuations spread rapidly and nearly symmetrically without the effects of the initial asymmetric rollup. Initially there are no internal layers of high gradient (except for the centreplane itself), but Figure 4 shows that turbulent motion quickly creates and maintains them. The actual levels of skewness and flatness are slightly lower than in the standard case, meaning that there is a long-lasting residual effect of the initial rollup. Comparing Figures 2 and 6, and considering the convergence of rms values of $\partial T/\partial x$ in Figure 4, it seems likely that the effects of initial conditions will eventually disappear further downstream.

CONCLUSION

Turbulent planar mixing layers with heat transfer have been successfully simulated with the AGE method for two types of initial conditions. For the usual inlet conditions, the simulation correctly reproduces physical behaviour including asymmetry in rms fluctuations and the development of marching and then non-marching probability distributions of temperature. With the flow heated some distance downstream from the inlet, the effects of the initial asymmetrical rollup are separated from those of the fully developed turbulent motions. It seems likely that the scalar composition of mixing layers in the early stages is quite sensitive to the nature of the initial rollup, which in turn could be influenced by the nature of the inlet splitter plate boundary layers.

ACKNOWLEDGMENT

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