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Scalar Entrainment in the Mixing Layer

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New definitions of entrainment and mixing based on the passive scalar field in the plane mixing layer are proposed. The definitions distinguish clearly between three fluid states – (a) unmixed fluid (b) fluid 'engulfed' in the mixing layer, trapped between two scalar contours, and (c) mixed fluid. The difference between (b) and (c) is the amount of fluid which has been engulfed during the pairing process, but has not yet mixed. Trends are identified from direct numerical simulations and extensions to high Reynolds number mixing layers are made in terms of the Broadwell-Breidenthal mixing model. In the limit of high Peclet number ($Pe = ReSc$) it is speculated that engulfed fluid rises in steps associated with pairings, introducing unmixed fluid into the large scale structures, where it is eventually mixed at the Kolmogorov scale. From this viewpoint pairing is a prerequisite for mixing in the turbulent plane mixing layer.

1. Introduction

Existing definitions of entrained fluid are not specific about the state of the fluid (whether mixed or unmixed) that is carried by large scale structures. Corcos & Sherman [1984] used the instantaneous streamlines in the moving reference frame to identify a cat's-eye structure boundary. Similarly Hernan & Jimenez [1982] in their digital analysis of movies of the mixing layer, used a best-fit ellipse to frame each structure, and measured the area within the ellipses to estimate entrainment. Neither definition distinguishes between entrained fluid that is mixed, entrained fluid that is doomed to be mixed, and appear to allow for the possibility of 'entrained' fluid subsequently leaving the ellipse.

In this paper we use insights from direct numerical simulations to provide ideas on how the large-scale structure dynamics affect scalar transport in the mixing layer. For this purpose a two-dimensional time-developing code was used to solve the compressible Navier-Stokes equations (Sandham [1988]). The simulations were made at low convective Mach number ($M_c = 0.4$) so that the results can be applied to the low-speed mixing layer. The simulations are of course limited by two-dimensionality and the low Reynolds and Schmidt numbers that can be handled numerically. However some basic trends emerge clearly in the simulations and by using the Broadwell-Breidenthal model of the post-mixing-transition layer we are able to make some qualitative statements about the influence of pairing on mixing in the high Reynolds number mixing layer.

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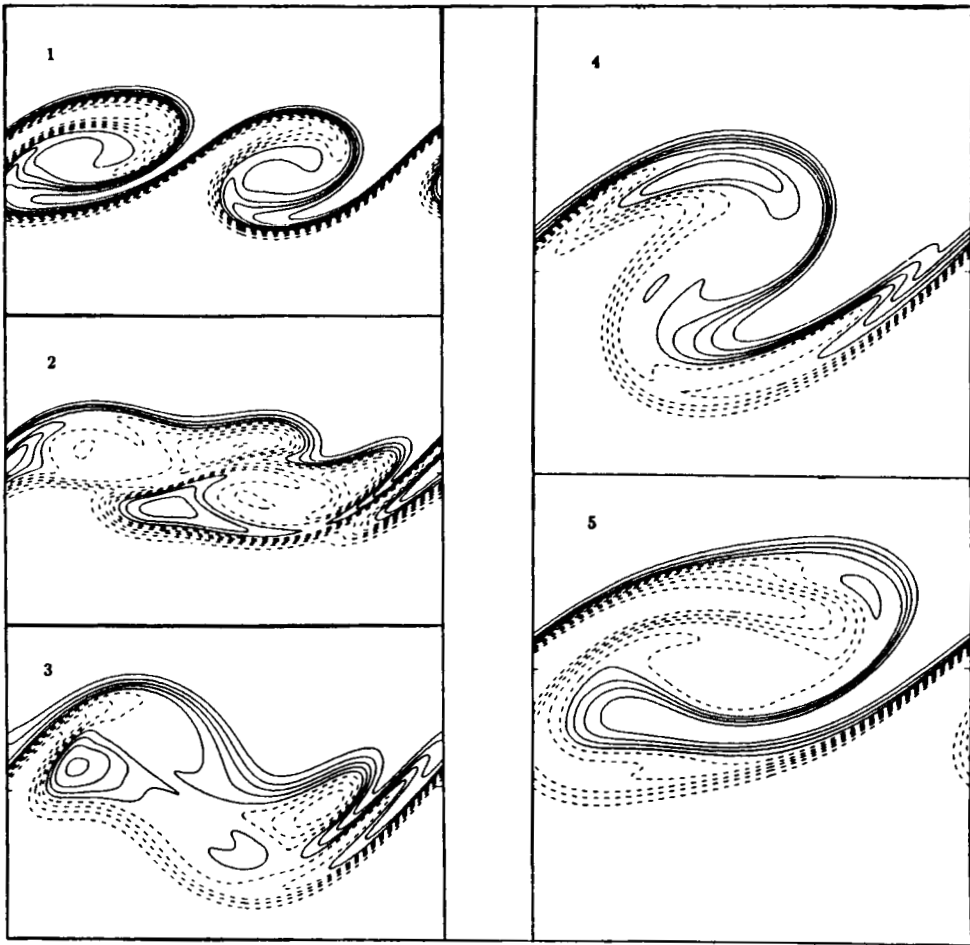
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FIGURE 1.   Time series of a pairing cycle.

2. Observations From Direct Simulations

From flow visualisations it is apparent that the pairing process is the dominant mechanism for local adjustment of the mixing layer eddy length scale to allow growth in the streamwise direction. To investigate this basic process we consider the simple case of the numerically-simulated time-developing mixing layer undergoing a pairing, shown in Figure 1. The mixing layer is viewed at approximately equal time steps in the cycle. At the first step shown it has already undergone one pairing and by the last (5th) time step the structure has filled its periodic box and is unable to grow or pair any further. The Reynolds number based on vorticity thickness was initially 200 and rose to 2000 by the end of the simulation. The Schmidt number was 1, and a 300 × 300 grid was used.

If the structure is assumed to maintain self-similarity from the first time step to the last, then the area must rise by a factor of 4. Two vortices have paired; so in the final structure half the fluid came from the original two structures and
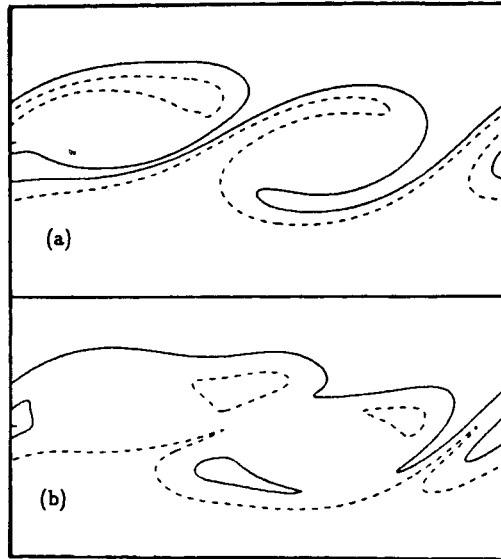
FIGURE 2. Scalar cut-and-connect process showing the 0.1 and 0.9 scalar contours (a) before (b) after.

the other half was introduced during the pairing cycle. Mixing by diffusion is one mechanism for the growth of the structure. A second mechanism can be identified from the scalar contour plots as a scalar cut-and-connect, which has the effect of trapping nearly-unmixed fluid within the structure. This is shown in more detail in Figure 2. Unmixed fluid is wrapped around the structure at time 1 (see Figure 1), with mixing only occurring by diffusion. Then, between times 1 and 2 this fluid is cut off from the outside and becomes trapped in the structure. Between times 3 and 5 mixing is occurring in two places – diffusion from the outside, and diffusion of the fluid inside the structure which was captured by the pairing.

   This observation suggested new definitions of fluid state based on the scalar contours. *Engulfed fluid* (E) is that fluid contained between the outermost scalar contours, for example fluid between the levels 0.1 and 0.9, where 0 and 1 represent the free-stream values. *Mixed fluid* (M) is that fluid throughout the mixing layer which is molecularly mixed between two levels (*e.g.* 0.1 and 0.9). The difference $E - M$ is the fluid that has been engulfed, but is yet to mix.

   The effect of Peclet number on the process was investigated by running 150×150 simulations at a Reynolds number of 200 and Schmidt numbers of 0.25 and 1.0. The results are shown in Figures 3(a) for $Sc = 0.25$ and 3(b) for $Sc = 1.0$. Engulfed fluid E was found by integrating around scalar contours, while mixed fluid M was calculated by scanning the computational domain for mixed fluid and adding area increments. The two measures are equal so long as all the fluid within the newly defined structure is mixed. It is seen from Figure 3(a) that at low Schmidt number molecular diffusion is very strong, and fluid is essentially diffusion-mixed before it is engulfed. The plots are shown for various scalar cutoff levels $0.1 - 0.9$ (containing
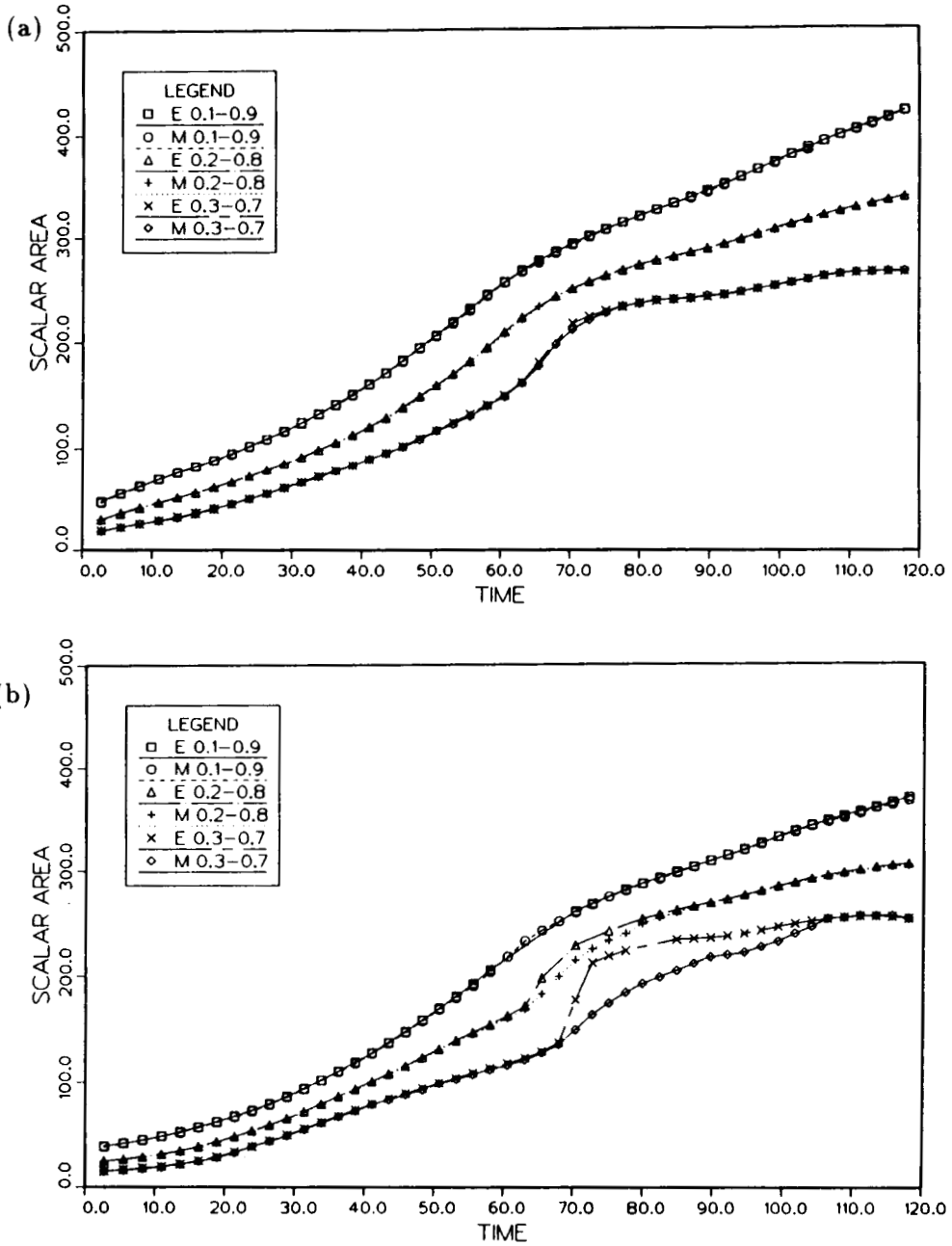
FIGURE 3. Growth of engulfed and mixed fluid at $Sc =$ (a) 0.25 and (b) 1.0.

80% of the mixed fluid), $0.2 - 0.8$ (60%), and $0.3 - 0.7$ (40%). The effect of lowering the limits on the cutoff is to exclude some of the diffusion effects and give some indication of how a higher Schmidt number flow would behave. At $Sc = 1.0$ (Figure 3(b)) and taking the 40% and 60% limits there is a clear trend emerging. The E

curve shows a sharp jump at the moment of the scalar cut-and-connect, trapping fluid within the structure, which later mixes. By extrapolating these results we speculate that in the limit of infinite Pe, for simulations with Re fixed below the mixing transition, the function E would be a step function, while the function M would remain essentially zero since the computations have no three-dimensional small scales to increase the interfacial area for mixing.

In the following section we use the Broadwell-Breidenthal picture of the mixing layer past the mixing-transition to include the small scales of the vortex core in our model pairing event, and to make some predictions about the influence of pairing on the mixing process.

3. Extension of Ideas to High Reynolds Numbers

A simplified model of mixing in the plane mixing layer was proposed by Broadwell & Breidenthal [1982] and has been extended to include chemical reactions of arbitrary rate by Broadwell & Mungal [1988]. In the model, fluid is viewed as mixing (1) in laminar strained-flame regions between the two free-stream fluids, and (2) inside the structure at the Kolmogorov scale. In the former process the amount of product that is formed has Reynolds and Schmidt number dependence, while in the latter process it does not. The model correctly predicts many features of the mixing layer experiments, including the differences between liquid and gas experiments and the variation of product formation with equivalence ratio, that cannot be explained with conventional gradient-diffusion models.

In the limit of high Peclet number, such as occurs in liquid mixing layers and in gases at very high Reynolds numbers, mixing in the laminar strained flame regions is reduced to zero and we need only consider mixing at the Kolmogorov scale. The ideas from the previous section show that the pairing is responsible for introducing unmixed fluid into the structures in a discrete manner. Immediately after the scalar cut-and-connect process the structure contains one-half old fluid and one-half new, unmixed fluid. The vorticity field at this stage consists of the two pairing vortices, plus their associated streamwise vortices and small scales. It is assumed that a cascade in scales occurrs and that mixing finally occurs at the Kolmogorov scale when the interfacial area of fluid has increased dramatically. Schematically the proposed process is given in Figure 4. From the Broadwell-Breidenthal model the time scale for mixing to occur after engulfment would be given by $T_M - T_E \sim L/\Delta U$, where L is a characteristic length scale at the start of the cascade.

Some experimental results of Roberts and Roshko [1985] can be interpreted in the light of the above ideas. Roberts performed chemical reactions in a liquid mixing layer ($Pe \to \infty$) at high Reynolds number and found that, when the layer was forced, new product formation dropped to zero. We can now postulate that the effect of forcing is to lock the mixing layer, stopping pairing and hence preventing new fluid being engulfed, which in turn prevents any new product being formed.

In reaching the above conclusions for $Pe \to \infty$ it has been assumed that the increase in interfacial area due to the presence of streamwise vortices in the flow is not sufficient to outweigh the reduction in diffusion coefficient. At lower Peclet
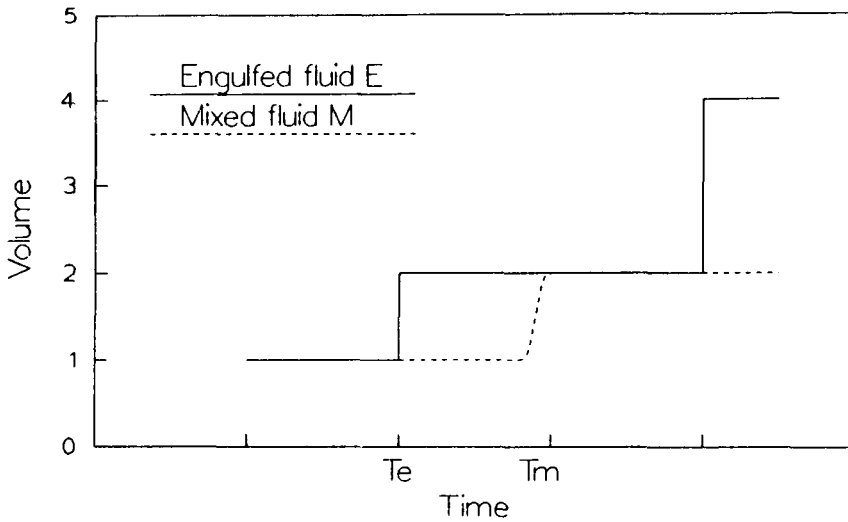
FIGURE 4. Prediction of growth in engulfed and mixed fluid for $Pe \to \infty$.

numbers, for example in the gaseous mixing layer, these streamwise vortices will be important, and have been invoked by Mungal & Dimotakis [1985] to explain some features of 'ramping' in the temperature time traces of a reacting mixing layer. Finite Peclet numbers will have the effect of reducing the jump in engulfed fluid and giving the E and M curves a positive slope between pairings, due to mixing in the strained laminar diffusion layers. At the Reynolds number used by Mungal & Dimotakis (6.8×10^4 based on visual thickness) it was estimated that about half the mixing occurred in these diffusion layers, and we would expect the jump in E to be reduced by approximately a factor of two.

The method used by Hernan & Jimenez [1982] to estimate entrainment in a gaseous mixing layer at high Reynolds number (but finite Pe) involved framing each structure with a best-fit ellipse. Figure 5 shows how this might work for the structure at time 5 in the pairing cycle. For times 2 and 3 (see Figure 1) it was more difficult to fit any meaningful ellipse to the structures. This method evidently includes unmixed fluid that is not contained in our engulfed fluid definition, and may exclude some mixed fluid. The amount of extra fluid included is a function of the particular structure orientation, so that the area of the ellipse may change even if no mixing is taking place. The conclusion of Hernan & Jimenez that entrainment mostly occurs between pairings should therefore be viewed with caution, since it may be influenced by the method that they used to measure entrainment. Also, we should not interpret their measurements of entrainment as giving any information about mixing. The model proposed here for finite Pe is that mixed fluid rises steadily in between discrete jumps which are associated with the mixing of fluid that was engulfed during pairing and has reached the Kolmogorov scale. The size of each jump is speculated to be Reynolds number dependent, reducing as Reynolds number is reduced.
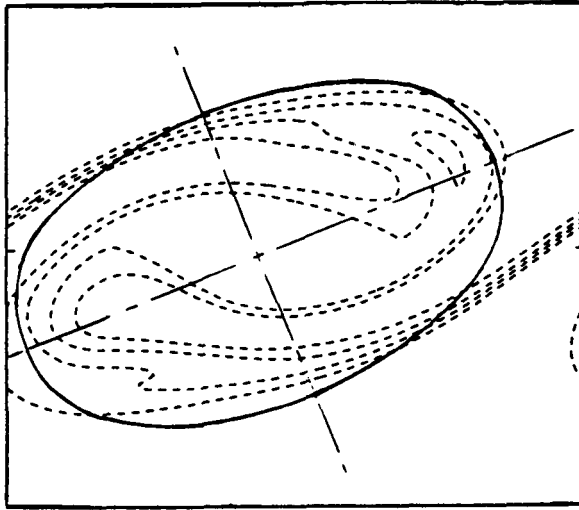
FIGURE 5. Result of fitting an ellipse to a structure.

4. Conclusions

Definitions of entrainment and mixing based on the scalar field of a numerically simulated plane mixing layer have been used to study the fundamental effects of pairing on the mixing process. It was found that pairing is responsible for the process of 'engulfment', bringing unmixed fluid into the structure, while actual mixing lagged behind. Use of the Broadwell-Breidenthal mixing model allowed the results from two-dimensional simulations to be extended to the high Reynolds number mixing layer, leading to a model picture of pairing for $Pe \rightarrow \infty$ as a step function doubling in fluid contained in a structure, followed by molecular mixing after a time lag for the cascade in scales to reach the Kolmogorov scale. It is concluded that for $Pe \rightarrow \infty$ pairing is necessary for mixing, helping to explain some experimental findings of Roberts & Roshko [1985].

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