Chemically Reacting, Turbulent Shear Layer

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Introduction

A CHEMICALLY reacting, turbulent shear layer between two streams was investigated in a new, blowdown water tunnel. The two streams contained dilute, aqueous solutions of diffusion-limited reactants (phenolphthalein and sodium hydroxide, respectively) which mixed in the layer and reacted to form a visible reaction product. Using optical densitometry techniques, the amount of product was measured as a function of Reynolds number. These results for water (Schmidt No. $\doteq 600$) are compared with the previous mixing measurements of Konrad[1] in a gaseous shear layer ($Sc \doteq 0.7$) and the simple mixing model of Broadwell.[2] The unique flow visualization provided by the visible reaction product revealed a remarkable spanwise instability (superimposed on the large coherent vortices) which appears to be important in introducing three-dimensional motions into the flow.

Flow Geometry and Visualization

A side view of the flow geometry is sketched in Fig. 1. A turbulent shear layer is formed when two parallel flowing streams with different speeds begin to mix downstream of the trailing edge of a splitter plate partition. If the streams contain the appropriate reactants, then when the reactants mix at the intimate, molecular level within the layer, a visible reaction product is formed. Simultaneous plan and side views of the reacting flow are shown in Fig. 2. The flow is from left to right and, in the lower image (side view), the visible reaction product is seen to be concentrated in coherent, large scale vortical structures. These "large structures"[1,3] are fundamentally two-dimensional, as can be seen in the upper image (plan view). Near the test section side walls, the flow is perturbed and the mixing is locally enhanced. Because the side view integrates along the span and looks through the contaminated wall region, the basic two-dimensionality of the large scale vortices is more apparent in the plan view, away from the walls.

The most interesting feature of the photograph is the spanwise-sinuous wiggle seen in the plan view. Upstream of the wiggle the flow is nearly two-dimensional, while downstream, small scale, three-dimensional motions and streamwise streaks exist. Similar streaks had been previously observed in the shear layer,[1,3] but their origin remained obscure. It is believed that the wiggle is a manifestation of an initial three-dimensional instability and plays an important role in the introduction of small scale motions into the flow. As will be shown, the aqueous mixing is strongly enhanced by the presence of these small scale motions.

Results and Discussion

The amount of visible reaction product was measured by passing a narrow beam of light through the layer (see Fig. 1). From the attenuation of the beam by the reaction product, the total amount of product along the light path was calculated. The equivalent product thickness P is defined as

$$P(x,z,t) \equiv \int_{-\infty}^{\infty} \frac{[C]}{[B]_\infty} (x,y,z,t)\,\mathrm{d}y$$

where $[C]$ is the product concentration, $[B]_\infty$ is the freestream concentration of reactant B (phenolphthalein), and y is the orthogonal coordinate. The light beam passed through the flow normal to the plane of the shear layer (y direction), well away from the contaminated region near the walls.

The equivalent product thickness is normalized by the vorticity thickness

$$\delta \equiv \frac{\Delta U}{(\partial \bar{U}/\partial y)_{\max}}$$

where ΔU is the speed difference between the two streams. Crudely speaking, the ratio P/δ represents the fraction of the layer filled with reaction product. To the extent that a second-order reaction is very fast (diffusion-limited) and irreversible, the amount of reaction product is just equal to the amount of molecular scale mixing at that equivalence ratio.

The reaction product measurements are shown in Fig. 3. The time-averaged mean value of P/δ is plotted as a function of the large scale Reynolds number

$$Re \equiv \Delta U \delta / \nu$$

for a velocity ratio of 0.38. The equivalence ratio is about 10^2, with an excess of sodium hydroxide. The lower points in the figure are the present aqueous measurements ($Sc \equiv \nu/D \doteq 600$), and the upper curve is inferred from gaseous mixing measurements ($Sc \doteq 0.7$) of Konrad,[1] in which an inert sampling technique was employed. D is a molecular diffusion coefficient and ν is the vorticity diffusion coefficient, the kinematic viscosity. In both fluids a transition was observed at $Re \doteq 6000$. Across the transition the aqueous mixing increased by an order of magnitude, while the gaseous mixing increased by about 25%. Above the transition P/δ was independent of Re.

For Re below the transition, P/δ was a strong function of Sc, while above the transition, P/δ was only weakly dependent on Sc. At large Re the two curves differ by about a factor of two, even though Sc varied by three orders of magnitude. Due to the finite size of the sampling probe, the inert sampling technique (upper curve) always yields an upper bound on the molecular scale mixing. The chemical reaction used here is reversible, so that the chemical product measurements (lower curve) are a lower bound on the mixing. Thus the upper and lower curves are upper and lower bounds, respectively, on the mixing. The actual dependence of mixing on Sc at high Re may be even less than indicated by the measurements.

For a velocity ratio of 0.38, the wiggle in this flow appeared at $Re \doteq 2000$. The strongly increased mixing, just downstream of the wiggle at the transition, is due to the sudden presence of the small scale motions in the shear layer. It should be mentioned that the entrainment and growth rates of the layer are largely unaffected by the onset of the small scale motions.[1]

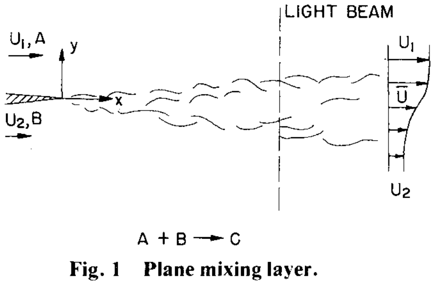

Fig. 1 Plane mixing layer.

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Index categories: Reactive Flows; Combustion and Combustor Designs; Jets, Wakes, and Viscid-Inviscid Flow Interactions.

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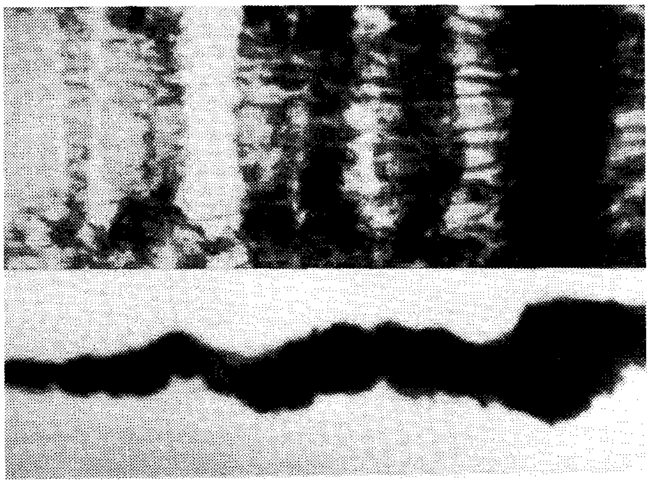

Fig. 2. Flow visualization of a reacting shear layer: simultaneous plan view (top) and side view (bottom).

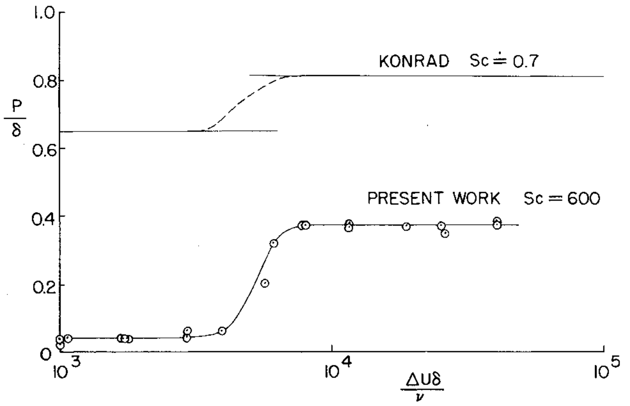

Fig. 3. Comparison of mixing in gaseous ($Sc \doteq 0.7$) and aqueous ($Sc \doteq 600$) shear layers.

The simple mixing model proposed by Broadwell[2] visualizes the mixing process as a sequence of events. The first step is the entrainment of pure, irrotational fluid into the layer. The entrained lump of fluid is subsequently broken down into smaller and smaller scales until finally the smallest scale, the Kolmogorov microscale, is reached. If diffusion is slow enough, then diffusion across the microscale will be the bottleneck in the sequence of events that culminate in molecular scale mixing. The mixing is then small scale diffusion limited.

Entrainment is visualized as the large scale engulfment of irrotational fluid by the large vortical structures.[3] These structures are assumed to behave in an inviscid manner, independent of Reynolds number; thus entrainment is also independent of Reynolds number. In the case of rapid diffusion, the model predicts that mixing occurs very soon after entrainment. The mixing is entrainment limited and thus independent of Reynolds number.

The time to diffuse across the microscale λ_0 is $\tau_{\lambda 0} \sim \lambda_0^2/D$; entrainment time is taken to be $\tau_\delta \sim \delta/\Delta U$; and the ratio of these two time scales is $T \sim Sc/Re^{1/2}$.

This model predicts that when the time parameter $T \gg 1$, the mixing is limited by small scale diffusion, whereas for $T \ll 1$ large scale entrainment is the slow process. At some intermediate value of T, a transition region must exist.

Conclusion

The present results are qualitatively consistent with Broadwell's simple model. For large $Re (T \ll 1)$, the mixing is entrainment limited and independent of Re, while for $T \gg 1$, the mixing is limited by small scale diffusion and is thus extremely sensitive to the presence of small scales. A spanwise-sinuous wiggle is believed to be important in the introduction of the small scales. Mixing is at most only a weak function of Schmidt number at high Reynolds number. A more complete report of this and other, ongoing work is planned for the near future.

Acknowledgment

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Simple Recompression Model for the Korst Base Pressure Theory

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Nomenclature

ℓ = coordinate along inviscid boundary
n = inverse of power law exponent
p = pressure
Re_θ = momentum thickness Reynolds number
u = velocity
Y = transverse coordinate in system following inviscid boundary
y = transverse coordinate in transformed system
y_m = increment of coordinate shift
β = angle of inviscid boundary with slip line (wall)
γ = isentropic exponent
δ = initial boundary-layer thickness
ζ = Y/δ
η = $\sigma y/\ell$ (similarity variable)
η_p = $\sigma\delta/\ell$ (position parameter)
θ = boundary-layer momentum thickness
ρ = density
σ = similarity parameter
ϕ = velocity ratio u/u_U

Subscripts

b = base region
D = dividing streamline
i = beginning of mixing
L = inner edge of mixing zone
m = inviscid boundary
r = region downstream of shock
S = stagnating streamline

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