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MIXING, CHEMICAL REACTIONS, AND COMBUSTION IN HIGH-SPEED TURBULENT FLOWS

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Summary/Overview

This research focuses on fundamental investigations of mixing, chemical-reaction, and combustion, in turbulent, subsonic, and supersonic flows. It is comprised of an experimental effort; an analytical, modeling, and computational effort; and a diagnostics- and instrumentation-development effort. Computational studies are focusing on fundamental issues pertaining to hydrocarbon ignition and combustion as well as investigations of the Rayleigh-Taylor instability.

Technical discussion

Transport and mixing in turbulent jets in a crossflow is important for fuel injection in SCRAMJETS (Mathur *et al.* 1999), blade and endwall cooling in gas-turbine engines, and other applications. Experiments measured the jet-fluid-concentration fields in turbulent transverse jets, using laser-induced fluorescence and digital-imaging techniques. One finding is that the resulting scalar field can be anisotropic, even at small length scales. Ensemble-averaged, two-dimensional, scalar power spectra are computed for liquid-phase transverse jets at $x/d_\mathrm{j} = 50$, where x is the downstream distance and d_j is the jet diameter, in a plane transverse to the flow direction (Fig. 1, left). Contours indicate increasing anisotropy at higher wavenumbers, *i.e.*, at smaller scales. Anisotropy also registers in the microscales of scalar fluctuations. Analogously to the Taylor microscale, a scalar microscale, $\lambda_{C,i}$, for a given direction, is introduced as, $\lambda_{C,i} = \langle C'^2 \rangle / \langle (\partial C'/\partial x_i)^2 \rangle$. Scalar microscales for $1.0\times10^3 \leq Re_\mathrm{j} \leq 20\times10^3$ are shown in Fig. 1, right. The scalar microscale in the vertical, y, direction is consistently larger than the horizontal, z, microscale. The observed scalar-field anisotropy is a consequence of extensional strain along the vertical direction, caused by the dominant, kidney-shaped vortex pair in the transverse jet. Anisotropic, large-scale flow dynamics can impose themselves on even the smallest features of the scalar field.

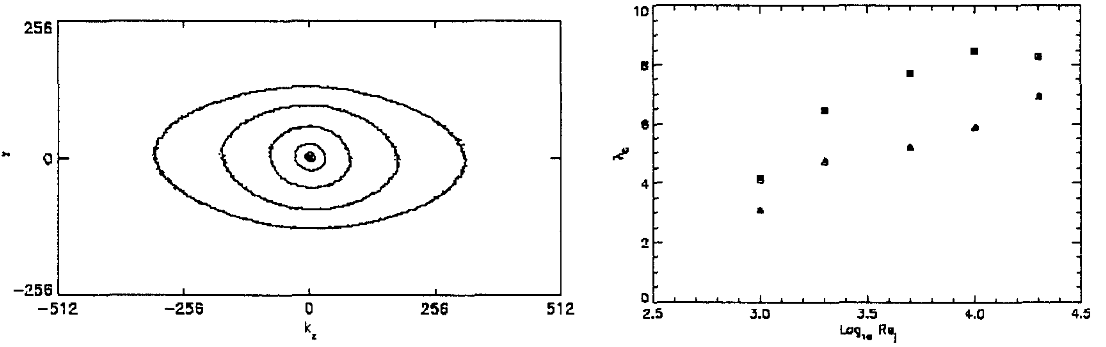

Fig. 1 Transverse-jet scalar field measures at $x/d_\mathrm{j} = 50$. Left: Ensemble-averaged, 2-D power spectrum for $Re_\mathrm{j} = 1.0\times10^3$. Right: Scalar microscale as a function of jet Reynolds number (squares: vertical, y, microscales; triangles: horizontal, z, microscales).

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Figure 2 depicts a space-time image of an isosurface of the jet-fluid concentration, illustrating the "kidney" vortex pair as well as a strong, secondary vortex, which was not evident in 2-D slices. The data are for a jet Reynolds number of 1000 and a jet-to-freestream velocity ratio of 10.1. A first documentation of this work will be available as a Ph.D. thesis (Shan 2001). Work in this area presently in progress is focused on quantifying the anisotropy as well as aspects of the three-dimensional behavior of the mixing and scalar field.

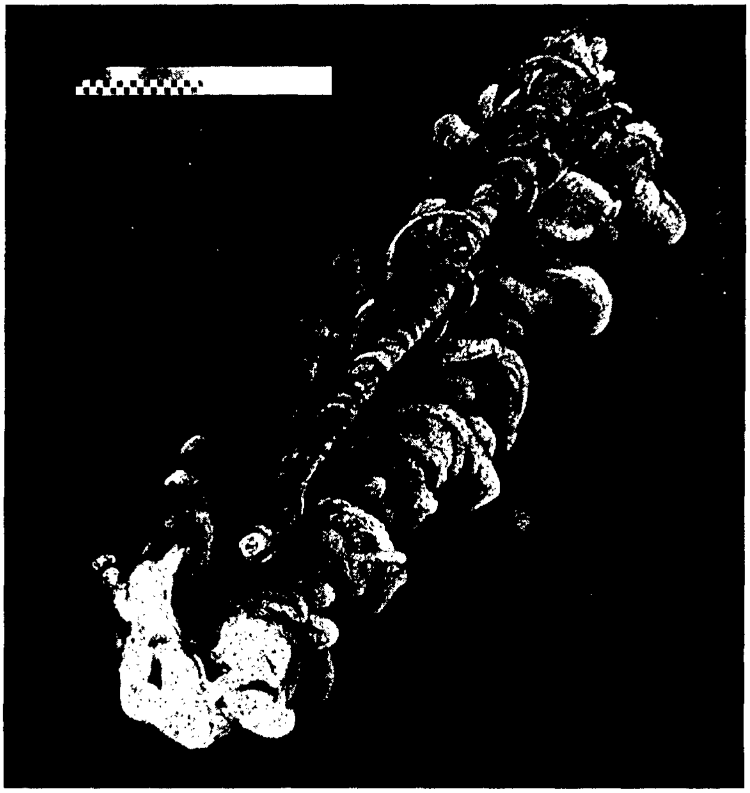

Fig. 2 Three-dimensional visualization of an isosurface in a transverse jet (Shan 2001, $Re_j = 10^3$, $U_j/U_\infty = 10.1$). Visualization by S. Lombeyda (Caltech, CACR).

Experiments were performed to explore the aerodynamic control of internal flows, as occur, for example, in subsonic diffusers and scramjet combustors. To date, the work has focused on subsonic diffusers, as a first step, and on the behavior of flow over a backward-facing perforated ramp, with variable mass injection, velocity ratio, and Reynolds number. Diagnostics included upper-guidewall pressure measurements, total-pressure measurements at the test-section exit, and schlieren images recorded on a 1024^2-pixel, 30fps CCD camera. A performance parameter in such flows is the pressure coefficient, $C_p = 2(p_2 - p_1)/\rho U^2$. Figure 3 plots C_p versus the freestream-to-injection velocity ratio, for the two freestream velocities indicated. Point 1 is on the top guidewall, above the ramp start. Point 2, also on the top guidewall, is at the downstream location of the total-pressure-probe array. The pressure coefficient is higher at smaller velocity ratios and at higher freestream velocities, indicating Reynolds number effects. As the velocity ratio is increased, the pressure coefficients converge and decrease, as flow in both cases approaches a conventional shear layer with a small streamwise pressure gradient. Work in progress is focusing on measurements of mixing between the freestream and injected fluid, using the $(H_2+NO)/F_2$ chemical reaction, to assess the behavior of turbulent shear layers in the vicinity of solid boundaries as well as explore the additional benefits of dilatation in diffuser operation. This work is part of the graduate research of W.-J. Su and M. Johnson.

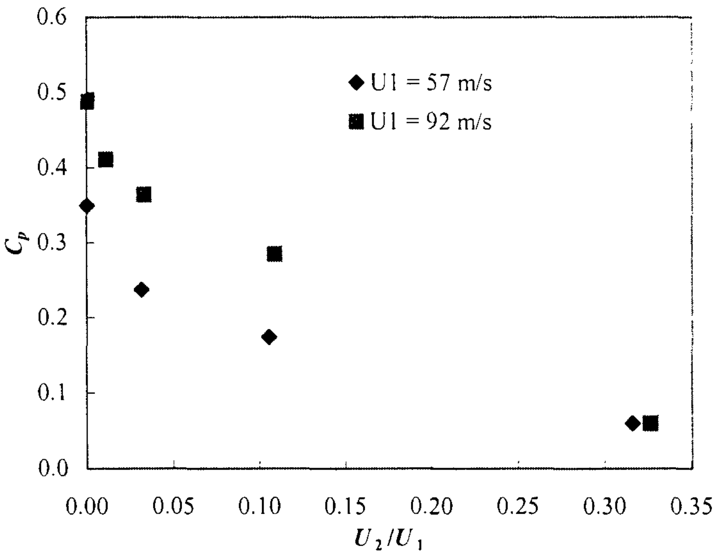

Fig. 3 Internal-flow pressure coefficient (see text) as a function of mass-injection (U_2) to freestream (U_1) speed ratio.

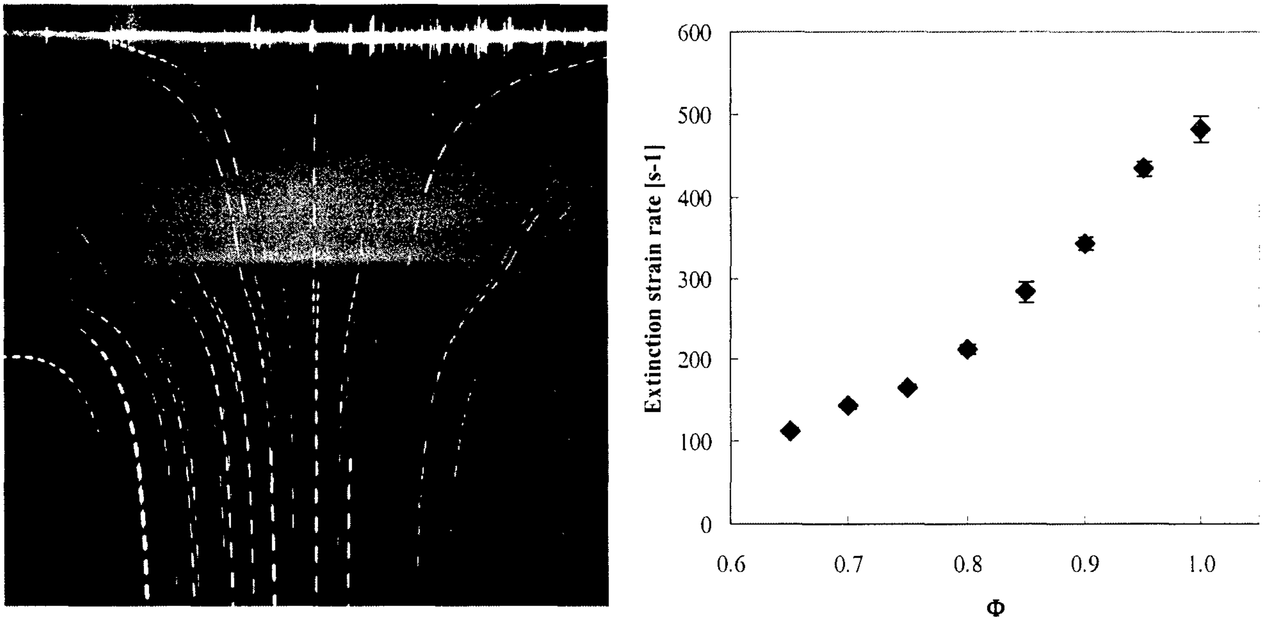

Fig. 4 Left: CH4-air flame (Φ = 0.8, Re_d = 500, chemiluminescence and PSV). σ_{max} = 112 s^{-1}. Right: Extinction strain rates, σ_{ext}, against a room-temperature plate, vs. equivalence ratio, Φ.

A new experimental method was developed for the study of premixed hydrocarbon-air flames in a stagnation-flow configuration. Experiments were conducted at p = 1atm focusing on methane-air and ethylene-air flames and investigated a range of fuel concentrations (equivalence ratio, Φ) and ratios of stagnation-plate separation distance to nozzle diameter (L/d_j). Methane-air flame properties measured include laminar flame speeds, flame speeds for strained flames vs. imposed strain rate, and extinction strain rates. The experiments relied on digital imaging of flame chemiluminescence, particle-streak velocimetry (PSV), laser-Doppler velocimetry (LDV), and jet-exit velocity measurements using a Bernoulli pressure-drop method. Figure 4 (left) displays the flow-field for a methane-air flame (Φ = 0.8, $Re_d \cong$ 500). The results are in good agreement with previous experimental data. New extinction strain-rate data for CH_4-air flames against a room-temperature stagnation plate were acquired and compared against numerical simulations for four different chemical-kinetic schemes. Figure 4 (right) displays a preliminary set of measured extinction strain rates for lean methane-flames. In attempting to simulate the extinction strain-rate values, we noted that the conventional one-dimensional formulation for the streamfunction used in the flame codes does not capture cold-flow velocity profiles along the stagnation streamline and, as a consequence, the measured strain-rate field at the L/d_j values was relied upon. A careful reexamination of the boundary conditions at the cold plate, vis-à-vis reacting species, is also underway. A first report of this work was recently presented (Vagelopoulos and Dimotakis 2001).

Direct Numerical Simulation (DNS) studies of the Rayleigh-Taylor instability have continued, with a first documentation of this work accepted for publication (Cook & Dimotakis 2001). Work in progress is focusing on post-processing existing three-dimensional data. A new set of DNS runs will study density-ratio effects and mixing in accelerating flows, and increase Reynolds numbers to values closer to the mixing transition (Dimotakis 2000). This is a collaborative effort with A. Cook (LLNL), and T. Mattner and D. Meiron of Caltech, and is cosponsored by the Caltech ASCI/ASAP program.

Preparatory work for experimental investigations of the behavior of spheres and drops in the transitional Reynolds number regimes pertaining to droplet combustion is continuing. In this regime, disturbances grow, spatial and temporal symmetries can be broken, and topological structure varies. Our objective, in part, is to document and understand these phenomena. To this end, a new, dedicated, liquid-phase drop tank facility was designed that will permit multi-dimensional, fully resolved (spatially and temporally) data to be recorded. The new facility is under construction. To allow the flow to be imaged in the frame of the sphere/drop, a drive mechanism, consisting of a computer-controlled platform will move the digital-imaging system along with the transmitting/receiving optics in the frame of the moving sphere or droplet. In the case of sphere flows, the sphere-controlling mechanism is coupled to the transmitting/receiving optics mechanism. This work is part of the graduate research of S. Malhotra.

References

Cook, A. W., and Dimotakis, P. E. 2001 "Transition stages of Rayleigh-Taylor instability between miscible fluids," *J. Fluid Mech.* (to appear).

Dimotakis, P. E. 2000 "The mixing transition in turbulence," *J. Fluid Mech.* **409**, 69-98.

Mathur, T., Billig, F., Streby, G., Gruber, M., Jackson, K., Donbar, J., Donaldson, W., Jackson, T., and Smith, C. 1999 "Supersonic combustion experiments with a cavity-based fuel injector," 35th *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit* (20-24 June 1999, Los Angeles, CA).

Shan, J. W. 2001 *Mixing and Isosurface Geometry in Turbulent Tranverse Jets*, Ph.D. thesis, California Institute of Technology.

Vagelopoulos, C. M., and Dimotakis, P. E. 2001 "Rapid recording of flame propagation and extinction behavior in methane-air mixtures," 2nd U.S. Joint Meeting (Combustion Institute, 25-28 March 2001, Oakland, CA), Paper 136.