Measurements of Molecular Mixing in an Expansion-Ramp Combustor

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1 Introduction

In high-speed combustion systems, the rate at which fuel and air are mixed on a molecular scale dominates the overall combustion rates [1, 2]. Advances in air-breathing propulsion devices rely on efficient mixing of fuel and air streams, while minimizing total pressure losses. If hydrocarbon fuels are to be utilized, low strain-rate regions must be maintained in the mixing and combustion regions of the flow for flameholding.

This investigation studies the expansion-ramp injection geometry in subsonic-transonic flow for mixing and flow control for air-breathing propulsion systems (see Fig. 1). This geometry maintains the lowpressure-loss benefit of traditional shear layers, while providing a low strain-rate region for flameholding. The expansion-ramp geometry has potential for mixing both subsonic and supersonic air streams with fuel, making it a promising combustor component for dual-mode ramjet/scramjet propulsion systems.

In the expansion-ramp combustor, the high-speed air stream is expanded over a ramp inclined at 30 degrees to the flow, causing separation. The fuel stream is injected through perforations in the expansion ramp and a shear layer is formed between the high-speed air and low-speed fuel streams. For low levels of injection, the shear layer attaches to the lower guidewall and creates a recirculation zone that transports hot products and radicals from the end of the mixing region toward the initial portion of the shear layer.

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Figure 1: Composite schlieren image of non-reacting transonic flow with expansion-ramp injection. Upper stream: Mach number $M_1 \approx 1.02$ (pure N₂), lower stream: $U_2 \approx 33$ m/s (pure N₂).

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By adjusting the injection rate, relative to the shear-layer entrainment requirements, the recirculating flow can be controlled. The recirculation region is characterized by low strain rates, as in cavity-based flameholders, but does not suffer the total-pressure losses or drag of a cavity with an aft wall.

The fraction of molecularly mixed fluid in the flow is estimated using the "flip" experimental technique [3]. Molecular-mixing measurements using this technique are not affected by spatial resolution limitations and exploit the fact that chemical product formation is limited by mixing, rather than kinetic, rates.

2 Expansion-Ramp Combustor Experiments

The experiments described here were performed in the Supersonic Shear Layer Laboratory at Caltech. This facility is a two-stream blow-down wind tunnel capable of delivering flows up to $M_1 \approx 3.2$ in the upper stream, and $M_2 \approx 1.3$ in the lower stream, with a nominal run time of 2–6 seconds. The facility is designed to employ fast-kinetic reactants. The top stream can be seeded with hydrogen (H₂) and nitric oxide (NO), and the bottom stream with fluorine (F₂). Gas mixtures for both streams are created using the partial pressure technique, with inert diluents chosen to match the gas properties of the two streams. The H₂-F₂ reaction is hypergolic at room temperature with NO added to the top-stream flow.

A servo-motor actuated sonic valve maintains a constant pressure in the top-stream plenum during the run. The flow to the bottom stream is delivered from a teflon bag to minimize the amount of fluorine required. During the run, the outside of the teflon bag is pressurized with nitrogen from a large (12.7 m^3) surge tank, creating a constant lower-stream supply pressure, and the flow is metered with a calibrated sonic valve. Both streams are introduced into the test section of height h = 9.78 cm after being accelerated through nozzle contractions designed to minimize turbulence generation. The bottom stream is injected through a perforated expansion ramp (3611 1.57 mm diameter holes, open-area fraction 0.60) angled at $\alpha = 30^{\circ}$ to the horizontal. A composite schlieren image of a non-reacting experiment is given in Fig. 1. More details on the experiment can be found in Ref. [4].

Chemical product formation is limited by mixing, rather than chemical-kinetic, rates when the Damköhler number, $Da = \tau_{\rm m}/\tau_{\chi}$, exceeds a critical value [3]. In this expression, $\tau_{\rm m}$ is the characteristic fluid-dynamic mixing time and τ_{χ} is the characteristic chemical-reaction time.

The mixing time scale, $\tau_{\rm m}$, is taken to be the Lagrangian time of flight of a fluid parcel within the shear layer, $\tau_{\rm m} = L/U_{\rm c}$, where $L \approx 36 \,{\rm cm}$ is the distance from the start of the expansion ramp to the temperature and pressure probes. The large-scale structure convective velocity, $U_{\rm c}$, is given by $U_{\rm c}/U_1 = (1 + rs^{1/2})/(1 + s^{1/2})$, where $r \equiv U_2/U_1$ and $s \equiv \rho_2/\rho_1$ are the freestream velocity and density ratios, and 1 and 2 refer to the top and bottom streams, respectively [3].

The chemical time scale, τ_{χ} , is estimated using the "balloon-reactor" model [5]. In this model, the chemical and thermodynamic state of a fluid parcel initially mixed at the entrainment ratio of the flow is solved as a function of time (or distance: $x = U_c t$) at constant pressure. This model includes entrainment fluxes at the expected entrainment ratio from the top and bottom streams to achieve the appropriate growth rate, or volume change, of the shear layer in time. The progress of the balloon reactor is calculated using the CANTERA software package and a H₂/NO/F₂ kinetic model. τ_{χ} is defined to be the time at which the maximum slope of the temperature profile intercepts its equilibrium value.

Using the convective velocity to estimate the mixing time and the balloon reactor to estimate the chemical time allows the estimation of Da. Previous investigations in the same facility indicate that for Da > 1.5, all fluid that is molecularly mixed will effectively react to completion. The experiments presented here are characterized by Da > 1.5, and have also been experimentally confirmed to be in the mixing-limited regime by repeating an experiment with intentionally reduced kinetic rates.

3 Measurements of Molecular Mixing

Very few experimental techniques are available to measure molecular-scale mixing. The flip technique allows the fraction of molecularly-mixed fluid to be estimated without spatial-resolution limitations [3].

The stoichiometric mixture ratio, $\phi = [F_2]/([H_2] + [NO]/2)$, is flipped between two experiments by controlling which stream is rich in reactants. For a fast-chemistry system, the probability of mixed fluid at each location is then

$$P_{\rm m}(y) = \left[1 - \xi(\phi_1)\right] \left[\left. \frac{\Delta T(y)}{\Delta T_{\rm f}} \right|_{\phi=\phi_1} + \left. \frac{\Delta T(y)}{\Delta T_{\rm f}} \right|_{\phi=\phi_2} \right] , \qquad (1)$$

where $\xi(\phi_1) = \phi_1/(\phi_1 + 1)$ is the stoichiometric mixture fraction of the low- ϕ experiment [3].

The normalized temperature profiles derived from a pair of flip experiments at $\phi_1 = 1/8$ and $\phi_2 = 8$ in a flow with $U_1 \approx 120 \,\mathrm{m/s}$ and $U_2 \approx 11 \,\mathrm{m/s}$ are presented in Fig. 2. The temperature rise, $\Delta T(y)$, is determined by measuring the temperature at x = L using multiple fast-response (< 20 ms) thermocouples at a rate of 1 kHz in a reacting and corresponding non-reacting reference experiment. The temperature rise is the difference between the mean of the two data records during the steady-state portion of the experiment (1-2s). The uncertainty in the mean temperature values is less than 1% for all cases studied here when radiative losses are included. The stoichiometric adiabatic temperature rise, $\Delta T_{\rm f}$, is the difference between ambient temperature and the equilibrium temperature of the stoichiometric mixture at constant enthalpy and pressure. The stoichiometric adiabatic temperature rise, $\Delta T_{\rm f}$, of the low- ϕ experiment is chosen to be twice that of the high- ϕ experiment in order to match the flow in the two cases. The temperature profile for the high- ϕ experiment ($\phi = \phi_2$, bottom stream rich in reactants) has a maximum value significantly higher than that of the low- ϕ experiment ($\phi = \phi_1$, top stream rich in reactants), indicating that the entrainment of the mixing layer is biased towards upper-stream fluid. The probability of mixed fluid at any location within the mixing region is given by Eq. 1 and is included in Fig. 2. The probability profile of mixed fluid reaches a value of unity within the core of the mixing layer and maintains a high value to the lower guidewall.

Figure 2 also plots the normalized temperature and probability of mixed fluid profiles for a flow with $U_1 \approx 300 \text{ m/s}$ and $U_2 \approx 30 \text{ m/s}$. The temperature profiles are again shifted such that their peak is on the side of the mixing layer that is lean in reactants, but the peak values are almost equal, indicating an entrainment ratio near unity. The probability of mixed-fluid profile again reaches a value close to unity in the core of the layer, but the mixed region is notably thinner than in the low-speed experiment. The level of mixing is reduced as the top stream velocity, Reynolds number, and Mach number are increased.



Figure 2: Normalized temperature and probability of mixed fluid profiles for flip experiments. Left: $U_1 \approx 120 \text{ m/s}$ and $U_2 \approx 11 \text{ m/s}$. Right: $U_1 \approx 290 \text{ m/s}$ and $U_2 \approx 30 \text{ m/s}$.

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Figure 3: Scaled mixing thicknesses as a function of the top-stream velocity for $U_2/U_1 \approx 0.1$.

A measure of the total amount of mixing in the flow is the mixed fluid fraction, given by $\delta_{\rm m}/h = \int_{-h/2}^{h/2} P_{\rm m}(y) dy/h$. $\delta_{\rm m}/h$ is an estimate of the total (mole) fraction of fluid within the duct that has mixed on a molecular scale. It takes into account the effects of changing growth rate of the mixing layer and the amount of mixing within the layer. The fraction of mixed fluid within the mixing layer is given by $\delta_{\rm m}/\delta_{\rm t} = [1-\xi(\phi_1)]\{(\delta_{\rm p}/\delta_{\rm t})_{\phi=\phi_1}+(\delta_{\rm p}/\delta_{\rm t})_{\phi=\phi_2}\}$, where the product thickness, $\delta_{\rm p} = \int_{-h/2}^{h/2} (\Delta T(y)/\Delta T_{\rm f}) dy$, is the integral of the normalized temperature profile, and $\delta_{\rm t}$ is the distance from the lower guidewall at which the temperature profile reaches 1% of its maximum value (visual thickness of mixing layer) [3].

Figure 3 presents the fraction of mixed fluid as a function of the top-stream velocity for velocity ratios of $U_2/U_1 \approx 0.1$. The total amount of mixed fluid, δ_m/h , decreases from close to 60% at 100 m/s to 45% at $M_1 \approx 1$ ($U_1 \approx 328 \text{ m/s}$). The decrease in the total amount of mixed fluid is a consequence of the reduced growth rate of the shear layers with increasing compressibility [3] and the effect of compressibility and Reynolds number on the mixing. To investigate the change in mixing within the shear layer itself, the fraction of mixed fluid within the mixing region, δ_m/δ_t , is also included in Fig. 3. The fraction of mixed fluid within the mixing layer, δ_m/δ_t , is found to decrease from 70% at 100 m/s to 65% at $M_1 \approx 1$. Free shear layers exhibit δ_m/δ_t values that are less than 50% for low-speed experiments and are near 40% for compressible shear layers. This mixing geometry achieves significantly higher levels of mixing compared to free shear layers and shows promise for inclusion in dual-mode propulsion systems.

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