Turbulent Mixing and Combustion in a Reacting Shear Layer

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The temperature field is investigated in a gaseous mixing layer consisting of low-concentration hydrogen and fluorine. The results show the presence of large, hot structures separated by tongues of cool fluid that enter the layer from either side. The cores of the structures appear to be well mixed. The usual bell-shaped mean temperature profiles result from a duty cycle whereby a given point sees alternating hot and cool fluid, which results in the local mean. The adiabatic flame temperature is not achieved on average at any point across the layer. It is found that, in general, two different mean temperature profiles result from a given set of reactant compositions if the sides of the layer on which they are carried are reversed. These observations are not consistent with gradient diffusion concepts.

Introduction

EXPERIMENTAL investigations in recent years[1,3-5,7] of the two-dimensional mixing layer suggest that entrainment (i.e., the process by which irrotational fluid is brought into the turbulent layer) and mixing (i.e., mixing at the molecular level) are dominated by the dynamics of large-scale vortical structures. The mechanism of mixing[2] appears to be one in which the large structure entrains high-speed and low-speed fluid which subsequently mix molecularly in regions associated with the large structures. This view of the turbulent entrainment and mixing is in contradiction to the traditional gradient diffusion/eddy diffusivity viewpoint in which both phenomena are modeled by a diffusive flux which is proportional to the local mean concentration gradient.

In this investigation, the mixing and product formation of a two-dimensional shear layer are investigated, employing weak reactant concentrations of hydrogen and fluorine, both carried in inert nitrogen. These reactants form hydrogen fluoride with release of heat and thus serve to identify or label the molecularly mixed fluid. The heat release has been kept low so that the overall properties of the mixing layer are not significantly changed from the cold case.

Experimental Apparatus

The reacting shear layer, Fig. 1, is produced in a new blowdown facility shown in Fig. 2. By using a fixed mixing volume and a partial pressure technique, a given concentration of fluorine in nitrogen is loaded into a gas-tight teflon bag contained within the left reactant vessel (0.57 m^3, 20 ft^3 volume). A similar technique is used to load a similar charge of hydrogen in nitrogen into the right reactant tank. The outside of the teflon bags communicates with a much larger surge tank (12.7 m^3, 450 ft^3 volume), which provides the flow that is necessary to collapse the bags and displace the reactant charges while still maintaining an essentially constant upstream stagnation pressure. The flow is metered at a pair of sonic valves which remain choked during the course of a run.

The contraction section is used to expand the flow from round to rectangular sections and contains two sets of perforated plate and four stations of fine mesh screen for turbulence manipulation. The high-speed contraction ratio is 6:1 with an exit area of 5×20 cm (2×8 in.), while the low-speed contraction ratio is 3:1 with an exit area of 10×20 cm (4×8 in.). The test section is 76 cm (30 in.) long, with the first 51 cm (20 in.) useful for flow measurements.

Once the flow exits the test section the hot toxic exhaust gas enters a 51 cm (20 in.) diam duct and is washed on the fly by a high-pressure sodium hydroxide spray system which both cools the flow and partially neutralizes the hydrogen fluoride and unburned fluorine. The exhaust gas is then captured in two large downstream teflon bags (11.3 m^3, 400 ft^3 total capacity) and is treated at a later time. Figure 3 shows a side view of the facility.

Runs were performed for flow velocities of 22 and 8.8 m/s for a speed ratio $r = 0.40$. The high-speed turbulence level is about 0.7% rms. All measurements are taken at the $x = 45.7$ cm (18 in.) station where the visual width of the layer is about 7.6 cm (3 in.). The Reynolds number based on velocity difference and vorticity thickness is 30,800, which is well past the mixing transition observed by Konrad[5] and Breidenthal.[1]

Measurements

For each run, the streamwise pressure gradient is set to zero by adjustment of the low-speed sidewall. Velocity is measured by a rake of 15 pitot tubes and recorded on a miniature manometer bank which was photographed during a run. Temperature is recorded by a rake of eight cold wires, placed across the width of the layer, each driven by a constant current of 0.4 mA, i.e., as resistance thermometers. A typical wire is made of 2.5 μm-diam platinum/10% rhodium welded to Inconel prongs with a span of 1.5 mm. Each wire is sampled at 10 kHz during a run for a total data rate of 80 kHz, which is recorded on a DEC LSI 11/23.

An important feature is the calibration technique that was applied to each wire. Prior to a run, a small hot jet and a small cool jet whose temperatures were accurately known were applied to each probe in such a way that the entire wire and prong tips equilibrated to the jet temperature, and the probe voltages were recorded. These two measurements thus provide the calibration constant to convert recorded voltage to temperature rise. During a run, the hot flow performs the same function as the hot jet, namely, it brings the prong tips to a local mean temperature about which the wire performs excursions. The mean temperature is, therefore, accurate to within the calibration procedure, while excursions from the

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mean suffer from conduction error, which can be as high as 10-20% for the wires used in these experiments. The mean temperature profiles shown below are quite repeatable from run to run; however, the absolute reactant concentrations are known only to within approximately 3-5%, resulting in a corresponding uncertainty for the absolute value of the heat release of the same order.

Chemistry

The chemical reaction utilized here is

$$H_2 + F_2 = 2HF,\ \Delta Q = -130 \text{ kcal/mole}$$

Stated another way, this corresponds to a temperature rise of 93 K for 1% F_2 in N_2 and 1% H_2 in N_2 under constant-pressure, adiabatic conditions (this is the so-called adiabatic flame temperature). The chemical reaction actually consists of two second-order chain reactions

$$H_2 + F = HF + H, \qquad H + F_2 = HF + F$$

which requires some F atoms to initiate the chain. This was accomplished by adding a trace amount of nitric oxide to the hydrogen carrying stream. The reaction

$$F_2 + NO = NOF + F$$

was sufficient to ensure that the required F atoms were present in the layer and ensure proper ignition. In any event, the flow is one in which the resulting chemical time scales are fast compared to the fluid mechanical time scales. The Damkohler number, which is the ratio of the mixing time to the chemical time, varies from 1100 for the large scales to 5 for the smallest scales.

The equivalence ratio φ is defined here as the ratio of the low-speed freestream molar concentration, c_{02}, to the high-speed freestream molar concentration, c_{01}, divided by the low-speed to high-speed stoichiometric ratio, i.e.,

$$\varphi = \frac{c_{02}/c_{01}}{(c_{02}/c_{01})_s} = \frac{c_{02}}{c_{01}}$$

since the molar stoichiometric ratio for the hydrogen-fluorine reaction is unity.

Results and Discussion

Figure 4 shows the resulting time trace from the eight cold wires for an equivalence ratio of unity. The adiabatic flame temperature (labeled Tflm) for this flow is 93 K above ambient, and the time traces show the instantaneous temperature recorded by each probe as a function of time, normalized by the highest temperature seen by any probe during this time interval (labeled Tmax). The horizontal axis corresponds to 51.2 ms of real time. Flow can be viewed as being from right to left with the high-speed fluid on top. In addition, the time axis is greatly compressed: such a plot would only be to scale if the horizontal distance were about nine times the distance between the high-speed and low-speed probes.

Three important features are noticeable in this plot: 1) the presence of large, hot regions or structures, 2) the presence of cool fluid tongues that extend well into the layer, and 3) the observation that within the core of the large structure, the temperature from one edge of the layer to the other is roughly constant, i.e., the structure appears to be well mixed. These observations are consistent with earlier results.[1,3-5]

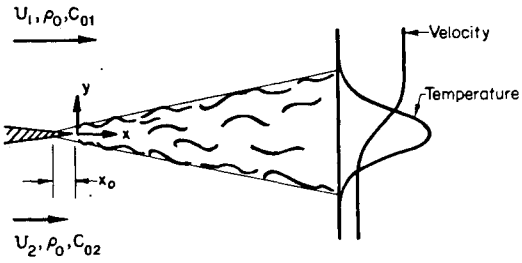

Fig. 1 Turbulent shear layer geometry.

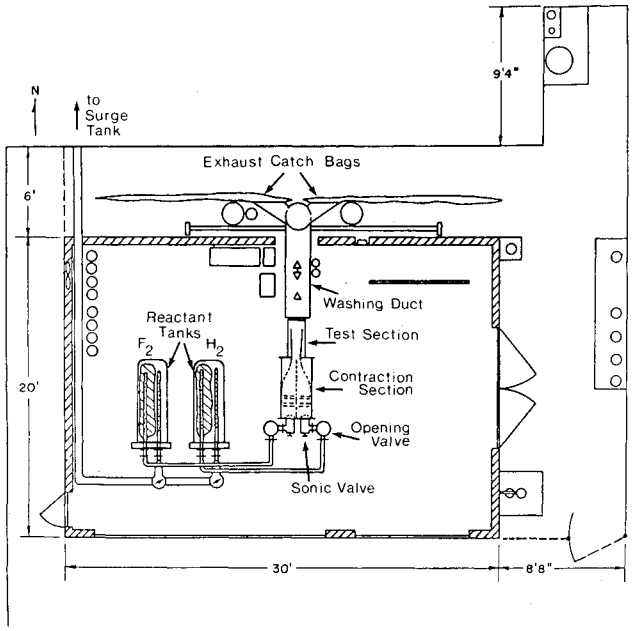

Fig. 2 Layout of GALCIT reacting shear flow lab.

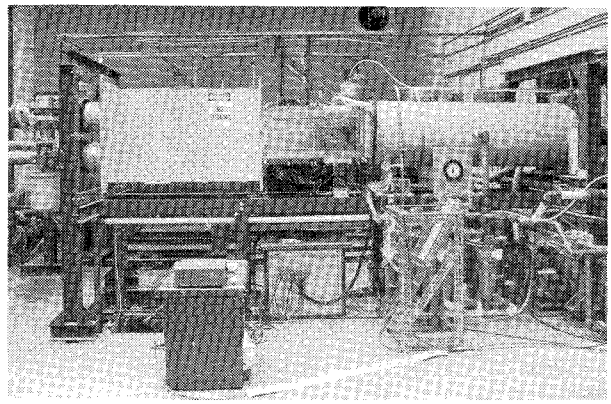

Fig. 3 Side view of facility.

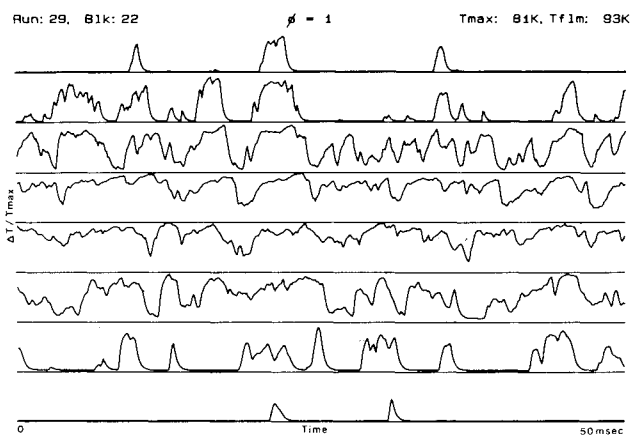

Fig. 4 Temperature vs time trace, $\varphi = 1$.

Figure 5 shows the results of averaging the time traces for an entire run. A complete run consists of 24 records (such as Fig. 4) for a total of 98,304 recorded points or 12,288 per probe. It is significant that the adiabatic flame temperature is not achieved on average at any location, a result previously noted by Wallace.[8] The mean profile results from a duty cycle phenomenon, i.e., a given probe spends varying lengths of time, depending upon its position within the layer, in alternate regions of hot and cool fluid. This results in a low mean temperature towards the outer edges of the layer and a higher mean temperature within. In addition, Fig. 5 shows the highest and lowest temperatures recorded by each probe during the course of a run. It is clear that the layer can be quite hot across its entire width (owing to the passage of a large structure) or quite cool across its entire width (owing to the presence of the cool fluid tongues). It must be noted that none of the data shown here are compensated for the thermal lag and conduction error of the wire, but, as noted earlier, these errors do not affect the mean temperature profile.

Figures 6 and 7 show similar results for an equivalence ratio of 4. The adiabatic flame temperature for this flow is 149 K above ambient. All of the main features mentioned earlier are apparent for this case, namely large hot structures, cool fluid tongues, and well mixed cores. The mean temperature profile again does not achieve the adiabatic flame temperature on average and shows a moderate shift towards the lean reactant, in agreement with Wallace.[8] The layer can still be quite hot or quite cool across its entire width, as shown by the high and low plots.

These features were observed for many flows for a range of equivalence ratios from 1/8 to 8, with the two cases discussed above being quite typical examples (further details can be found in Ref. 6). The mean temperature profiles for a set of runs of equivalence ratio 1/8, 1/4, 1/2, 1, 2, 4, 8 are shown in Fig. 8. It is interesting to note that any pair of runs of equivalence ratio φ_0 and $1/\varphi_0$ used identical compositions which were carried on different sides of the layer (and hence have the same adiabatic flame temperature) but, interestingly, produced different mean temperature profiles. Figure 8 shows that with the exception of $\varphi = 1$, which repeats to within the experimental error, the results for $\varphi = \frac{1}{2}$, 2, $\varphi = \frac{1}{4}$, 4, and $\varphi = \frac{1}{8}$, 8 are different, even though the pairs of runs have the identical adiabatic flame temperature. This result[2,5] is partly related to the fact that the layer entrains approximately 30% more fluid from the high-speed side and, hence, the amount of the lean reactant contained in the layer, which ultimately determines the mean temperature profile, is different in the two cases. Figure 8 also shows that the maximum mean temperature shifts by only 25% of the visual width of the layer for a factor of 64 change in equivalence ratio. Such moderate shifts have also been reported earlier by Wallace.[8]

Finally, Fig. 9 shows the amount of product contained in the layer for a fixed concentration of high-speed reactant, as a function of equivalence ratio. The product thickness, δ_{PI}, is defined as

$$\delta_{PI} = \int \frac{c_p(y)}{c_{01}}\,dy$$

where $c_p(y)$ is the concentration of product across the layer and c_{01} is the high-speed freestream molar concentration. Since product is analogous to temperature rise, the product thickness is obtained from the measured mean temperature profile, $\Delta\bar{T}(y)$, the molar heat capacity of the carrier gas, C_p, and the heat release per mole of reactant, ΔQ, i.e.,

$$\delta_{PI} = \int \frac{C_p \Delta\bar{T}(y)}{c_{01}\Delta Q}\,dy$$

The product thickness is normalized by the vorticity thickness of the layer, δ, where

$$\delta = \frac{U_1 - U_2}{(\partial U/\partial y)_{\max}}$$

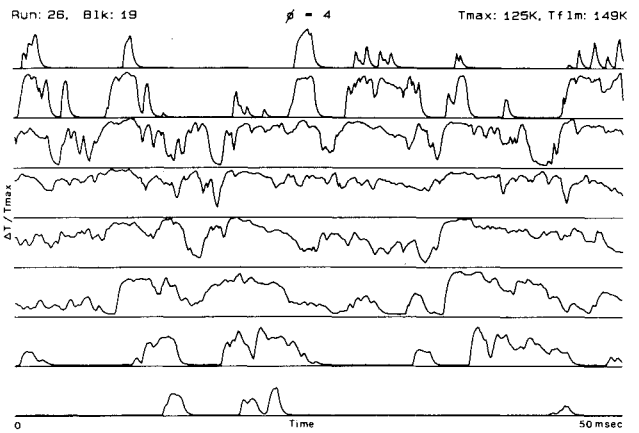

Fig. 6 Temperature vs time trace, $\varphi = 4$.

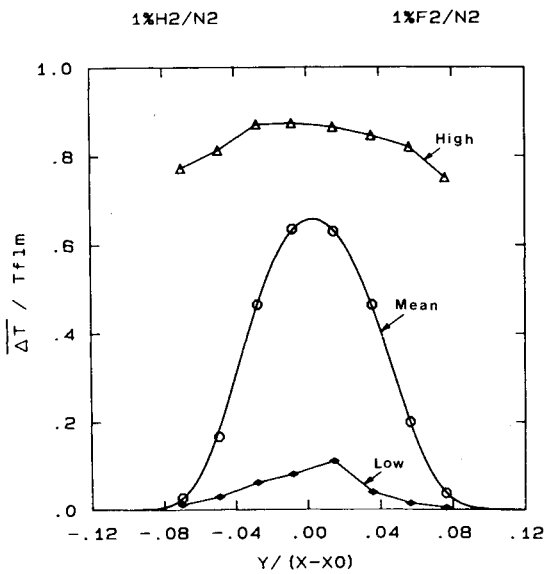

Fig. 5 Mean temperature profile, $\varphi = 1$.

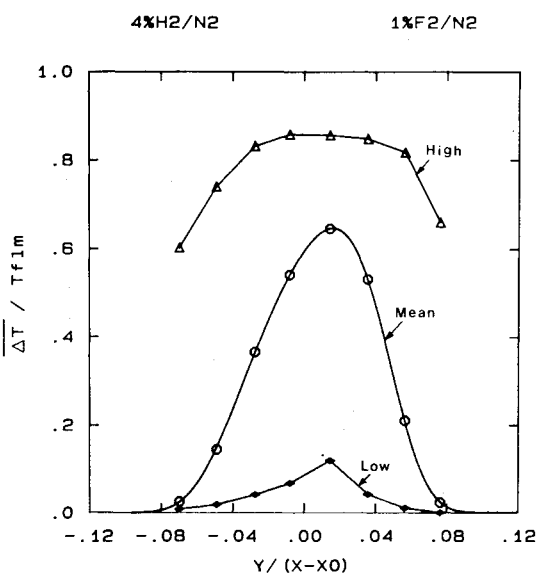

Fig. 7 Mean temperature profile, $\varphi = 4$.

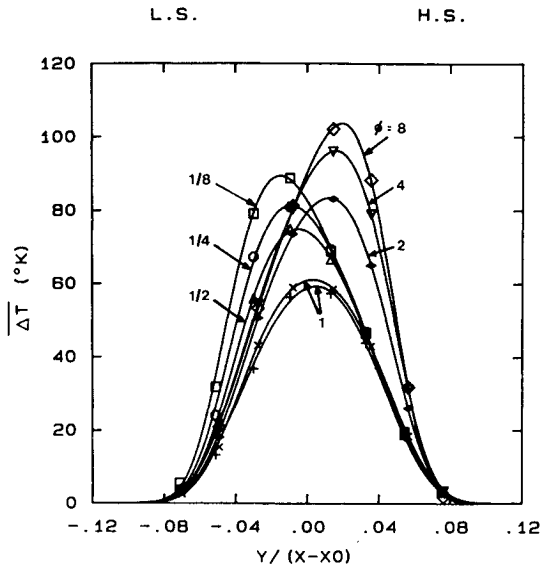

Fig. 8 Mean temperature profiles, all φ.

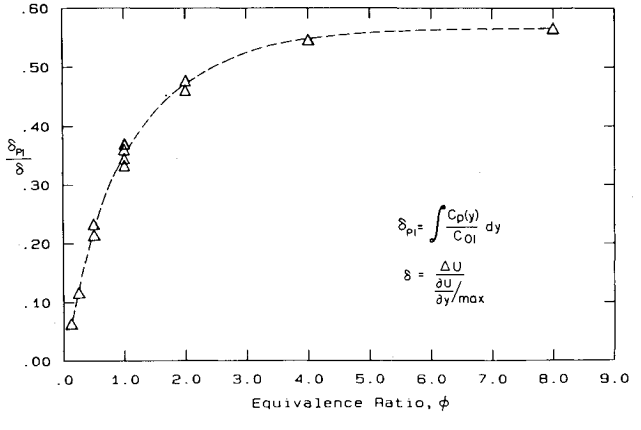

Fig. 9 Product thickness vs equivalence ratio.

For small values of φ the amount of product increases almost linearly as the low-speed reactant is burned out by an excess of high-speed reactant. With further increase in φ, an asymptotic limit is reached (past $\varphi = 6$) where the high-speed reactant is now burned out by an excess of low-speed reactant with no further increase in the amount of product. These observations are in general agreement with the earlier results of Wallace.[8]

Conclusions

The results presented here suggest that the processes of mixing and entrainment into a two-dimensional turbulent mixing layer are dominated by the dynamics of the large-scale structures. Consequently, the layer can be quite hot or quite cool across its entire width. The mean temperature results from a duty cycle associated with the passage of the large, hot structures. It is also found that, in general, it is possible to obtain two different temperatures for a given pair of reactant compositions owing to the asymmetric entrainment of fluid into the layer. The observed behavior of product formation in the layer differs significantly from traditional gradient diffusion—eddy diffusivity predictions. It is believed that these results will also be useful in comparisons with those computational models, which, in the limit of fast chemistry, attempt to predict the amount of product formed in the turbulent mixing layer.

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