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Experimental Study of the Flowfield of a Two-Dimensional Premixed Turbulent Flame

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A turbulent reacting shear layer in a premixed propane/air flow has been studied in a two-dimensional combustor, with a flame stabilized behind a rearward facing streamlined step. Spark shadowgraphs show that in the range of velocities (7.5-22.5 m/s corresponding to Reynolds numbers of 0.5×10^4-1.5×10^4 cm^{-1}) and equivalence ratios (0.4-0.7) studied, the mixing layer is dominated by Brown-Roshko type large coherent structures in both reacting and nonreacting flows. High-speed schlieren movies show that these eddies are convected downstream and increase their size and spacing by combustion and coalescence with neighboring eddies. Tracing individual eddies shows that on average eddies accelerate in the reacting shear layer as they move downstream, with the highest acceleration close to the origin of the shear layer. Combustion is confined to those large structures which develop as a result of vortical action of the shear flow. On the average, the reacting eddies have a lower growth rate than nonreacting eddies. A turbulent boundary layer created by means of a tripping wire upstream of the edge of the step virtually eliminates the large coherent structures in the shear layer, while for the case in which the wire could not trigger the transition to turbulence, the large coherent structures dominated the reacting and nonreacting flows.

I. Introduction

LEAN premixed prevaporized (LPP) combustion in aircraft gas turbine engines is one possible approach to the reduction of oxides of nitrogen and particulate emissions at higher power and cruise modes of operation and the reduction of unburned hydrocarbons and carbon monoxide emissions at the idle mode of operation.[1] These gains are likely to be obtained only with the introduction of new or increased problems of stability, flashback, and autoignition. The advantages and problems for application of LPP combustion to gas turbine combustors have been discussed in detail in Ref. 2.

Although there has been extensive and thorough experimental research on turbulent flame propagation and stability in the past (for example, Refs. 3 and 4), investigation of these processes in the light of the new findings in turbulent flow research has become of renewed basic interest. Recent experiments on some simple nonreacting turbulent flows, such as free shear layers and jets, have resulted in new views of the structure of these turbulent flows. Laufer[5] has concluded that "these turbulent flows are not as chaotic as have been previously assumed, and that there is some order in their motion with an observable chain of events reoccurring randomly with a statistical definable mean period." The new view suggests, "that with every shear flow is associated an identifiable, characteristic structure and that the development of the flow is controlled by the interactions of these structures with each other."[6] These views of the structure of turbulence have strong experimental support in free shear layers, circular jets, turbulent wakes, and boundary layers.[5,7] The basic findings of this research have established the concept of "coherent large scale structures" in turbulent shear flows.

Until recently, it was thought that free shear layers consisted of two regions, one turbulent and the other nonturbulent, with the turbulent region being characterized by random, three-dimensional motions and the presence of vorticity fluctuations. Viscous forces were continuously propagating these vorticity fluctuations into the nonturbulent region along the interface between the two regions ("entrainment by nibbling"). It is now suggested that large coherent structures have the prime role in the development and growth of free shear layers. For nonreacting free shear layers behind a splitter plate, Brown and Roshko[8] and Winnant and Browand[9] have clearly shown that large eddies are formed in a quasi-orderly fashion, are carried through the mixing layer, and grow through coalescence and engulfment. It is in these processes that the irrotational fluid is ingested and enfolded in the large-scale structures. Meanwhile internal mixing is occurring by the action of the small-scale turbulence and viscosity, and the new fluid is digested and incorporated into the structures.[6]

There has been far less evidence, experimental work, and even effort in the application of these concepts to reacting flows such as combustion. In their pioneering work on bluff body flame stabilization based upon the similarity between nonreacting and reacting flows behind bluff bodies, Nicholson and Field[10] suggested that "some sort of eddies or vortices or at least curvilinear flow patterns do exist in the burning regions" and also "that mixing can be accomplished solely by the well-ordered quasi-streamlined flow in the vortex trail." Only recently have there been efforts to apply the concept of "coherent large scale structures" and some related quantitative results of nonreacting shear flows to reacting shear layers. Konrad[11] has applied measured probability density functions in nonreacting flows to predict reaction rates for similar fast-reacting flows. Marble and Broadwell[12] have predicted the fuel consumption rate for diffusion flames in the mixing region between two streams and also for turbulent fuel jets. Experimental evidence of the existence of large coherent structures in reacting flows and the effect of combustion on these structures has not been reported. Recently published work by Chigier and Yule[13] confirms the existence of coherent large structures in the transition region of a turbulent jet diffusion flame.

We have undertaken an experimental study to observe the importance of large-scale, coherent structures in a shear flow

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both without and with combustion. A two-dimensional combustion tunnel was constructed for the study of premixed, prevaporized, turbulent flames stabilized behind a rearward facing streamlined step. The mixing layer in which combustion occurs, while not a free shear layer, possesses many characteristics of a free shear layer. Flow visualization has been used to study the structure of this shear layer for both reacting and nonreacting flows. Inlet velocity, inlet temperature, and equivalence ratio were experimental variables. Geometry, pressure (1 atm), and reactants (premixed propane/air) were held constant for all experiments.

II. Experimental Apparatus and Procedures

The cross section of the experimental apparatus is shown in Fig. 1. Air and fuel mix in three venturi nozzles which are attached to the approximately 1 m long premixing chamber. The premixing chamber has a rectangular cross-section 51 mm high and 173 mm wide. It is equipped with a photodiode flame detector and an adjustable over pressure detector which activate the fuel shutoff. A 1.5-mm square cell ceramic flow straightener 64 mm long with 31% blockage has been used to smooth any large flow discontinuities and to prevent flame propagation into the mixing section.

The test section entrance is equipped with a step which is streamlined in the upstream direction and has a blockage ratio of 0.5. The step, designed according to the method introduced in Ref. 14, delivers a uniform entrance velocity and also stabilizes the flame. Optical access to the test section is provided by two 12.7-mm-thick fused quartz windows on the sides of the test section. Important factors in the design of this system are: thorough mixing of propane and air before entering the test section and a uniform velocity flow-field at the entrance to the test section. The first criterion was met through choice of the mixers and mixing section length (about 1 m). The extent of mixing was tested by injecting CO_2 (which has the same molecular weight as propane) at the mixing venturi and measuring the composition of CO_2 at the entrance to the test section. Over the entrance cross-section the deviation between maximum and minimum CO_2 volume percentage is less than 2% for all cases. Flow velocity was measured by a pitot-static tube and a water micromanometer. The deviation between the maximum and minimum velocity is less than 8%, neglecting wall effects. Turbulence intensity measured by hot wire anemometry is about 3% and uniform over the entrance to the test section except near the upper wall where higher levels indicate the effects of a turbulent boundary layer.[15] Conditions at the upper wall do not affect the combustion zone.

Schlieren and shadowgraph optical techniques were used for visualization of reacting flows and the schlieren system for nonreacting flows. The stop used was a variable slit with knife edges on both sides.

III. Flow Visualization Results

Schlieren and shadowgraph flow visualization techniques have been found to be particularly useful and informative for two-dimensional shear layers[9] and two-dimensional flames.[10] In the present investigation these techniques were used for: 1) taking long exposure (20 ms) photographs of the flame, 2) taking very short exposure (spark, < 1 μs) photographs of the reacting and nonreacting flows inside the combustor, and 3) taking high-speed movies (up to 7500 frames/s) of the flame and of the nonreacting flow. Figure 2 contains three schlieren photographs, the first two of the flame (reacting shear layer behind the step) and the last of the corresponding nonreacting shear layer. Figure 2a is a long exposure time (20 ms) photograph of the flame which shows the extent of the spread of the flame averaged in a manner similar to what is observed by the eye.[16] The well-defined region behind the step is conventionally called the recirculation zone and the well-defined bright region is conventionally called the flame zone.[17] Figure 2b shows the spark schlieren (exposure time < 1 μs) of the flame with the same conditions as in Fig. 2a, but with strikingly different features now visible. A laminar, unstable shear layer leaves the step, expands at a short distance (compared to the length of the test section) from the step (eddy formation position x_0), and is transformed into a series of roll-up eddies which grow to the size of the test section. The interesting features of these eddies are their shape, their growth as they move downstream, and the apparent zone of reaction at the boundary between the eddy and reactant flow. Figure 2c shows the flow at the same conditions but without combustion. Obviously the flowfield (which is visible because the step is hot) is not as clear as in the reacting case. This is because the schlieren effect, which is based upon refractive index gradient, fades away downstream of the step. Despite its haziness it clearly shows that the large eddies are formed behind the step and they grow downstream of the step.

Reacting Flows

The effect of Reynolds number on these large eddies and overall flow pattern is shown in Fig. 3. These Reynolds numbers are based upon entrance velocities, viscosity of air at entrance conditions, and 1-cm characteristic distance. The equivalence ratio has been kept roughly constant (within 3%) so that variations in the chemistry of the flames is minimal. The Reynolds number increase is by a factor of only 2.44, which is not enough to show any drastic effect on the flame or flow structure. Over the range examined, the effect of increase in Reynolds number seems to be reduction in the stability of the initial layer, a shortening of the distance of the eddy formation position with respect to the step edge, and an increase in the small-scale turbulence inside the large eddies. The main features do not change with increase in Reynolds

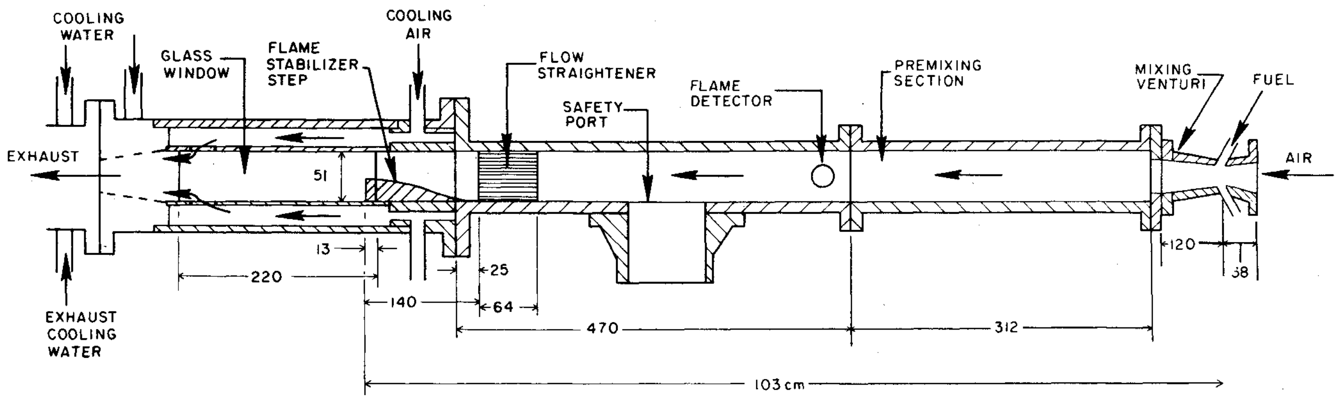
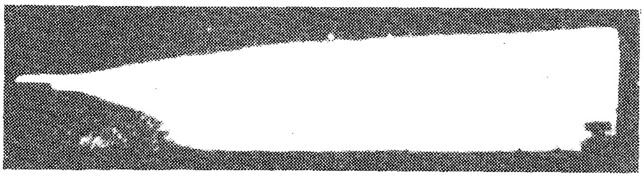
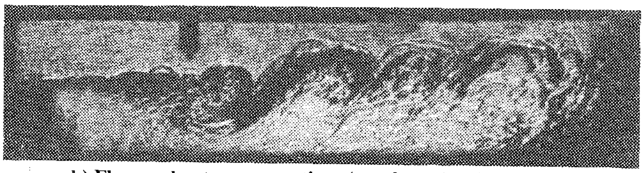


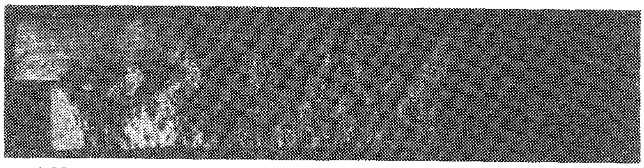
Fig. 1 Two-dimensional combustor test section (dimensions in millimeters).



a) Flame, long exposure time (20 ms), $\phi = 0.52$.

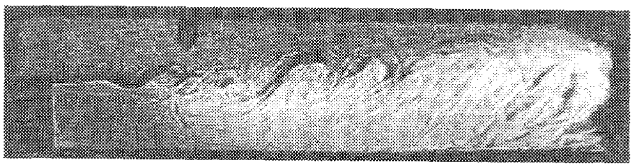


b) Flame, short exposure time (spark, < 1 ms), $\phi = 0.57$.

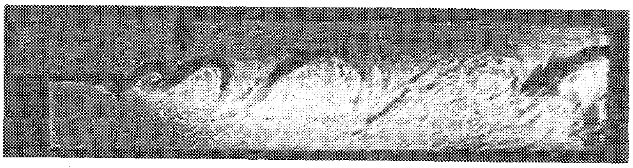


c) Nonreacting flow, short exposure time (spark, < 1 s), $\phi = 0.00$.

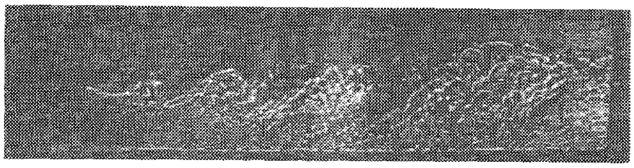
Fig. 2 Schlieren photographs of flowfield inside combustor test section, velocity 13.5 m/s, $N_{Re} = 8800\ cm^{-1}$, $T_0 = 295$ K, flow from left to right.



a) Velocity 9.1 m/s, $N_{Re} = 5900\ cm^{-1}$, $\phi = 0.60$.



b) Velocity 13.3 m/s, $N_{Re} = 8600\ cm^{-1}$, $\phi = 0.60$.



c) Velocity 22.2 m/s, $N_{Re} = 14400\ cm^{-1}$, $\phi = 0.58$.

Fig. 3 Spark shadowgraphs of flame behind step for different reactant inlet velocities and Reynolds numbers, $T_0 = 295$ K, exposure time < 1 μs, flow from left to right.

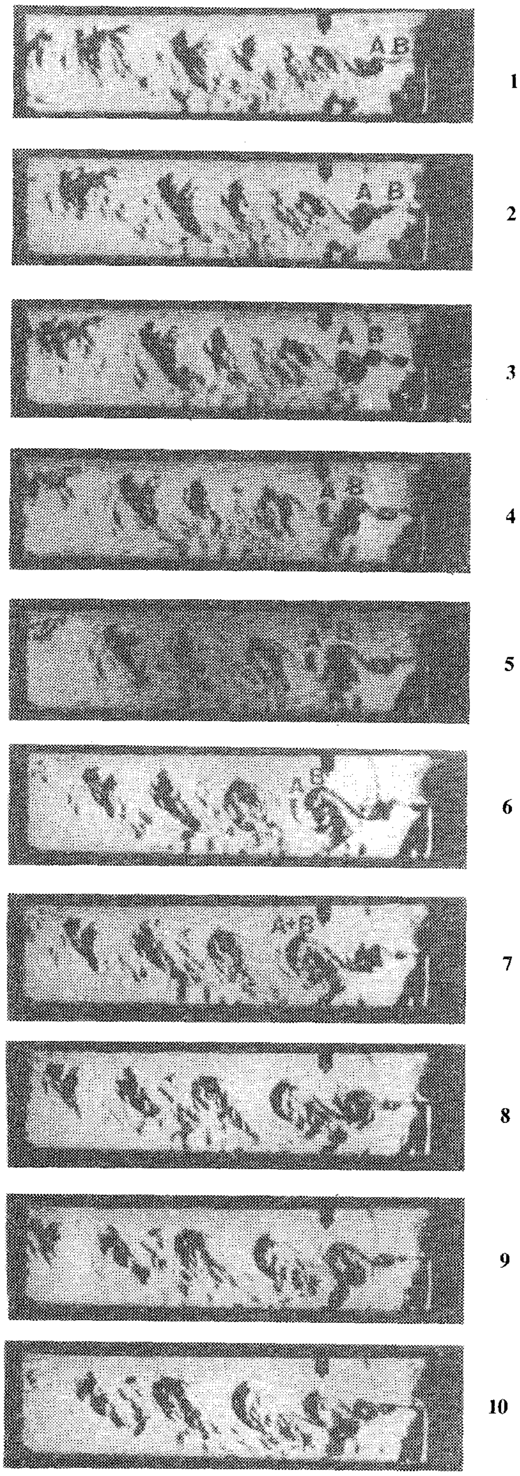


Fig. 4 Sequential series of frames from high-speed Schlieren movie of flame; time interval between frames is 0.67 ms, $V_0 = 13.3$ m/s, $N_{Re} = 3900\ cm^{-1}$, $\phi = 0.53$, $T_0 = 454$ K, flow from right to left.

number: the large-scale structures exist, are coherent, and grow as they move downstream. Spark schlieren photographs of the flame at different equivalence ratios also show that the generation and growth of large eddies toward downstream is largely unchanged. A calculation of the Reynolds number along the mixing layer for reacting and nonreacting flows[18] and other evidence, such as the rate of the flame propagation, suggest that the layer becomes turbulent.

For a better understanding of the process of development of these large-scale structures, a series of schlieren movies of the flow were taken. Figure 4 shows a sequence of 10 frames from one of the high-speed schlieren movies of the reacting flow behind the step. This sequence clearly shows that the large eddies start to form as a result of instability of the laminar shear layer[9] and that they roll up and grow as they are carried downstream through the mixing layer. The propagation of the flame is controlled by the growth of these eddies as they move downstream.

The formation of any observable eddy corresponds to the bulging of the laminar shear layer behind the step. This is an inviscid phenomenon which is commonly observed in free shear layers. The positions of occurrence of this bulge, which is identified as the eddy formation position x_0, has been reduced from the high speed movies. The histogram of this position is observed to be Gaussian.[18] Corresponding histograms have been constructed for different values of

Table 1 Effect of velocity V_0, equivalence ratio ϕ, and inlet temperature T_0 on eddy formation position

1) $T_0 = 295$ K, $\phi = 0.60$			
V_0, m/s	9.2	13.4	22.5
$\bar{x}_0$, cm	1.7	1.3	0.9
2) $T_0 = 295$ K, $V_0 = 9.2$ m/s			
ϕ	0.52	0.58	0.63
$\bar{x}_0$, cm	1.7	1.7	1.7
3) $V_0 = 13.3$ m/s			
T_0, K	295	454	
ϕ	0.55	0.53	
$\bar{x}_0$, cm	1.3	1.6	
4) $T_0 = 295$ K, $\phi = 0$ (nonreacting flow)			
V_0, m/s	8.8	13.0	18.8
$\bar{x}_0$, cm	1.6	1.4	1.2

Table 2 Effect of velocity V_0, equivalence ratio ϕ, and inlet temperature T_0 on eddy shedding period

1) $T_0 = 295$ K, $\phi = 0.60$			
V_0, m/s	9.2	13.4	22.5
$\bar{\tau}$, ms	2.9	1.7	1.2
2) $T_0 = 295$ K, $V_0 = 9.2$ m/s			
ϕ	0.52	0.58	0.63
$\bar{\tau}$, ms	2.8	2.9	2.5
3) $V_0 = 13.3$ m/s			
T_0, K	295	454	
ϕ	1.9	0.8	
$\bar{\tau}$, ms	0.55	0.53	
4) $T_0 = 295$ K, $\phi = 0$ (nonreacting flow)			
V_0, m/s	8.8	13.0	18.8
$\bar{\tau}$, ms	2.5	1.9	1.5

initial velocities, equivalence ratios, and entrance temperatures and the results for average values of x_0 are summarized in Table 1. The position of the eddy formation moves toward the step with increasing flow velocity, does not change with equivalence ratio, and moves away from the step with increasing temperature. The latter is considered to be due to the reduction of Reynolds number with the increase in inlet temperature. The period of formation of eddies is another interesting feature of these structures (see Table 2). The time between eddies decreases with increasing flow velocity and does not show any definite trend with increasing equivalence ratio. Schlieren and shadowgraph records of the flame show that the large eddies contain the reaction zone of the flame and that roll up of each eddy corresponds to engulfment of hot products from the recirculation zone into the layer of fresh reactants in which the reaction front propagates.

An interesting phenomenon first observed by Winnant and Browand[9] to be the cause of the growth of the free shear layer in a water tunnel, and later confirmed by Brown and Roshko[8] in their high Reynolds number experiment of a free shear layer between two gas flows, is amalgamation or coalescence of eddies, which simply means that one eddy takes over the one ahead of it and they form one larger eddy. This process is also called eddy pairing. According to Roshko[6] this phenomenon is partially responsible for the growth of the large eddies and consequently the shear layer.

In the flow under consideration this pairing process is clearly seen in Fig. 4. If the first two eddies A and B in the first frame are followed in the subsequent frames, it can be seen that as the eddy ahead moves forward it is pushed down and the next eddy moves forward and up. At the same time they rotate around each other and finally become one identity (at least optically) as shown in the frame 7. This phenomenon is more clearly shown in Ref. 9, where the camera has followed the eddies at the average speed of the two flows. This phenomenon can be characterized by calculating the percent of the eddies which survive as they move downstream. This will be discussed in the section on eddy coherence. The

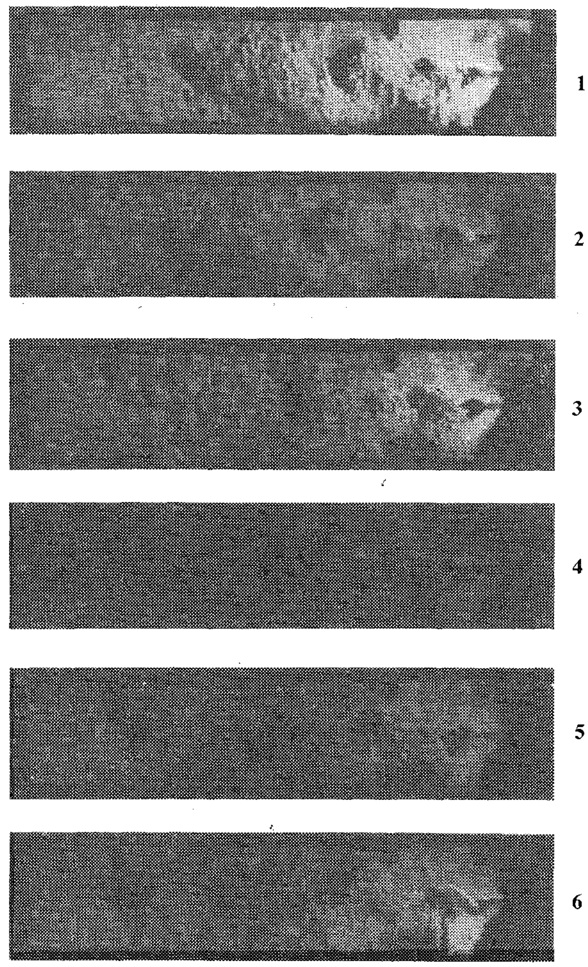


Fig. 5 Sequential series of frames from high-speed Schlieren mo' of nonreacting flow in test section; time interval between frames is 1.13 ms, $V_0 = 13.0$ m/s, $N_{Re} = 8474$ cm^{-1}, $T_0 = 295$ K, flow from right to left.

coalescence of eddies observed on the schlieren movies may be by the action of fluid dynamics, observed by Winnant and Browand,[9] or by chemical reaction. By the latter it is meant that because of chemical reaction, the observable interface between two eddies might disappear and the two be identified as one while fluid dynamically they might be two different structures. This problem cannot be resolved from data reduced from the schlieren or shadowgraph movies.

Nonreacting Flows

Observation of flowfield without reaction was made possible by using the residual temperature gradient existing in the thermal boundary layer on the surface of the step and the temperature difference between the incoming flow and the air in the recirculation zone immediately following fuel shutoff and flame extinction. This effect would persist for only a few seconds following fuel shutoff. A sequence of frames from such a schlieren high-speed movie is shown in Fig. 5. Development of the vortices in the initial stages of the mixing layer is quite clear and they appear similar to the vortices of the reacting flow of Fig. 4, although not as clearly defined since the refractive index gradients are weaker. As for the reacting flow, the process of coalescence of eddies can also be clearly seen in Fig. 5. The disappearance of eddies here is purely a fluid dynamical process. These observations suggest that heat release which results in expansion and increase in kinematic viscosity of the gas mixture in the mixing layer does not considerably affect the vortex shedding behind the step.

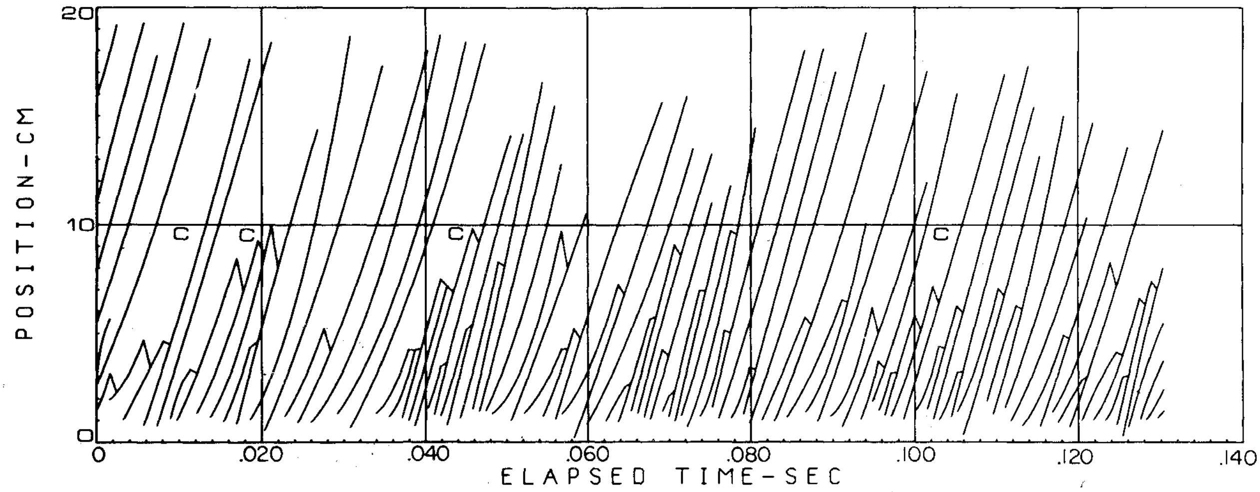


Fig. 6 Eddy trajectories for flame stabilized behind step, $V_0 = 13.6$ m/s, $N_{Re} = 8800$ cm^{-1}, $\phi = 0.57$, $T_0 = 295$ K.

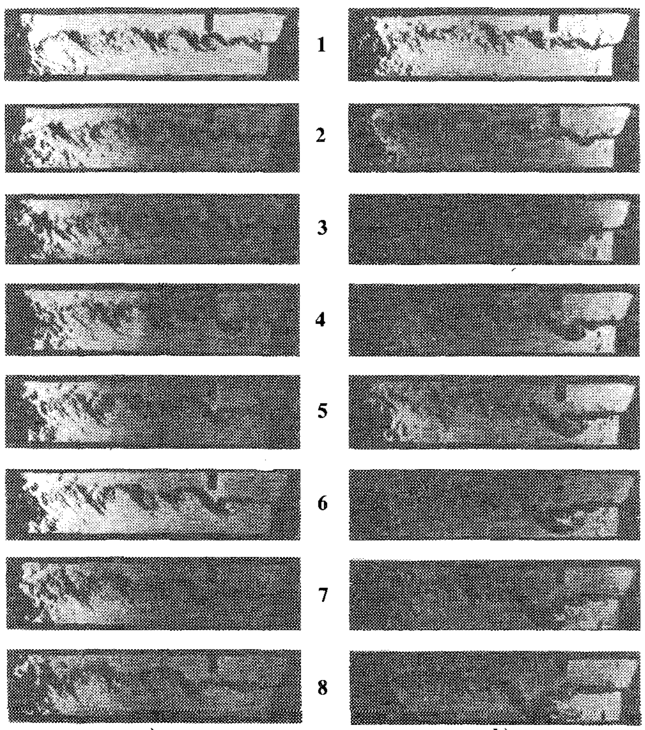


Fig. 7 Two sequential series of same high-speed Schlieren movie of flame stabilized step; $V_0 = 13.6$ m/s, $N_{Re} = 8800$ cm^{-1}, $\phi = 0.57$, $T_0 = 295$ K, flow from right to left. a) Normal formation and development of eddies in mixing layer, time interval between the frames is 1.16 ms. b) Coalescene of sequence of eddies and process of intrusion into recirculation zone, time interval between frames is 1.22 ms.

Eddy Coherence

The vortices shown in Figs. 2-5 can be followed frame by frame on high-speed schlieren movies and the movement of these eddies in the mixing layer plotted against time on an x-t diagram. Such a diagram was first introduced by Brown and Roshko[8] to show the coherence and lifetime of eddies in their free mixing layer experiment. An x-t diagram for 100 consecutive eddies in the present reacting shear layer is shown in Fig. 6. Time has been calculated starting from an arbitrary frame of the film of the motion picture, knowing how the framing rate is changing with frame number since the framing rate is not constant. The curves have been plotted using a second-order polynomial curve fit. Each curve corresponds to the trajectory of a vortex. The trajectories are nearly parallel to each other, showing that the vortices move with nearly the same convective velocity at each point in space and with a general trend of increasing velocities as they move downstream. Because this is a reacting flow with energy release and expansion, the observed acceleration is expected. Nonreacting flows behave similarly but with less acceleration of the vortices.[18]

Coalescence or vortex pairing is shown by dashed lines in Fig. 6. After each pairing a new vortex is formed, which has been arbitrarily assumed to be the continuation of the second vortex. This assumption is based upon the observation of this process on schlieren and shadowgraph movies, see Figs. 4 and 5. From Fig. 6, the percent of eddies which survive as they move downstream can be determined.[18] An exponential decay in the number of eddies as they move downstream, qualitatively in agreement with the findings of Roshko,[6] is observed. In high-speed schlieren and shadowgraph movies of the frame, a periodic intrusion of large eddies into the recircualtion zone was observed. It was noted that each of these intrusions corresponds to coalescence of a series of eddies usually close to the step edge. Four of these intrusions are identified by a "C" on Fig. 6. A picture of this intrusion is shown in Fig. 7 which shows two portions of the same schlieren high-speed movie. Figure 7a shows a normal mode of formation of vortices behind the step with occurrence of one pairing, while Fig. 7b shows the amalgamation of a series of consecutive vortices leading to a gross mass flow into the recirculation zone. It was observed that the intrustion was more frequent in leaner flames, while in nonreacting flows it could not be identified.

The resemblance of the forms of vortices observed in spark photographs and high-speed movies, their quasiorderly formation downstream of the step, and their motion in the mixing layer with fairly consistent velocity in space suggest that, in both reacting and nonreacting flows, the large structures formed as a result of the instability of the original laminar separated layer are coherent. They grow and increase their spacing[18] as they move in the mixing layer downstream of the step.

Effect of Combustion on the Shear Layer

There is close resemblance in the development of eddies in the reacting and nonreacting shear layers under investigation. Because of the increase in viscosity with reaction, there is an order of magnitude reduction in the Reynolds number.[18] schlieren and shadowgraph records of the mixing layer suggest that there is a reduction in small-scale turbulence due to heat release in the layer. The rate of formation and formation position of eddies in the reacting and nonreacting layers are comparable (Tables 1 and 2). This result is in sharp

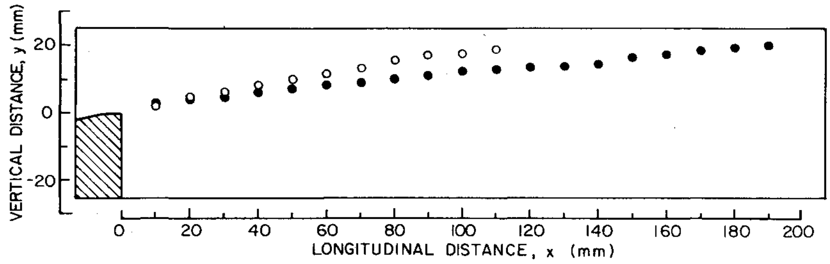


Fig. 8 Mixing layer spread in test section; • reacting layer, $V_0 = 13.6$ m/s, $N_{Re} = 8800$ cm^{-1}, $\phi = 0.57$, $T_0 = 295$ K; ○ nonreacting layer, $V_0 = 13.0$ m/s, $N_{Re} = 8474$ cm^{-1}, $T_0 = 295$ K.

contrast with the observation by Chigier and Yule[13] in an unconfined jet diffusion flame. This is attributed to the reverse flow in the recirculation zone and the acoustics of the chamber and upstream flow channel.[18]

Growth of the shear layer was calculated for reacting and nonreacting cases employing the data from the high-speed schlieren movies of the flowfield in the test section. The averaging was done for 40 nonreacting and 100 reacting eddies. Because of the slight dependence of spreading rate upon equivalence ratio,[4] spreading rate for only one equivalence ratio was calculated. Figure 8 presents the average rate of growth of a reacting and a nonreacting mixing layer at nearly equal reference velocities. On the average, the growth of the reacting layer is up to 30% lower than the spreading rate of the nonreacting shear layer. The main factors that should be considered in explaining the above phenomenon are: increase in viscosity, dilation effect of the combustion, and increase in average velocity of the gas flow in the layer.

The effect of density variation on the spreading rate of the free shear layers has been experimentally investigated by Brown and Roshko.[8] They conclude that reducing the density in the lower velocity side reduces the spreading rate of the layer. This reduction will depend upon the density and velocity ratios of the two mixing streams. For the case of density ratio of 1/7 in a half jet (similar to the present experiment), the spreading rate is reduced by close to 30%. Considering the dilation effect of combustion in this system, and neglecting the effect of increase in velocity, about a 20% reduction in the spreading rate should be expected, somewhat less than what is observed. We believe that the additional reduction in the spreading rate due to combustion should be attributed to acceleration of products of combustion in the free shear layer in the confined flow of these experiments. Despite the first impression that flame propagation might increase the visible spread of the shear layer, the results presented here show that the fluid dynamic effects of the heat release (dilation and resulting acceleration) supercede the propagation effect of the flame and reduce the visible growth of the free shear layer behind the step.

Boundary Layer Effect on Formation of Vortices

The boundary layer just upstream of the free shear layer is suspected to have a considerable effect on the growth of the layer because it affects the growth of the large-scale structures in the layer. Batt[19] concluded that tripping the boundary layer upstream of the free shear layer, even if it does not trigger the transition to turbulence, thickens the boundary layer and increases the spreading rate and turbulent intensity of the free shear layer. Recently, Browand and Latigo[20] have carried out an experimental study of the effect of upstream boundary

Table 3 Wire size and location for boundary layer trip tests

Case	Wire diameter, mm	Wire location, mm
1	0.5	11
2	0.5	2
3	1.1	11
4	1.1	2

layer on a nonreacting free shear layer. From their hot wire anemometry results, and without direct observation, they conclude that the introduction of small-scale turbulence has obstructed the large-scale interactions in the initial stages of the mixing layer. This has resulted in lower growth rate, but eventually the shear layer relaxes toward the higher growth rate observed for a shear layer with a laminar initial layer. By this argument, they conclude that at this later stage the important role of the large scale structures is re-established.

To establish the effect of the upstream boundary layer on the large-scale structures in the present reacting and nonreacting shear layers, the boundary layer was tripped by laying a wire on the top of the step. Wire sizes and their positions with respect to the edge of the step are shown in Table 3. Approximate values for the size of the wire and its position to ensure the transition before the trailing edge can be calculated following Schlichting.[21] The diameters of both wires were larger than the critical diameter for tripping the boundary layer. The boundary layer thicknesses at the edge of the step, based upon the flat plate and uniformly converging nozzle for a reference velocity of 13.5 m/s, were 2 mm and 1.2 mm, respectively. Based upon the above explanations, it is expected that the 0.5 mm wire will just disturb the boundary layer without any serious change in the layer, and the 1.1 mm wire at 11 mm upstream will trip the boundary layer in the sense that it causes transition to turbulence in the boundary layer.

Schlieren movies of reacting and nonreacting flowfields in the test section with the trip wires of Table 3 were taken. Figure 9 shows two series of still pictures from two schlieren movies of the flame with 0.5 mm boundary layer trips at 11 and 2 mm upstream of the edge of the step. It is evident that the basic features of large-scale structures remain unchanged. In both cases, large-scale vortices clearly dominate the reaction zone. In Fig. 8, the eddies almost lose their identity far downstream in the test section, while in Fig. 9 the eddies clearly retain their identity all the way through the test section. Figure 10 shows the effect of 1.1 mm trip wire on the flowfield inside the test section. Figure 10a (trip wire 11 mm upstream of step edges) shows almost no organized structures in the layer, while in Fig. 10b (trip wire 2 mm upstream of the step edge) the large coherent structures are distinct vortices and preserve their identity all the way through the test section. Comparison of these figures shows the effect of the position of the trip wire. It is believed that the boundary layer has become turbulent in the case of Fig. 10a (1.1 mm trip wire, 11 mm upstream of the edge), while in the other three cases the wire is buried in the laminar boundary layer acting as a disturbance to the layer. The large-scale structures are not completely absent from the flow, but regular and identifiable structures with distinct braids and eyes are no longer visible. Examination of the schlieren movies corresponding to Fig. 10 reveals that large eddies appear more frequently far downstream rather than close to the edge of the step and that the recirculation zone is lengthened. Higher grain level in the schlieren records shows a higher level of mixing and a smaller scale turbulence in the flow.

In the three cases in which the layer is dominated by large-scale structures, in contrast to the untripped case, the initial layer has a higher growth rate, the eddies are further

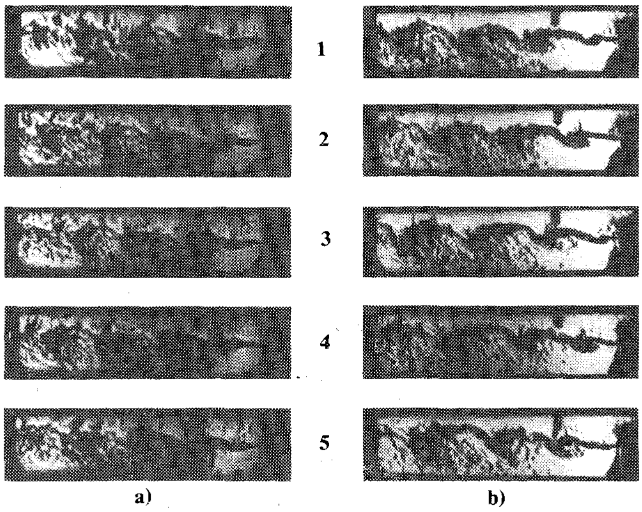


Fig. 9 Sequential series of frames from high-speed Schlieren movies of flame with tripped upstream boundary layer, $V_0 = 13.6$ m/s, $N_{Re} = 8800$ cm^{-1}, $\phi = 0.57$, $T_0 = 295$ K, flow from right to left, a) 0.5 mm trip wire located 11 mm upstream of edge, time interval between frames is 1.6 ms. b) 0.5 mm trip wire located 2 mm upstream of the edge, time interval between frames is 1.8 ms.

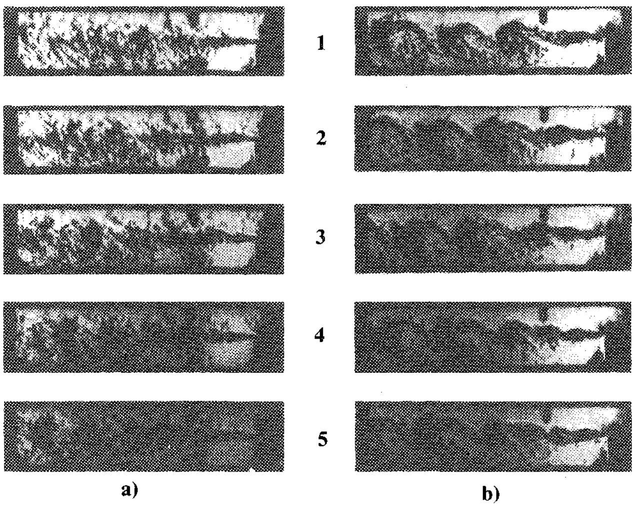


Fig. 10 Sequential series of frames from high-speed Schlieren movies of flame with tripped upstream boundary layer, $V_0 = 13.6$ m/s, $N_{Re} = 8800$ cm^{-1}, $\phi = 0.57$, $T_0 = 295$ K, flow from right to left, a) 1.1 mm trip wire located 11 mm upstream of edge, time interval between frames is 1.4 ms. b) 1.1 mm trip wire located 2 mm upstream of edge, time interval between frames is 1.3 ms.

separated (large eddy distances), and there is higher small-scale turbulence inside the large vortices. The coalescence of vortices was clearly observed in all of the above three cases. In similar nonreacting flows, the same trends were observed.

The results of these experiments explain the difference between the observations of Brown and Roshko[8] and the conclusions of Browand and Latigo.[20] Brown and Roshko[8] observed that placing wire trips just upstream of the trailing edge of the splitter plate did not disrupt the visible large structures a few boundary layer thicknesses downstream, while Browand and Latigo[20] placed the wire trips further upstream to insure transition in the layer and concluded that the effect of the trips was to obstruct the interaction of large-scale structures in the early stages of the formation of the mixing layer. From our experiments, we conclude that formation and interaction of the large coherent structures and the resulting shear layer growth depends upon the size and location of the disturbances in the upstream boundary layer.

Analysis of the schlieren movies for average eddy formation position and period shows that upstream disturbance of the boundary layer delays the formation of the vortices in the layer.[18] This is due to the thickening of the initial vorticity layer which makes it less susceptible to flow disturbances. We conclude that large coherent structures can form and play the major role in the development of the free shear layer if the initial layer is laminar; otherwise, the formation and interaction of the large coherent structures is not observed.

IV. Discussion and Conclusions

In our laboratory combustor in which the flow is predominantly two-dimensional, we have been able to demonstrate that both nonreacting and reacting flows are dominated by large-scale, coherent vortex structures. The flame region is dominated by the fluid dynamics of the vortices, the sizes of which define the thickness of the apparent shear or mixing layer. The growth of the vortices and propagation of the flame are intimately linked. On the average the reacting eddies have a lower growth rate, are more closely distributed in space, and have a slightly smaller rate of coalescence than nonreacting eddies. The dynamics of vortex pairing, observed by Winnant and Browand[9] in nonreacting flows, is definitely one of the mechanisms for the introduction of fresh reactant into the shear layer. The frequency of this pairing decreases as the flow moves downstream, probably due to the wall effect on the vertical motion of the vortices. The number of vortices decays exponentially downstream. The segments of fresh reactants, from the top of the flow, and also fully reacted products from the recirculation zone, which are entrained in the mixing layer, are enveloped and strained before their disappearance into the eddies. This is similar to the process of entrainment observed in wakes where the reactants are entrained by the action of small-scale eddies as well as the growth of large eddies. Tripping the boundary layer changes the structure of the eddies both in reacting and nonreacting shear layers and, consequently, is expected to change the structure of the shear layer. Where the trip wire triggered the turbulent transition in the boundary layer, the coherent large-scale structures could not be distinguished in the layer. Otherwise, the tripping just disturbs the boundary layer and delays the formation of coherent structures in the layer.

Just how truly two-dimensional our flow is has not been fully established. The incoming flow is one-dimensional except at the walls, which should not have an effect on the bulk of the flow in the combustion region. Time averaged probe measurements of composition and temperature indicate that the flow rate is time averaged two-dimensional within 10% over the transverse direction, except at the walls. The Schlieren visibility of the vortices argues that they are predominantly two-dimensional structures and uniform along the optical path and that the mixing layer is uniform across the combustor. The decreased definition of the flow structures in the downstream region of the combustor could be evidence of an increased three-dimensionality of the flow or it could be the result of the fading of the optical density gradients in the other two dimensions. We did not check the form of the vortices in the third dimension as could be accomplished by observing the flame from the top of the combustor.

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