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Mechanism of Instabilities in Turbulent Combustion Leading to Flashback

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Unstable turbulent flow processes were studied experimentally in a combustion tunnel of a slender rectangular cross section provided with a rearward-facing step to simulate the action of the bluff-body flame holder under planar flow conditions. The flow pattern was recorded by means of high-speed schlieren cinematography taken across side walls that were fitted for this purpose with quartz windows, while the photographs were synchronized with pressure transducer measurements. As the flow rate of fuel was increased toward the lean flashback limit, three modes of instabilities were observed: 1) humming—a significant increase in the amplitude of the vortex pattern in the turbulent mixing zone; 2) buzzing—a large-scale oscillation of the flame up and down across the test section, eventually obliterating the vortex pattern of the mixing zone; 3) chucking—a cyclic reformation of the flame that appears as if it were periodically spilled over the edge of the step. The latter leads to flashback—the actual lifting of the flame from the edge of the step and its propagation upstream, a process that upon a certain penetration into the incoming flow is terminated abruptly, giving rise to an augmented chucking cycle. The mechanism of these phenomena is ascribed to the action of vortices in the recirculation zone and their interactions with the trailing vortex pattern of the turbulent mixing layer behind the step. Simplified configurations of vortices involved in such interactions are illustrated by sketches deduced from a numerical modeling analysis.

Introduction

IN conventional combustors for gas turbines the flame front is established at the stoichiometric contour in the primary zone. This produces optimum conditions for the generation of oxides of nitrogen and smoke.[1,2] The best remedy for this state of affairs is offered by "lean, premixed/prevaporized combustors."[3,4] Such systems require the use of a premixing chamber, while combustion is stabilized by a bluff-body flame holder.[5] Their operation is handicapped by potentially harmful combustion instabilities.[6,7] At the lean limit these cause blowoff; at the rich limit (approaching the stoichiometric ratio) they lead to flashback. The purpose of our studies was to explore the mechanism of the instabilities associated with the latter under highly turbulent flow conditions.

The stability of flames in premixed gases under laminar and turbulent conditions has been studied extensively. A review of the literature on flashback in turbulent combustors was presented in 1978 by Plee and Mellor[8] who identified four possible mechanisms of this phenomenon: 1) autoignition upstream of the flame, 2) classical flashback due to the normal burning speed exceeding the flow velocity of the unburned mixture either in the boundary layer or along the flow axis, 3) flame propagation through reverse flowfields that may occur when the characteristic dimension of a disturbance d is of the same order as the distance between the disturbance and the flame holder L, and 4) preignition of a separated flow region that may take place when $d \ll L$. In comments on this paper, Coats[9] pointed out that, according to experiments carried out at the National Gas Turbine Establishment in England, in most cases flashback was established as an outcome of low-frequency flow instabilities—a conclusion corroborated by our observations that in combustion stabilized in mixing layers it occurs primarily as a consequence of a local flow reversal triggered by large-scale vortex dynamics.

The fact that combustion stability is governed primarily by the turbulent mixing zone behind the trailing edge of a bluff-body flame holder, and by the recirculation zone immediately behind its base, has been highlighted in many publications.[2-4,7] Recently the effect of the recirculation zone on combustion instability under laminar as well as turbulent conditions has been studied by Huck and Marek,[10] using an axisymmetric combustion chamber with a sudden increase in cross-section area at the inlet port. When the size of the port was decreased, prolonging the residence time of the gases in its vicinity, a marked improvement in combustion stability was noted, indicating the influence of the size of the recirculation zone in this respect.

Reported here is an experimental investigation of the mechanism of combustion instabilities leading to flashback. The results were obtained by the use of high-speed schlieren cinematography, combined with synchronized pressure transducer records. The combustion chamber had an oblong rectangular cross section to model the essential features of planar flow and was provided with a rearward-facing step acting as the flame holder. Premixed propane/air mixtures were used as the working substance.

Upon the re-examination of the salient features of stable combustion, we found that the trailing vortex pattern can be modulated by the introduction of a resonant acoustic disturbance, while in the absence of this disturbance three modes of instabilities were observed as the equivalence ratio approached one. These we called, for lack of better names, humming, buzzing, and chucking.

Experimental evidence of these instabilities is presented here in comparison to the undisturbed, as well as the acoustically modulated, stable combustion. This is preceded by the description of the laboratory apparatus and followed by an interpretation of the experimental observations in terms

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of the simplest possible vortex interaction patterns, deduced from a numerical modeling technique we developed for the analysis of turbulent combustion.

Experimental Apparatus

Our experiments were performed using a combustion tunnel displayed in Fig. 1. The combustion chamber was of rectangular cross section, 50 mm high and 173 mm deep. The flame was stabilized by a streamlined contraction culminating in a rearward-facing step that blocked half of the cross-section area. The sides of the combustor were fitted with quartz windows, allowing an unobstructed optical access over the full extent of the flowfield.

Fuel and air were introduced upstream of a 1-m-long mixing duct, separated from the test section by screens and packed with stainless-steel wool. Downstream, the rectangular combustor was fitted, through a transition section, to a 21.2 cm (6 in.) diam pipe where cooling water was injected at two locations. Below the water injectors, 1.3 m downstream from the step, a butterfly valve was installed to control the pressure in the test section. Flow rates of both air and fuel were metered by critical flow nozzles, an array of such nozzles being used for the fuel to accommodate a wide range of operating conditions. In addition to the main fuel supply system, a solenoid-operated secondary loop was provided, triggering a step change which increased the fuel flow rate.

The structure of the flowfield was recorded by schlieren cinematography using a conventional *Z*-configuration mirror system, 1 kW Zenon arc lamp, and a Hycam high-speed movie camera operated normally at 5000 frames/s. The test section was equipped with a Senso-Metric SMI pressure transducer mounted in the center above the step. The transducer signal was recorded by an oscilloscope and transformed by a General Radio FFT spectrum analyzer.

The combustion tunnel presented in Fig. 1 was used by Ganji and Sawyer[11,12] for the study of the large-scale vortex structure occurring under stable combustion conditions. The mixing duct was then empty of steel wool and, instead of screens, it was provided at the end with a ceramic honeycomb. Thus, with an inlet temperature of 295 K, the lean flashback limit was found to be at an equivalence ratio of 0.6 for an inlet velocity of around 10 m/s, shifting to 0.7 at about 20 m/s. Throughout this range the rms of turbulent velocity fluctuations was on an order of 5% of the mean.

With steel wool packing and screens depicted in Fig. 1, the intensity of turbulence was reduced to 2%. As a consequence, the lean flashback occurred at much higher equivalence ratios, around 0.9 for inlet flow velocity of 13.3 m/s. Properties of stable combustion under such circumstances were investigated by Pitz and Daily[13,14] with laser Doppler velocimetry as the primary diagnostic instrument.

Experiments

To emphasize the different mechanisms of the various instabilities we observed, the experimental records presented here were obtained with the combustor operated at essentially the same inlet conditions, corresponding to the mass average flow velocity of 13.3 ± 0.1 m/s and the Reynolds number of $(2.16 \pm 0.03) \times 10^4$ under atmospheric pressure and room temperature. The loading of the combustor was then relatively light, corresponding to the Lefebvre factor[8] of

$$\theta^{-1} = 2\ \mathrm{kg/(s \cdot atm^{1.75} \cdot m^{2.75})}$$

Lean propane/air mixtures at atmospheric pressure and room temperature were used as the flowing substance. Since the normal burning velocity was in this case around 20 cm/s (a value on an order of 1% of the average flow velocity of the unburned medium), the flame front was almost tangent to the local velocity vector of the flowfield into which it propagated. The flame established itself essentially at the interface between the unburned and burned medium, coinciding with the streamline rather than cutting across, as it does at lower flow velocities. Therefore, on schlieren records the flame marked the outer boundaries of large-scale vortices which are the contours of such interfaces.

The experimental procedure was as follows. With the flow control valves in the fuel line preadjusted and the secondary valve closed stable combustion in the test section was established. When the high-speed movie camera reached the desired speed, it sent a signal to the solenoid which opened the secondary valve increasing the equivalence ratio. After a suitable time delay of 5-10 ms, allowing an instability under study to occur, the oscilloscope was triggered and at the same time the film was marked by the pulse from a light-emitting diode, thus synchronizing the movie with the pressure measurement.

The experimental records we present pertain to the following modes of combustion.

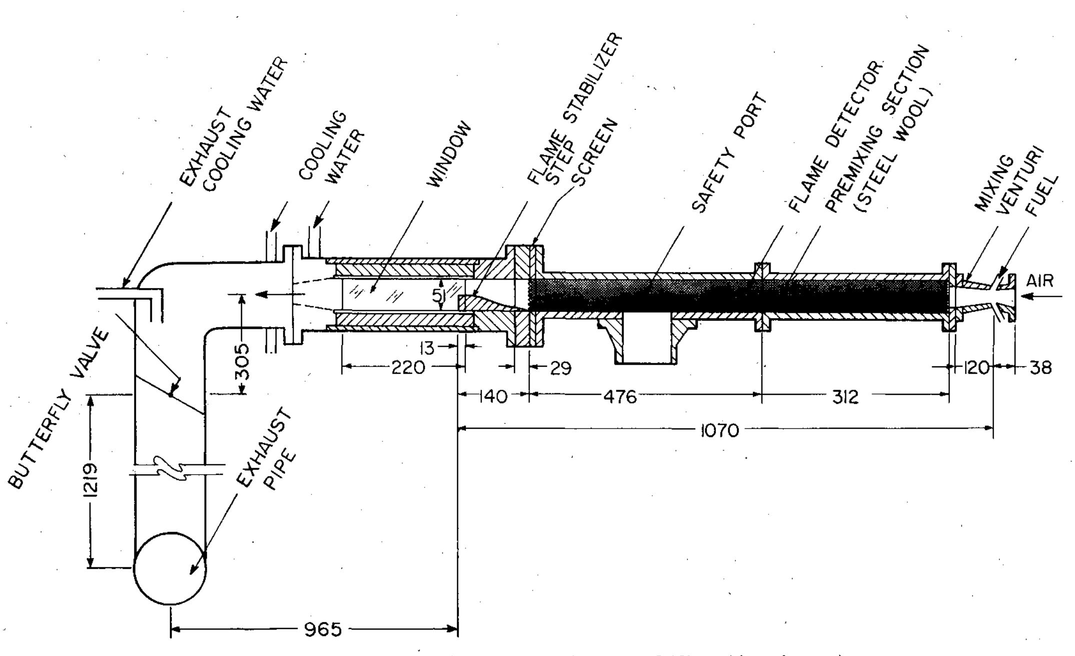

Fig. 1 Cross section of the combustion tunnel (dimensions in mm).

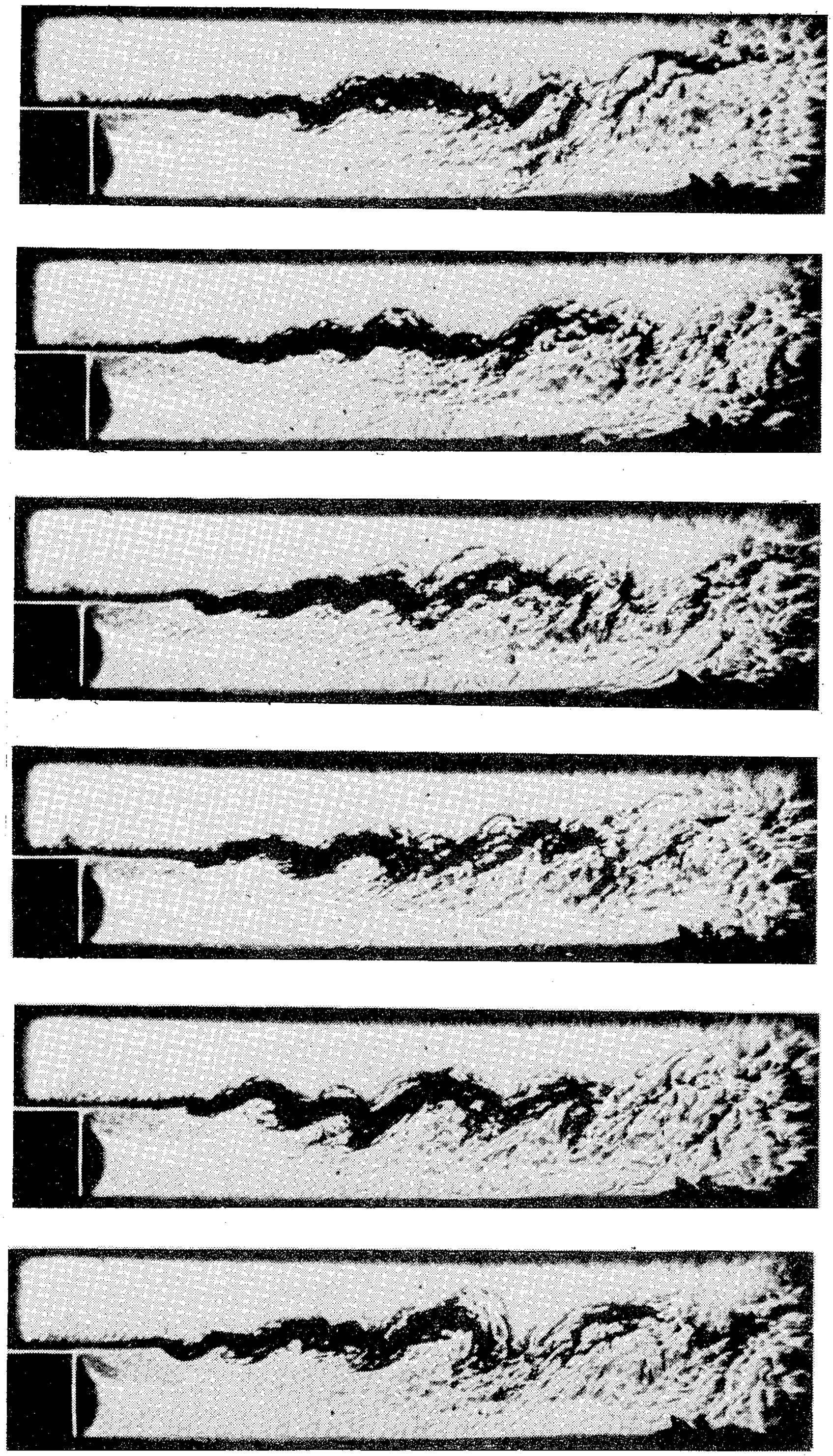

Fig. 2 Cinematographic schlieren record of stable combustion (equivalence ratio, 0.57; time interval between frames, 5 ms).

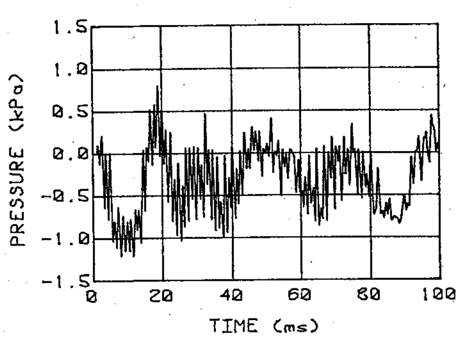

Fig. 3 Pressure transducer record of stable combustion.

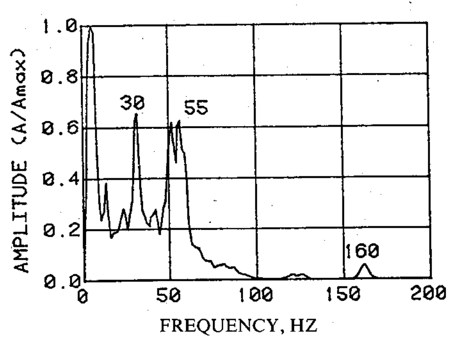

Fig. 4 Power spectrum of Fig. 3.

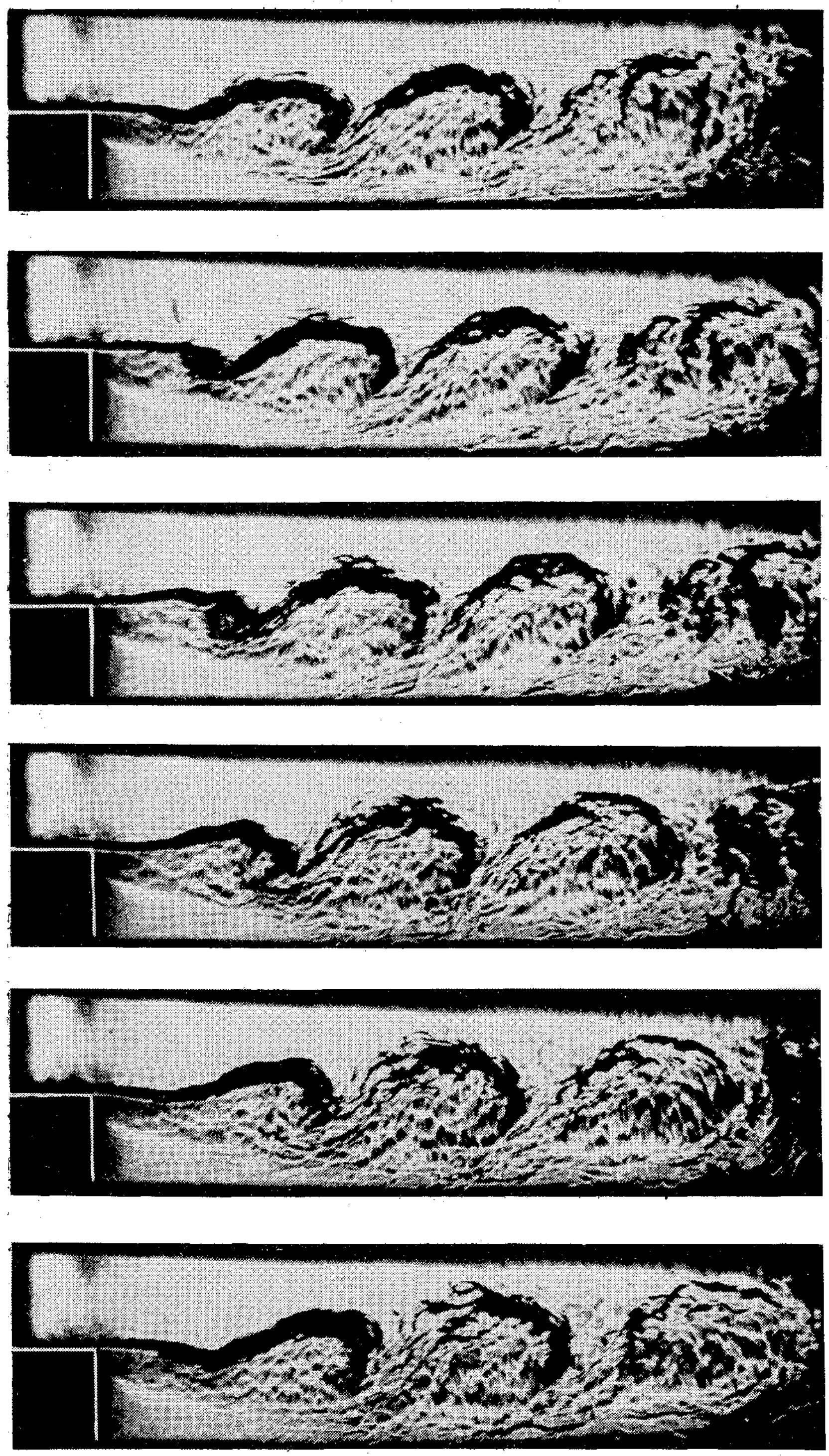

Fig. 5 Cinematographic schlieren record of acoustically modulated stable combustion (loudspeaker frequency, 200 Hz; equivalence ratio, 0.57; time interval between frames, 1 ms).

Stable Combustion

As pointed out in the introduction, to provide a proper basis for the investigation of instabilities, records of stable combustion were obtained at essentially the same inlet flow conditions. The structure of the flowfield observed then is presented in Fig. 2, displaying prints of frames from schlieren movies selected at time intervals of 5 ms. The corresponding pressure record is given in Fig. 3 and its power spectrum in Fig. 4. The latter exhibits a number of distinct peaks, indicating that stable combustion consists actually of a set of coexiting instabilities.

The somewhat irregular vortex pattern depicted in Fig. 2 could be set into a coherent structure, at a relatively small expense in energy, by an acoustic field of a loudspeaker mounted on the safety port at the bottom of the mixing duct (see Fig. 1). Extracts of the cinematographic schlieren records of the vortex pattern, obtained when the loudspeaker was operated at a frequency of 200 Hz, are displayed in Fig. 5. Outside of this frequency band no noticeable effect was observed, demonstrating the significance of resonant coupling between the acoustic field and the vortex interaction processes.

The response of turbulent mixing layers in inert gas flow to resonant perturbations was studied by Oster et al.[15] using a vibrating flap on the splitter plate and by Fielder et al.[16] using a loudspeaker radiating into the flowfield. The results they obtained demonstrated that such perturbations are indeed capable of modulating the process of vortex pairing.

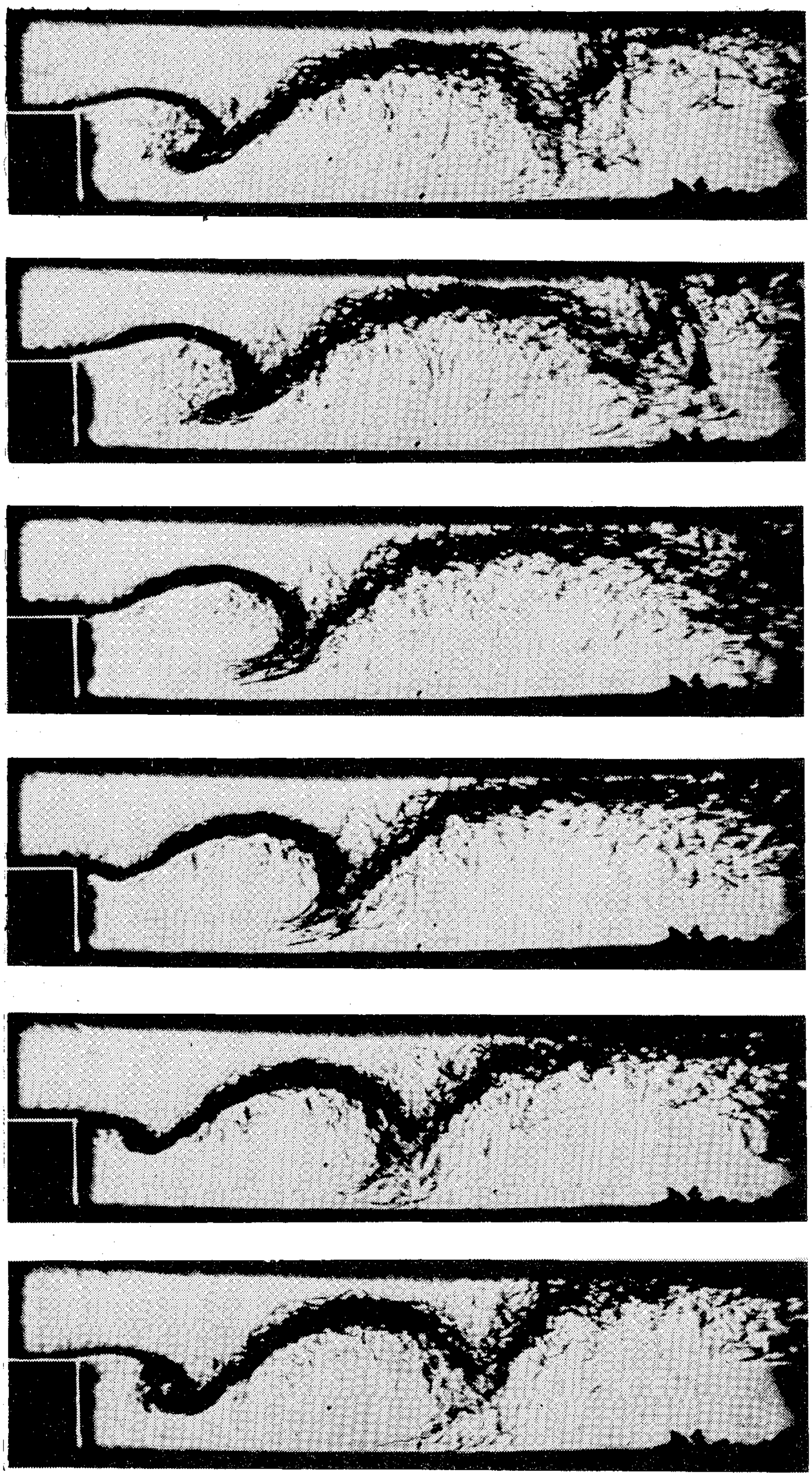

Fig. 6 Cinematographic schlieren record of humming (equivalence ratio, 0.86; time interval between frames, 1 ms).

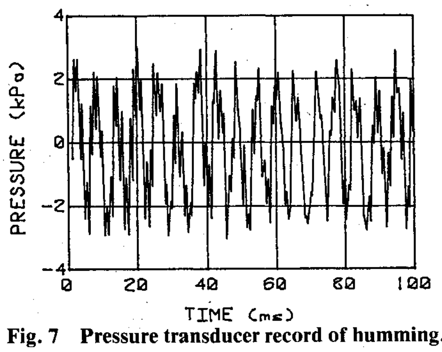

Fig. 7 Pressure transducer record of humming.

Humming

The unstable mode of combustion occurring first with the butterfly valve open was manifested by a loud humming sound. The fuel flow rate was for this purpose increased to yield an equivalence ratio of 0.86.

The mixing layer was then significantly enlarged and the vortex pattern was set into a long wavelength, as shown in Fig. 6. The corresponding pressure record (Fig. 7) displayed quite regular oscillations of a much larger amplitude than that of stable combustion. Its power spectrum revealed a pronounced single peak of high amplitude at a frequency of 175 Hz that evidently arose out of that recorded in the power

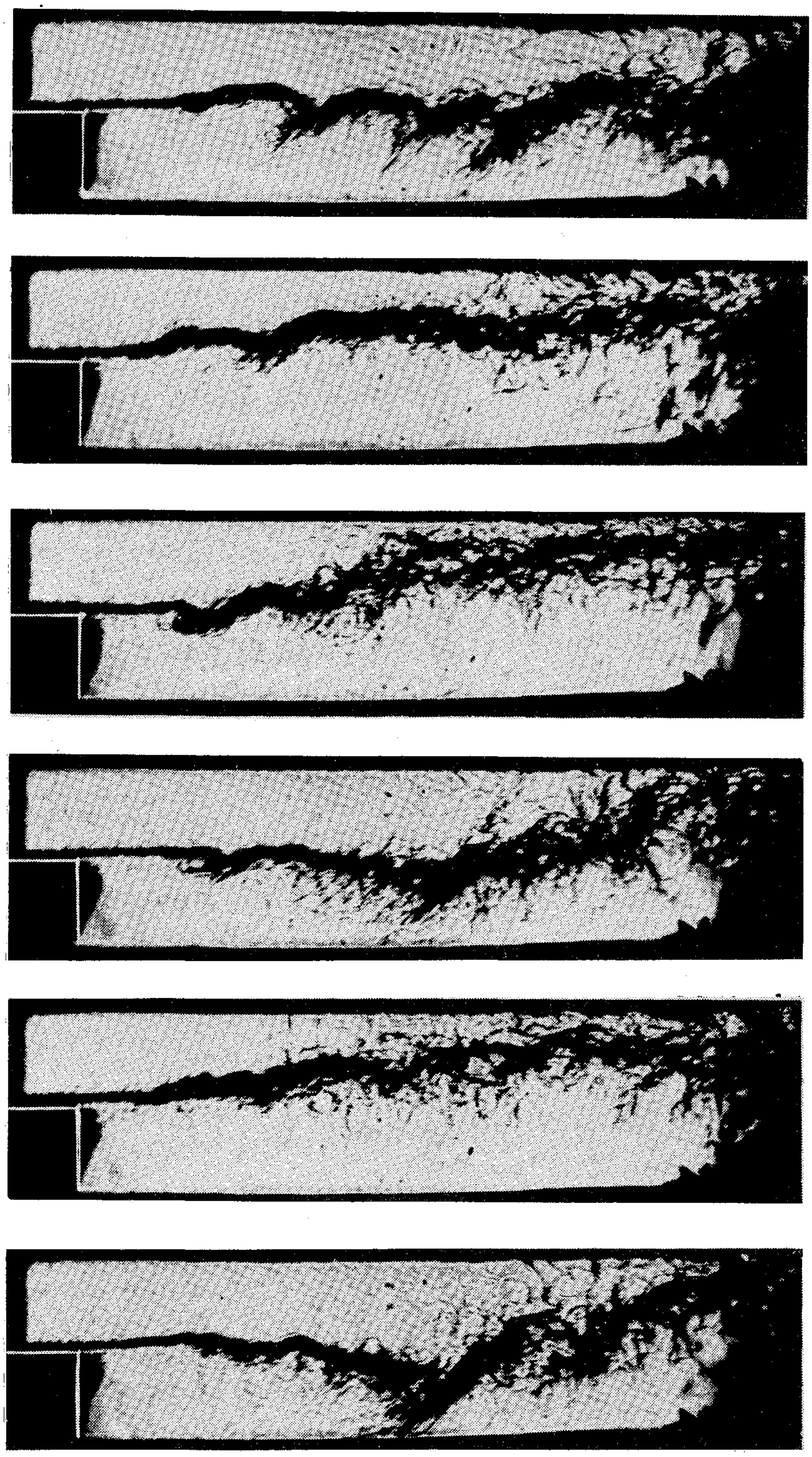

Fig. 8 Cinematographic schlieren record of buzzing (equivalence ratio, 0.80; time sequence of frames, 0, 8, 14, 22, 36, 48 ms).

spectrum for stable combustion at 160 Hz with a much smaller amplitude.

The augmentation in the amplitude of these oscillations suggests that humming is an instability modulated by acoustic feedback. It is therefore phenomenologically akin to that of an acoustically modulated stable combustion described above. By the same token, this mode of instability is, in effect, metastable in that it can be sustained for a long period of time.

Buzzing

When the butterfly valve was closed, increasing the pressure level in the combustor by about 10 mm of water, the unstable mode of combustion encountered first lead to a distinct buzzing noise at a much lower frequency than humming.

As revealed by the schlieren record displayed in Fig. 8, the trailing vortex pattern flattened out, stretching the flame and giving rise to its flapping up and down across the combustor. In contrast to the metastable behavior of humming, this instability was truly transient. It existed for a relatively short period of time and the structure of its flowfield was not exactly repeatable. Thus, in order to present its salient features, the frames for Fig. 7 were selected respectively at time intervals of 8, 14, 22, 36, and 48 ms, after the first, covering a range of almost three cycles.

The corresponding pressure record (Fig. 9) revealed a cyclic variation at a uniform frequency of 70 Hz, thus establishing a distinct tone for the noise produced by buzzing.

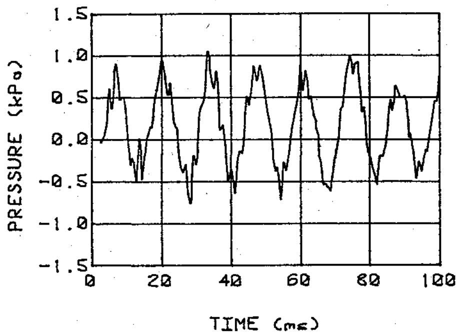

Fig. 9 Pressure transducer record of buzzing.

Chucking

As the transient process of buzzing progressed, the dip formed at the end of the first flame convolution became more and more pronounced, as evident in the fourth and sixth frames of Fig. 8. Eventually the formation of this dip took over and acquired a cyclic nature at a somewhat lower frequency. This mode of instability is referred to as chucking and a representative cycle of its flow structure is presented in Fig. 10. Its most characteristic feature was the formation of a flame tongue displayed in the third frame, as if it were spilled over the edge of the step. Associated with it was a vertical flame extending over the full cross section of the combustor and pushed downstream by the expanding tongue, as evident in the fourth frame.

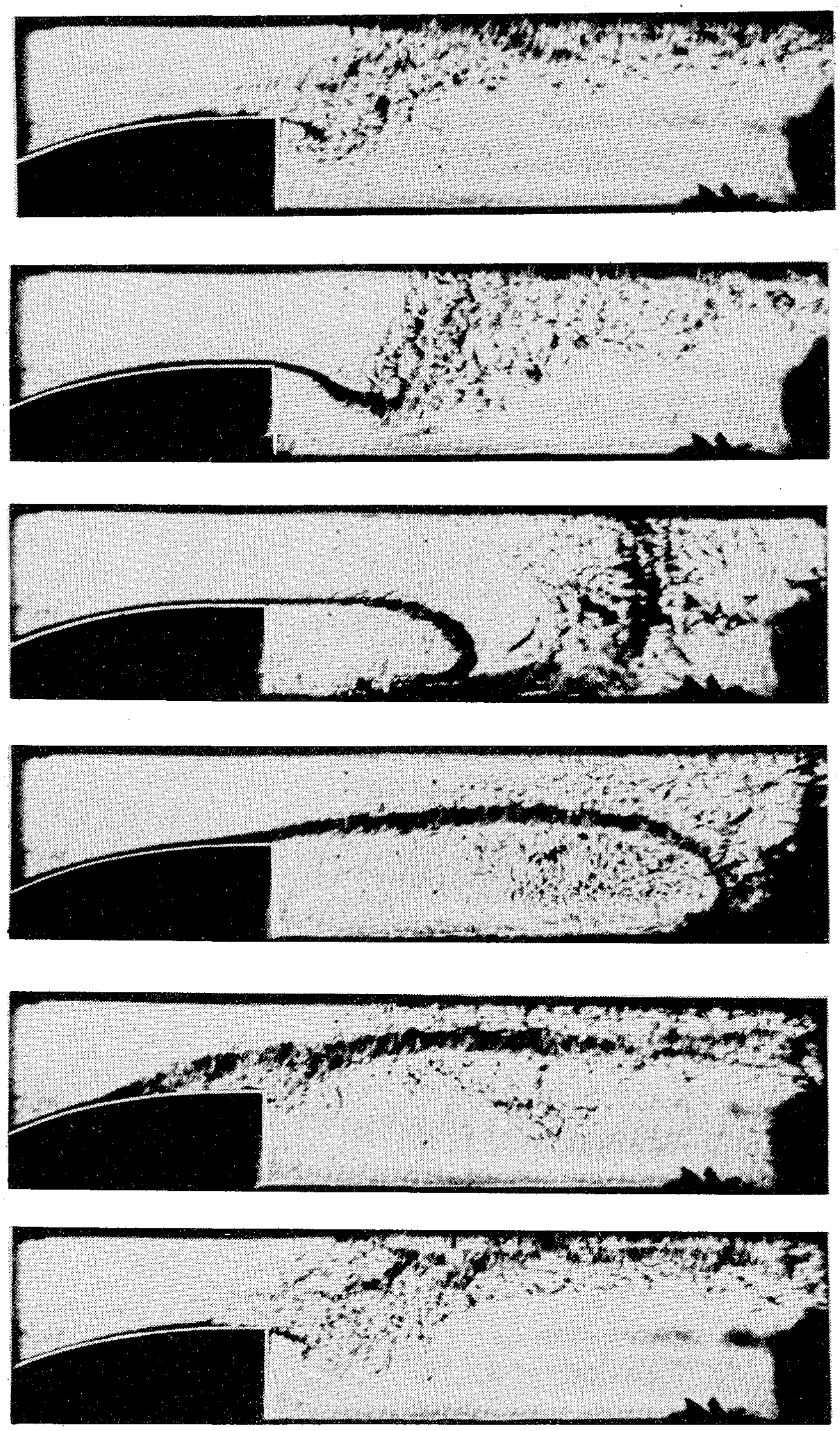

Fig. 10 Cinematographic schileren record of chucking (equivalence ratio, 0.85; time interval between frames, 4 ms).

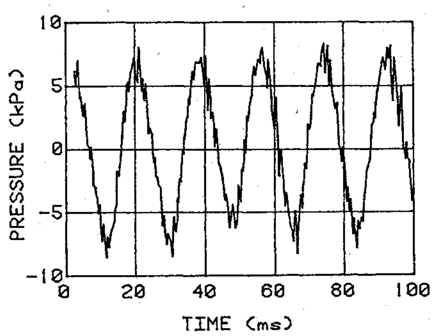

Fig. 11 Pressure transducer record of chucking.

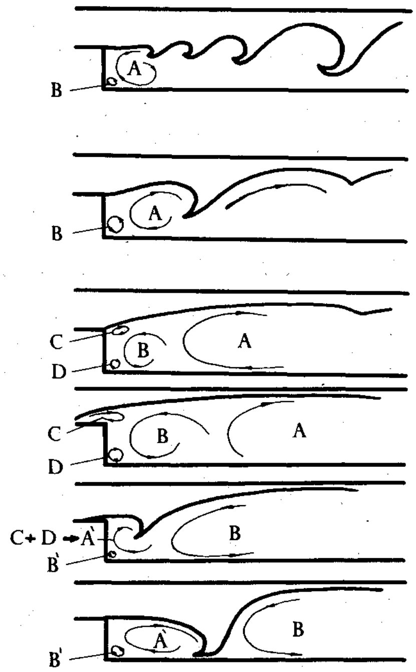

Fig. 12 Sketches of the interactions between the recirculation and trailing vortices deduced from schlieren records and numerical modeling analysis.

Initially the cyclic process involved the repetition of the flow structure depicted by the first four frames of Fig. 10, a mode that could settle down into a metastable state. In a transient mode, the extent of the flame tongue increased upward as it was turned at each cycle, leading eventually to flashback—the actual lifting of the flame from the edge of the step and its propagation upstream (as depicted in the fifth frame in Fig. 10). Upon a certain penetration into the incoming flow the upstream propagation of the flame terminated abruptly, giving rise to an augmented chucking cycle starting with a gradual reformation of the flame (as displayed in the last frame of Fig. 10).

The corresponding pressure record of chucking is given by Fig. 11. Its amplitude was much higher than that of buzzing, while the frequency was lower. The power spectrum revealed a single narrow band with a peak at 55 Hz. This corresponds to the frequency of the formation of a single vortex extending over a full length of the combustor (that is, 25 cm), while the average flow velocity causing its displacement is 6.65 m/s.

Interpretation

The instabilities in turbulent combustion of premixed gases stabilized by the base flow behind a bluff body are intimately related to large-scale structure of turbulent shear flow, a subject which today occupies a good deal of attention. Its prominent features were described by Roshko,[17] while those pertaining to the base flow behind a step, including in particular the effect of the recirculation zone, was investigated experimentally by Kim, Kline, and Johnston.[18] The turbulent flowfield behind the step (with and without combustion) under the same geometrical conditions as those of our experiments, were studied by Ghoniem, Chorin, and Oppenheim[19,20] using a numerical modeling technique due to Chorin (the random vortex method) that has been extended to include the effects of the exothermic process of combustion for this purpose.

Subsequently, this numerical technique has been used to study the nonstable processes reported here. Although final results are not yet available, we have been able to derive on this basis a conceptual interpretation of the flow pattern associated with the combustion instabilities reported here. For the sake of clarity, this is presented here in the simplest, highly idealized form, depicting the interaction between the recirculation vortices at the base of the step and the trailing vortices behind its edge that, in our opinion, governs the unstable processes leading to flashback.

This is illustrated in Fig. 12. Shown at the top is the trailing vortex pattern associated with stable combustion. Here, the flame front delineates the outer edges of the mixing layer at the contour of the interface between the burned gases and the fresh charge. Below (not detectable by schlieren optics) is the recirculation vortex A that is, as a rule, established behind the step, irrespective of whether the flowfield is associated with combustion or not. As pointed out by Kim et al.[18] and corroborated by us,[19,20] this gives rise to a counterrotating vortex B.

In the presence of combustion, when burned gases are produced both of these vortices grow, as shown in the second sketch of Fig. 12. The growing recirculation vortex of the burned gases causes vortex A to be pushed downstream (as shown in the third sketch), while vortex B increases in size. As a consequence of the counterclockwise circulation of this vortex, it must give rise to vortices C and D, as required by compatibility with flow of the fresh charge. When vortex B becomes larger (as shown in the fourth sketch), vortex C may be forced upstream, causing a flow reversal on top of the step, tripping the boundary layer, and pushing the flame upstream. In our opinion, this is the characteristic feature of the turbulent flashback we observed. The flame front is attached at its upstream edge of the boundary layer, but behind it is lifted from the wall by the action of vortex C.

As vortex B grows still further, it is convected downstream, while vortex C pairs with vortex D and forms a new vortex A′, and, concomitantly, a new corner vortex B′ (as shown in the fifth sketch). Finally, vortex A′ grows to a size comparable to that of vortex A and B′ to B (as in the second sketch). At the same time, vortex B is convected further downstream and the combined action of vortex A′ and B causes the flame to acquire a practically vertical orientation, extending across the full height of the combustor (as illustrated in the sixth sketch).

The first sketch in Fig. 12 was deduced from the results of the numerical modeling analysis for stable combustion. The acoustically modulated stable combustion bears a certain amount of resemblance, as it appears in Fig. 5, except that the vortex growth is evidently impaired. Their limiting size of about 7 cm indicated in Fig. 5 is indeed compatible with the average convective velocity of 6.65 m/s and the forcing frequency of 200 Hz. The second sketch in Fig. 12 illustrates the formation of the first vortex in humming displayed in Fig. 6. This is evidently due to the pairing of the recirculation vortex A with the first component of the set of trailing vortices. The next vortex downstream is in our opinion the result of the growth of vortex A in the course of its convection. The third sketch in Fig. 12 describes the reason for the flattening of the flame observed in buzzing (Fig. 8), the stretching due to the combined action of the counterrotating vortices A and B.

The convection of vortex B downstream ushers the pairing between vortices C and D, a relatively rapid process forming vortex A′ (as it appears in the last sketch of Fig. 12). The occurrence of this process does not have to be associated with the propagation of the flame upstream. Thus the repetition of the patterns depicted in the third and the sixth sketch represents the essential features of chucking. It is thus the fast pairing of vortices C and D that produces the pulsing motion of the flame tongue observed in schlieren cinematographic records. The sequence of events illustrated in the fourth and fifth sketches of Fig. 12 describes the augmented chucking associated with flashback, the eventual outcome of the combustion instabilities presented here.

Conclusions

Our studies lead to the following observations:

1) As a consequence of the relatively low normal burning velocity—20 cm/s vs 13 m/s of inlet flow velocity—the flame in premixed gases was oriented, in effect, along the interface between the burned and unburned medium. On the schlieren records it marked therefore the vortex contours between the cold mixture and the hot combustion products.

2) When the mixture was enriched by a step change in the flow rate of fuel, the combustion became unstable—a process manifested audibly by distinct noise.

3) Basic ingredients of combustion instabilities are present at stable operating conditions, when the noise level is relatively low.

4) The pattern of the flow phenomena associated with unstable combustion can be modulated by an acoustic field which may be either imposed by an outside source (such as a loudspeaker radiating sound into the combustion chamber at an appropriate frequency) or induced as a harmonic component of a standing wave when its pressure nodes are properly spaced—a process referred to as *humming*.

5) In the absence of acoustic effects, combustion instability is manifested by a traveling wave pattern of interacting vortices along the turbulent mixing zone. This leads to a flapping motion of the flame up and down across the combustion chamber, obliterating the trailing vortex pattern—a process referred to as *buzzing*.

6) Growth and convection of recirculating vortices associated with the process of pairing between their satellites causes a pulsing motion of the flame referred to as *chucking*.

7) Chucking, augmented by the action of a satellite vortex as it penetrates upstream, causing local flow reversal and tripping the boundary layer at the upper surface of the step, results in *flashback*.

Acknowledgments

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