SIXTH SYMPOSIUM
(INTERNATIONAL)
ON
COMBUSTION

Published for
THE COMBUSTION INSTITUTE

REINHOLD PUBLISHING CORPORATION
New York
CHAPMAN & HALL, Ltd., LONDON
A SHOCK-TUBE STUDY OF FLAME FRONT-PRESSURE WAVE INTERACTION

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Introduction

Many applications of combustion in a gaseous medium, and particularly those in jet and rocket propulsion, require burning rates far in excess of those corresponding to laminar flame propagation. It is generally recognized that these rates are achieved by the interaction of the flame with more or less random flow disturbances that are often somewhat loosely called "turbulence." Apparently because of this terminology, recent studies have concentrated on interactions of pipe flow or grid-generated turbulence with open or enclosed flames while, in comparison, the study of interactions with other kinds of flow disturbance has been neglected.

Linearized perturbation analysis has shown that in a flow devoid of rapid changes of average variables any random disturbance can be decomposed into three modes that are in first-order approximation independent of each other: namely, a vorticity mode (eddy turbulence), a pressure mode (random sound), and entropy spottiness. Whenever the average flow variables are subject to rapid changes, however, such as occur during passage through grids, shock waves, flame fronts, or changes of cross section of a duct, the three modes become strongly coupled in first order.

Thus, in a turbulent flame all three disturbance modes must be present. This may be of minor importance with open flames, since the pressure mode will be dissipated by sound radiating from the flame, and the entropy mode will appear only in the burned gases in the form of temperature and density fluctuations. In the case of flames enclosed in a duct, however, the pressure disturbances may become as significant as eddy turbulence, for the energy contained in pressure waves will in general become trapped in the various resonance modes of the duct. The combustion process in ducts is therefore generally accompanied by intense sound waves that may include random noise as well as resonance oscillations. Undoubtedly these pressure waves must affect the flame in various ways, but the nature of these interactions is at present ill understood.

The large majority of previous studies of pressure wave-flame front interactions was concerned with spontaneous generation of sound and vibrations by flames. A complete bibliography and adequate discussion of the numerous investigations in this field would be beyond the scope of this paper. Among their results, the following are of particular significance in relation to the present work:

(1) The rate of flame propagation in tubes during "vibratory movement" exceeds that during

18. VAN LINGEN: Physics, 1, 797 (1953).
"uniform movement" appreciably. This was observed in the earliest work on the phenomenon and confirmed in many subsequent studies.

(2) Both the amplitudes of the vibrations and the associated flame-propagation rates can be varied within wide ranges by terminating the open end of the flame tube with diaphragms of various diameters.

(3) During vibratory movement of moderate or large amplitude, flames undergo recurrent changes of structure.

Although the studies of spontaneous flame vibrations yielded these important results, the mechanism of the phenomena has remained somewhat obscure, and little quantitative information has been derived from them. One reason may be that, with any spontaneous phenomenon that is due to some feedback mechanism, it is difficult if not impossible to distinguish between causes and effects; another reason may lie in the complicated nature of the pressure and flow transients during large-amplitude vibratory movement.

It appears therefore desirable to study the effects of externally generated pressure disturbances of simple wave shape on flames propagating in tubes. Surprisingly, only one previous investigation of this type, in which sound waves were used as disturbance, appears to have been undertaken, with rather inconclusive results. In the present work the problem is attacked somewhat differently, by subjecting a flame to shock-wave disturbances. A brief account of preliminary work by this method has been published elsewhere. The design of the present apparatus does not permit the study of the interaction of a single shock wave with the flame, but rather that of a head-on collision between flame and shock wave followed by interaction with the wave transmitted by the flame and reflected at the bottom of the combustion chamber. Although this complicates the observed phenomena, it has the advantage of allowing the investigation of two different interactions in a single experiment. The technique appears adaptable for studying many other types of interactions with only minor modifications of apparatus.

Experimental

The apparatus is shown schematically in Figure 1. The shock tube consisted of a high-pressure chamber, a central portion, and a combustion chamber of the indicated lengths and of 3- by 3-in. internal cross section. It was mounted vertically, with the combustion chamber at the bottom, in order to avoid asymmetric flame shapes due to gravity effects.

Preceding each run, a diaphragm was inserted between the high-pressure chamber and the central portion, and clamped between the indicated O-rings by means of the threaded ring. The choice of diaphragm material depended on diaphragm pressure: up to about 7 psi one layer of cellophane was found to be suitable; from 7 to 15 psi two layers of cellophane were used; from 15 to 25 psi photographic film stock was best suited.

The combustion chamber was separated from the central portion by a thin collodion membrane held between two cork-rubber gaskets. The membranes were prepared by pouring a few drops of a commercially available collodion solution ("Testor's Microfilm") on water and, after evaporation of the solvent, lifting the film off with a wire frame. On the basis of interference colors the thickness of the membranes was estimated to be in the range of 300 to 600 μ. Although they were heavier than those employed in studies of refraction of shock waves at gaseous interfaces, their effect on the shock wave was considered negligible on the basis of results obtained by Jahn. Note that in the present work the mem-
brane breaks shortly after ignition and prior to passage of the shock wave, whereas in the interface study it is broken by the shock wave.

The combustion chamber was filled with combustible mixture by flushing it for at least 10 min. The flow entering and leaving through the valves indicated in Figure 1 had to be kept small in order to prevent the chamber pressure from rising more than a few inches of water above ambient pressure and causing rupture of the membrane. In the present work n-butane-air mixtures, mostly in stoichiometric proportion, were used. They were prepared by metering air and fuel separately with rotameters. In order to obtain accurate rotameter readings, the total flow had to be much larger than the portion used for flushing the combustion chamber. The excess was burned off on an auxiliary burner; the appearance of this flame provided a rough check on mixture composition. The small fraction of the flow used for filling the combustion chamber was metered by a third rotameter. Before closing the valves, the mixture escaping through the upper valve was tested by burning it on a small nozzle. The blowoff flow of this flame furnished a rather sensitive test of attainment of uniform and correct mixture composition in the chamber. The valves were then closed in succession by the indicated linkage, which was designed so that the outflow valve closed somewhat later than the inflow valve. Thus, the chamber pressure dropped to ambient pressure during this operation. Finally, compressed air was admitted to the high-pressure chamber. The pressure was preset with a regulator valve and measured with a precision gauge with an error of less than ±0.05 psi.

The cycle of operation of the device was initiated by igniting the combustible mixture with a spark plug located in the center of the bottom of the combustion chamber. In preliminary work, it had been found that in spite of the use of stoichiometric mixtures the initial flame surface was not free of some irregularities. Most of these could be eliminated by removing the grounded side electrode of the spark plug. A conventional 6-v battery ignition circuit was used. The instant of ignition was determined by a synchronous motor-driven multicam timer (Industrial Timer Corporation Type MC) that was started by the “Event” switch of the recording drum-camera. The timing accuracy of the 2-sec cycle timer used was about ±2 msec, sufficient to insure synchronization of the streak and oscillograph records.

In preliminary work, the time interval between ignition and rupture of the shock-tube diaphragm could not be varied at will, and was found to scatter also at least by ±2 msec. There were three independent sources for this scatter: variations (1) in the operation of a relay that served as ignition and shock-tube solenoid control, (2) in the operation of the solenoid, and (3) in the bulging of the diaphragm. It appeared impossible to eliminate this last cause of timing scatter entirely. Its influence was reduced appreciably, however, by increasing the acceleration of the diaphragm-piercing needle. This was achieved by energizing the solenoid, originally designed for 115-v ac operation, through the discharge of a 300-μF capacitor charged to 450 v. The instant at which this occurred was determined as follows: a voltage pulse from the ignition coil triggered one circuit in the twin thyratron unit (Fig. 1), the output pulse of this thyratron was fed into an electronic time-delay generator (Rutherford Model A-2) which, after a preset interval Δt, triggered a type 3022 thyratron that in turn discharged the capacitor through the solenoid. The time interval Δt was set at 15.0 msec for the majority of the runs discussed in the present paper.

A pressure transducer located 2.5 in. above the top of the combustion chamber served the dual purpose of measuring the time interval Δt between ignition and arrival of the shock wave at this transducer, and of timing the spark-light source. An electrokinetic transducer was used for this purpose; although its frequency response was inadequate for pressure recording in shock-tube work, its simplicity and large output made it ideally suited for triggering applications. The pulse from this transducer fired the other circuit of the twin thyratron unit. The output of this thyratron triggered the spark light-source after a time interval Δt provided by another electronic time-delay generator (Dumont Type 326).

By means of a selector switch, the proper starting and stopping pulses could be fed into an electronic time-interval meter (Berkeley Model 5510) for measuring any one of the intervals Δt, Δt, or Δt. The first two were preset before the runs, while the last one was measured during the experiments. The interval Δt was found to exceed Δt by about 8 msec, of which about 5 msec corresponded to the time the shock wave traveled...
from the diaphragm to the transducer, the rest of the interval between energizing the solenoid and breaking the diaphragm. For constant setting of $\Delta t$ and of diaphragm pressure, $\Delta t$ scattered by about $\pm 0.1$ msec. Since $\Delta t$ varied by only about $\pm 15$ usec, the scatter of $\Delta t$ was primarily due to variations of diaphragm bulging that affected the instant of its perforation by the needle. As the undisturbed flame traveled only about 0.1 in. in the interval of 0.2 msec, this unavoidable scatter was considered tolerable.

The interaction phenomenon was studied by means of spark schlieren photography, schlieren streak records, and by recording of pressure and flame-radiation transients. The conventional Z-type schlieren system indicated in the plan view at the bottom of Figure 1 consisted of two 12-in. diameter 5-ft focal-length parabolic mirrors and the usual prisms, slit and knife edge. Horizontal orientation of spark, slit and knife edge was used. The spark was triggered by an auxiliary "teaser" electrode connected to an induction coil that was energized by a thyratron-controlled condenser discharge. The delay between firing of the thyratron and of the spark was measured by means of a photoelectric cell with the time-interval meter. With correct polarity of the induction coil, this delay was found to be $7 \pm 1$ usec. In order to avoid fogging of the films by flame radiation, the camera shutter had to be operated at a short exposure synchronized with the spark. A shutter setting of $\frac{1}{250}$ sec was found to be satisfactory. Synchronization was achieved by means of a shutter solenoid operated by the multicam timer in the ignition control unit.

The schlieren photographs were taken through plate-glass windows that allowed a full view of the interior of the combustion chamber from the bottom to a height of 9.5 in. Details of the window design are shown in Figure 2. The glass plates were sealed into steel-window frames by means of Duco cement. The frames were designed so that a small gap remained between the glass and the body of the combustion chamber and thus no strain was exerted on the glass. The plates were not entirely free from striations that are faintly visible on the schlieren photographs shown below.

The streak records were taken on 70-mm film with a drum camera (Southern Instruments, Ltd. Model M-1020) that was modified by replacing its original lens with one of 9-in. focal length and by incorporating the solenoid-operated shutter. When a film speed of 50 ft/sec was used, a shutter setting of $\frac{1}{25}$ sec with proper synchronization of camera and shutter gave nonoverlapping records that included the instant of ignition, the interaction, and several returns of the shock wave owing to reflections at the ends of the tube. A 100-w zirconium arc light source was used with the schlieren system described above. The combustion-chamber window that faced the camera was blocked except for a central vertical slot of $\frac{1}{16}$-in. width. A time base was provided by means of a flash tube (Sylvania type R1130B) operated at 10,000 pulses/sec.

Pressure transients were recorded by means of two condenser-type transducers (Rutishauser pickup Model HR-3 and electronic indicator Type ST-12) located 0.5 in. above the bottom and 2.0 in. below the top of the combustion chamber, respectively. Flame radiation in a direction normal to the shock-tube axis was collected by one of the schlieren mirrors and was recorded with a type 931A photo-multiplier placed at the mirror focus. The combustion-chamber window facing the other mirror was blocked with white cardboard in these runs. The previously mentioned drum camera, with its original lens of 3-in. focal length, and two dual-beam oscilloscopes (Dumont Model 322A) were used for recording the transients. The scopes were arranged at right angles to each other and the four traces were displayed simultaneously by means of an optical beam splitter. The fourth channel provided a 0.1-msec time base. No special provision was necessary for recording the instant of ignition, since the photo-multiplier...
trace recorded a strong deflection at this instant, owing to pickup of a voltage pulse by this high-impedance device. A film speed of 50 ft/sec was used.

Results and Discussion

SPARK SCHLIEREN PHOTOGRAPHS

The early stages of the interaction between a stoichiometric butane-air flame and a shock wave of pressure ratio 1.3 are shown in Figure 3. The photograph to the left shows the flame a few μsec before the start of interaction. The origin of the time scale used in this and the following figures was arbitrarily selected as the instant of this first photograph. The times referred to in the following photographs were obtained from their respective Δt settings by subtracting that for the first photograph: 0.6 msec. The time elapsed between ignition and the origin of the time scale was thus Δt + 0.6 msec, or 23.6 ± 0.1 msec for this series of runs.

The major portion of the flame surface shown in the first photograph is devoid of any irregularities. As mentioned before, this was achieved by removing the side electrode of the spark plug. The origin of the remaining distortions near the bottom of the combustion chamber is obscure but, since their shape recurred in many of these photographs, they were presumably caused by minor irregularities of the bottom of the combustion chamber. The shock wave, and weak secondary waves originating at the junction of the combustion chamber and the central portion of the shock tube, are visible above the flame.

The second photograph shows the incident shock wave intersecting the flame, and the rarefaction wave reflected by the flame. The transmitted shock wave is only very faintly visible on the original photograph and therefore has been traced by a dashed line. A phenomenon related to irregular refraction of shock waves at interfaces takes place at the outer portion of the flame that is steeply inclined with respect to the shock wave. Owing to the high speed of sound in the burned gas, the transmitted shock wave coming from the central portion of the flame has here propagated ahead of the intersection between incident shock and flame and created a retransmitted wave in the unburned gas that is well visible in the photograph.

The third photograph shows a somewhat later stage. The incident shock in the unburned gas surrounding the flame and the reflected rarefaction wave are still visible, but the transmitted shock is not discernible in this photograph or any others that were taken during this stage of the interaction. The complicated pattern of waves visible above the flame results from multiple reflections of the rarefaction wave at the walls and at the flame front.

Up to this point the interaction has proceeded as one would expect on the basis of theoretical considerations: essentially, the flame has acted like a contact surface separating unburned and
burned gases. Figure 4 shows the beginning of a new stage of the interaction phenomenon that starts in the photograph to the left with the formation of a smooth indentation in the center of the flame. At the same time a dark band, indicating an upward-propagating compression wave, appears just above the flame. The streak records discussed below showed that this wave is identical with the shock wave transmitted by the flame and reflected at the bottom of the combustion chamber. Its appearance as a broad band is presumably due to distortion of its shape owing to the two interactions with the curved flame surface.

ever, in view of the impulsive acceleration of very short duration associated with passage of a shock wave, the concept of Taylor instability may have to be modified considerably. Constant acceleration acting on a slightly wavy contact surface (or flame front) creates positive or negative restoring forces, depending on whether it acts in the stabilizing or unstabilizing direction. If, however, the acceleration acts only during a very short time interval, these forces will be of equally short duration and will thus create flow velocities that later on persist with little change. One may thus conclude that in this case the interface distortions will grow approximately linearly with time after the interaction, regardless of the direction of passage of the shock wave. The final deformations will be in the opposite or in the same direction as the initial ones, depending on whether the acceleration was “stabilizing” or “unstabilizing” in the Taylor sense.

The conclusions of this conjecture seem to be well borne out by the results of the present study. The incident shock wave accelerates the flame in the “stabilizing” direction and causes an indentation in the center of the flame front, thereby reversing its original shape. The transmitted wave, after reflection at the bottom of the chamber, traverses the flame at a time when this indentation has just started to form. Since this wave accelerates the flame in the “unstabilizing” direction, it enhances the indentation, causing its transformation into a spike.

SeveraI additional features of interest can be seen in Figures 4 and 5. The tip of the spike is seen to detach from the stem and to broaden into a cap. Figure 5 shows that the edge of this cap begins to shed a fine-grained trail. The surface of the stem, which initially remains smooth, begins to fold about 0.8 msec after the start of interaction; in the last photograph of Figure 5 it looks like the typical schlieren image of a turbulent flame. The flattening of the tip and the disintegration of the surface of the spike have been discussed in connection with Taylor instability. The formation of the spike and the roughening of its surface must be accompanied by an increase of flame surface area and thus of instantaneous volumetric rate of burning. This should cause emission of compression waves by the flame, and indeed the photographs show a second dark band emerging from the flame at 0.5 msec. At 0.8 msec, the first shock wave, visible below the top of the photograph, has straightened, the second wave is
seen below, and several weak additional compression waves can be seen closer to the flame.

The irregular disturbance visible near the top of the photographs of Figure 5 is the contact surface between air and combustible mixture that also contains fragments of the membrane that initially separated these gases. This interface at first moves upward after ignition, but later is pushed down by the incident shock wave and the reflected rarefaction wave, comes into the field of view, and finally moves up again under the influence of the upward-propagating compression waves.

The final stages of the interaction are shown in Figure 6. The inversion of the flame into a deeply drawn-out funnel is seen to persist, accompanied by further development of turbulent flame structure. Very fine-grained structure appears to develop near the bottom of the combustion chamber, presumably owing to the impact of the spike at the bottom, which seems to set up a circulation outward along the bottom, upward along the walls and down again in the center. The structure of the flame gradually becomes coarser, and the last photograph shows that the leading edge of the flame has become essentially laminar, consisting of four lobes that move up along the walls of the chamber. The changes of flame structure that occur during this final stage of the phenomenon are rather gradual, and for this reason no further emission of pressure waves by the flame can be detected on the photographs.

The interaction of a stoichiometric butane-air flame with a stronger shock wave of pressure ratio 1.6 is shown in Figures 7, 8, and 9. The first photograph differs little from the analogous one in Figure 3, except that the transmitted wave is better visible for this stronger shock. The following three photographs show that the formation of the spike occurs more rapidly for the stronger shock wave. A very fine-grained structure appears early in the process, and throughout the later stages the flame appears more highly turbulent than for the weaker shock wave. The compression waves emitted by the flame are seen to steepen more rapidly into shock waves; the last photograph of Figure 8, for instance, shows two fully developed shock waves near the top, followed by another steep compression wave and several weaker waves.

The last photograph of Figure 9, taken 5.4 msec after the beginning of interaction, shows, in addition to the strong density gradients of the turbulent flame funnel, some weaker gradients in the burned gas. In earlier work, using high-speed motion pictures,\(^1\) it was observed that these gradients persist for an appreciable time after burning has ceased. Thus they are of the nature of entropy spottiness left behind by the turbulent flame.

A series of photographs was also taken of the interaction of a rich butane-air flame, of equivalence ratio 1.38, and a shock wave of pressure...
ratio 1.3. Despite the cellular structure of the undisturbed flame, the interaction was found to proceed very similarly to that of the stoichiometric flame. The later stages, in particular, starting or periodic formation of spikes of unburned gas penetrating into the burned gas, has been described by various authors. The increase of average flame-propagation rate during vibratory movement is understandable on the basis of the periodic formation of turbulent flame funnels, and the emission of secondary compression waves by the flame provides the driving mechanism. Note also that the vibration-induced cell structure which occurs during vibratory movement of small amplitude may be regarded as a periodic inversion of flame cells, and its analysis as a generalization of Taylor instability.

**STREAK RECORDS**

While the interaction phenomenon can be understood only on the basis of its three-dimensional nature revealed by the spark photographs, a quantitative analysis useful for application of the wave-diagram method to combustion phenomena in nonsteady compressible flow must necessarily replace the problem by an equivalent one-dimensional description. Therefore, the derivation of equivalent one-dimensional boundary conditions for pressure-wave reflection and transmission at a flame front will be a primary aim of future work using the techniques described in the present paper. In addition to the pressure and radiation records discussed below, experimentally derived wave diagrams will be required for this purpose. Simplified and approximate wave diagrams can be constructed from the spark photographs. As an example, the diagram for interaction of a stoichiometric butane-air flame with a shock wave of pressure ratio 1.3 is shown in Figure 10; the appearance of the photographs at several stages is sketched in the lower part of the figure.

More complete and accurate wave diagrams that can be evaluated in terms of wave and particle velocities were obtained by means of streak records; three of these are shown in Figure 11. The main features of these records can be readily identified by comparison with Figure 10. The incident shock wave, the reflected rarefaction wave, the flame front and its gradual transformation into a turbulent burning zone, and the compression waves emerging from the flame during and after interaction are clearly discernible. The transmitted shock wave and its reflection from the bottom of the combustion chamber were again only rather faintly visible on the original records, and were therefore traced as dashed...
For interaction with $\Delta t_1 = 20.0$ msec, as mentioned earlier, the flame indentation can be seen to occur before the return of the transmitted shock wave to the flame front.

A feature that was not included in Figure 10 is the contact region between unburned mixture and air, that shows up as a broad band in the upper parts of the top and bottom records of Figure 11. The slope of this band yields the particle velocity in the contact region. Particle paths are also visible more faintly in the unburned gas following the interaction, presumably owing to slight density spotiness caused by the intersecting waves. Weak waves propagating in either direction can also be seen in this region, so that all three characteristics are visible there. Some of the faint lines, however, are due to oblique secondary waves; since their slopes do not correspond to true wave speeds, they must be avoided in the evaluation of the records.

The very prominent streaks in the turbulent flame zone indicate the movement of burning gas particles. Near the bottom of the combustion chamber two diagonally intersecting systems of streaks are visible, confirming the formation of a circulation after impingement of the spike at the bottom.

Evaluation of the records showed, in general, good agreement with theoretically expected wave speeds and particle velocities. The measured speeds of the incident and the transmitted shock waves were used for computing the ratio $T_b/T_u$ of the absolute temperatures of burned and unburned gases in the following manner. The shock-pressure ratio and thus the Mach number of the incident wave was known and was further checked by the measured particle velocity behind the shock. A trial pressure ratio of the transmitted shock wave was calculated from the relation for transmission of a weak wave, using an assumed value for $T_b/T_u$. From the known wave speed in the burned gas and this pressure ratio, a value of $T_b/T_u$ was obtained and was used for improving the calculation of the pressure ratio. This iteration converged very rapidly; the final values of $T_b/T_u$ obtained from several records were all in the range between 7.0 and 7.5—the latter corresponding closely to adiabatic flame temperature of a stoichiometric butane-air mixture.

For as yet undetermined reasons, the particle velocity behind the reflected rarefaction wave, as well as the pressure change across this wave, as measured on the oscillographic records (see below) corresponded to appreciably lower temperature ratios. Early emission by the flame of compression waves that weakened the rarefaction wave may have been the cause of this discrepancy.

![Fig. 10. Simplified wave diagram of interaction between stoichiometric butane-air flame and shock wave of pressure ratio 1:3.](image)

![Fig. 11. Streak records of interaction between stoichiometric butane-air flames and shock waves. Top: shock pressure ratio 1.3, $\Delta t_1 = 1.50$ msec; center: shock pressure ratio 1.3, $\Delta t_1 = 20.0$ msec; bottom: shock pressure ratio 1.6, $\Delta t_1 = 15.0$ msec.](image)

It seemed of particular interest to compare the measured velocity of downward motion of the tip of the spike with the computed particle velocity in the burned gas behind the transmitted shock wave. For an incident shock wave of pressure ratio 1.3, the spike velocity was found to be about 510 ft/sec, while the particle velocity
should be only about 320 ft/sec. Similarly, for a shock-pressure ratio of 1.6, the spike velocity was 980 ft/sec compared with a theoretical particle velocity of 640 ft/sec. These results show clearly that the interaction generated a circulation, downward in the center and upward near the walls, that was superimposed on the flow calculated on the basis of one-dimensional theory, and further confirm the mechanism of modified Taylor instability discussed earlier.

PRESSURE AND RADIATION TRANSIENTS

A portion of a drum-camera record of flame radiation and pressure transients during interaction of a stoichiometric butane-air flame with a shock wave of pressure ratio 1.3 is shown in Figure 12. The upper pressure trace, taken with the transducer placed 2.0 inches below the top of the combustion chamber, shows the arrival of the incident shock wave, which occurred 23.2 msec after ignition, followed by an interval of constant pressure of 0.7 msec in duration. This is followed by the rarefaction wave reflected by the flame, the transmitted wave and, finally, the secondary compression waves emitted by the flame. The times of arrival of these waves agree well with those derived from the spark photographs and streak records, as can be verified by drawing a horizontal line at the location of the transducer through the wave diagrams (Figs. 10 and 11). The lower trace, corresponding to the pressure 0.5 in. above the bottom of the combustion chamber, shows the arrival of the transmitted shock wave followed by a succession of compression waves.

The information that may be of greatest interest is the excess pressure rise owing to the combustion process. Both traces show a slight rise preceding interaction. The maxima of both traces exceed the diaphragm pressure of 10 psi by about 3 psi. Detailed evaluation and interpretation of pressure records taken under various conditions, for the purpose of obtaining equivalent one-dimensional boundary conditions at the flame front, will be carried out as a separate investigation by Dr. G. Rudinger of this Laboratory.

It appeared desirable to obtain some measure of instantaneous volumetric burning rate, independently from the information that may be derivable from pressure records and experimental wave diagrams. For this purpose, flame-radiation records were taken simultaneously with the pressure records. It is realized that radiation may depend on other variables besides burning rate. At least one influence, that of changes of flame structure owing to turbulence, appears to be negligible. The effect of pressure on flame radiation apparently has not been studied adequately in the pressure range of interest in the present work.

The radiation transient shown in the top trace of Figure 11 shows an initial rise preceding interaction, followed by a steeper approximately linear rise that finally tapers off to a maximum. The steeper rise starts 23.5 msec after ignition, i.e., at the beginning of interaction, and the maximum occurs about 3.7 msec later. Neither the passage of the incident shock wave nor that of the transmitted wave reflected from the bottom seems to cause any sudden changes of flame radiation, and one may thus conclude that direct effects of pressure on radiation were not significant.

Thus, the radiation transient would seem to yield at least an approximate measure of instantaneous volumetric burning rate. Insofar as this interpretation may be correct, the result agrees with that of the spark photographs, which showed the gradual formation of a turbulent flame funnel after the shock waves had traversed the flame. The maximum of radiation occurred before the flame began to move upward beyond the edge of the window, and may thus indicate the beginning of decay of flame turbulence. The last photograph in Figure 6, taken at a time beyond the maximum, indeed shows reappearance of laminar structure in a portion of the flame.

A series of records of interactions between stoichiometric butane-air flames and shock waves of various pressure ratios was taken. There was some doubt whether the time interval between ignition and arrival of the shock wave at the flame may have an appreciable effect on the
course of interaction. An auxiliary series was therefore first taken, for which the pressure ratio, 1.3, was held constant while the time interval \(\Delta t\) was varied from 13.0 to 17.0 msec. No significant changes of the radiation records could be detected over this range. In the series with varying pressure ratio, \(\Delta t\) was adjusted in such a way that the interval \(\Delta t\) remained constant at 23.0 \pm 0.1 msec.

The results of these runs are shown in Figure 13. A comparison run taken with flame alone is also included. The rate of rise of the radiation after the start of interaction, as well as the maximum radiation is seen to increase with increasing shock pressure ratio, while the time required for reaching the maximum decreases. Unfortunately, the maxima for flame alone and for shock-pressure ratio 1.15 occurred so late that the flame may have moved partly beyond the edge of the window, and their significance is therefore doubtful. An attempt was made to overcome this difficulty by collecting the radiation by means of a bore-sight prism inserted into the shock tube in the vicinity of the diaphragm, but this method gave unsatisfactory results and was abandoned. The ratio of the maximum radiation to the radiation emitted by the flame in the comparison run without shock-wave interaction at the same instant after ignition may be regarded as a measure of the effect of the shock wave on burning rate. Figure 14 shows a plot of this ratio as a function of shock-pressure ratio.

**Summary and Conclusion**

The interaction of initially laminar stoichiometric butane-air flames with shock waves of several pressure ratios has been investigated. Schlieren spark photographs and streak records showed that reflection and transmission of the incident shock wave coming from the side of the unburned gas initially took place according to theoretical expectation. Later on, however, interaction of the flame with the incident wave and with the wave transmitted by the flame and reflected at the bottom of the combustion chamber led to formation of a spike of unburned gas that penetrated rapidly into the burned gas. The resulting inverted flame assumed a turbulent structure that persisted for several msec after the wave interaction. The mechanism responsible for flame inversion has been tentatively identified with a modified version of Taylor instability.

Transients of pressure near the bottom and the top of the combustion chamber, and of flame radiation, were recorded. Detailed evaluation of these records in terms of equivalent one-dimensional boundary conditions at the flame front has not yet been carried out. The radiation transients showed gradual increases during and after wave interaction of stoichiometric butane-air flames with shock waves of various pressure ratios.

![Fig. 13. Flame radiation transients during interaction of stoichiometric butane-air flames with shock waves of various pressure ratios.](image)

![Fig. 14. Ratio of maximum flame radiation to radiation emitted by flame without shock wave interaction at the same instant after ignition.](image)
interaction leading to maxima that depended on shock-pressure ratio. The absence of abrupt changes of radiation during passage of the shock waves through the flame led to the conclusion that the radiation may be regarded at least as a rough measure of instantaneous burning rate. For the strongest shock wave of pressure ratio 1.6 that was used, the radiation maximum was 9.6 times larger than the radiation emitted by the flame without wave interaction at the same instant after ignition.

Acknowledgments

The author is greatly indebted to Dr. G. Rudinger for many valuable suggestions and discussions, and to Messrs. L. M. Somers and R. Phibbs for assistance in the design and construction of apparatus and in the performance of the experiments. In earlier work, Mr. D. Schwartz provided valuable assistance.

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COMBUSTION STUDIES IN A STIRRED REACTOR

By H. C. HOTTEL, G. C. WILLIAMS AND M. L. BAKER*

The study of intense mixing as applied to combustion has a two-fold significance: (a) all high-output combustion systems give evidence of dependence on the principle of quickening the reaction of the components of the feed by mixing them with hot products, and (b) the combustion rates attained in some of these systems are so high as to indicate that they can be and in some cases are chemically limited. The studies reported here were made to compare—under conditions of as intense mixing of premixed entering fuel and air with their products of combustion as appeared feasible to attain—the combustion rates of two fuels differing in chemical structure but identical in molecular weight and atomic composition and, after adiabatic combustion to equilibrium, iden-
COMBUSTION STUDIES IN A STIRRED REACTOR

...tional in all properties. Secondary objectives were the examination of the effects of varying the feed-hole size to vary the mixing, and the determination of reaction order.

The principle of evaluating chemical rate-controlling processes in combustion by feeding a well-stirred system to the quench-point was first applied by Longwell and Weiss, who employed a spherical reactor to which a homogeneous fuel-air mixture was admitted through a central feed source and from which reaction products left through outlet holes on the external surface of the combustion chamber. The method appeared to have great potentialities for establishing the significance of any chemical limitations on combustion, and the present authors have employed a quite similar device. The principle on which the method is dependent will be reviewed briefly.

If the combustion is controlled by chemical kinetics, the rate of combustion of fuel \( yN_F \) (where \( N_F \) is the molar fuel feed rate and \( y \) is the fraction consumed by combustion) may be tentatively described by the following equation:

\[
yN_F = ke^{-\frac{E}{RT}}Vc_Fc_O^\beta
\]  

where \( V \) is the reactor volume and \( c_F \) and \( c_O \) are the concentrations of fuel and oxygen, respectively.

The assumptions that the reaction is of order \( \alpha \) in fuel and \( \beta \) in oxygen and involves no intermediates and that the effect of temperature can be allowed for by the conventional Arrhenius expression may appear naive; they should be considered at this point heuristic assumptions, justified if they correlate the data. Accordingly, the constants, \( E \) and \( k \), should not be given the significance "activation" energy and "collision factor" which they have in describing a single chemical act; but they would have fundamental significance if one reaction in the combustion process were much slower than all the rest. In general, these terms refer to a "gross chemical change" which may take place in a great number of steps.

If the perfect gas laws are used in order to replace \( c_F \) and \( c_O \) by \( f_F \) \((P/RT)\) and \( f_O \) \((P/RT)\) where \( f \) represents mole fraction, Equation (1) becomes

\[
yN_F = ke^{-\frac{E}{RT}}Vf_Ff_O^{\beta}(P/RT)^{\alpha-\beta}
\]  

(2)

If it is assumed for simplicity that the temperature attained and the gas composition are unique functions of \( y \), the fraction reacted, then \( y \), \( f_F \) and \( f_O \) may be calculated from an energy balance as a function of temperature and fuel-air ratio, \( \phi \); and Equation (2) becomes, after substituting \( n \) (the reaction order) for \( (\alpha + \beta) \)

\[
N_F/kP^nV = d(E, T, \phi, \beta, n - \alpha) \tag{3}
\]

Typical plots of temperature versus the group, \( N_F/kP^nV \) for a fixed value of \( \phi \), for \( \alpha = 1 \) and \( n = 2 \) and for two assumed values of activation energy, \( E \), are presented in Figure 1. For reactions with low values of activation energy the operating characteristics of a completely stirred reactor would conform to Curve B. For highly exothermic reactions of high activation energy, i.e., for combustion processes, the reactor follows Curve A, with its stable branch (heavy line), its unstable branch or ignition condition (lighter line), and its bottom branch, numerically indistinguishable from the x-axis unless preheat is high, and following from the form of rate equation used, predicting a finite reaction rate at any temperature above zero. The fact that blowout occurs at point x allows inferences concerning reaction rates and reaction kinetics to be made from experiments on blowout in stirred reactors, since \( N_F/Vp^n \) at blowout becomes a unique function of air-fuel ratio of a form dependent on the postulated mechanism.

![Figure 1: Characteristic curves of temperature vs generalized rate for well-stirred reactors](attachment:image.png)