EXPERIMENTS CONCERNING THE MECHANISM OF FLAME BLOWOFF FROM BLUFF BODIES

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INTRODUCTION

The general problem of flame stabilization on bluff objects centers about the determination of the maximum stream velocity at which stable combustion may be achieved for various flame holder geometries, gas mixtures and conditions of the approaching combustible stream. Since the process involves both gas dynamic problems and chemical kinetic problems of great complexity, the most reasonable approach is one of similarity, that is, to determine under what conditions the behavior of one flame holder is similar to the behavior of another one. Because a very large number of physical and chemical variables is involved in a combustion problem, similarity conditions can be formulated most easily after experimental investigations have indicated which parameters or groups exert little influence on the mechanism and hence may be neglected. The experiments described in this paper were conducted with the object of clarifying the role of the more important parameters in the flame holding mechanism. The results indicate that a relatively simple formulation of the similarity conditions may be obtained in which the fluid mechanical parameters and chemical parameters are effectively separated.

EQUIPMENT AND INITIAL EXPERIMENTS

The present experiments as well as the previous investigations described in references 1 and 2 were performed using a rectangular combustion chamber of 2″ x 4″ cross section. A photograph of the test chamber is shown in Figure 1. The flame holders used spanned the two-inch dimension and were located very near to the combustion chamber inlet. A homogeneous mixture of gasoline vapor and air entered the combustion chamber from a large plenum chamber through a nozzle of 20:1 contraction ratio. The gas stream entering the combustion chamber presented a uniform velocity profile and was of very low but unknown turbulence level. The mixture temperature was controlled by a heat exchanger located upstream of the plenum chamber and the temperature of gas entering the combustion chamber was, in general, maintained at 150° F. The combustion chamber was short, extending only seven inches beyond the flame holder in order to avoid complications associated with interaction between flame front and combustion chamber wall. The chamber and the flame holders were water cooled to maintain them at approximately the temperature of the approach air stream. Vycor glass windows in the duct, as seen in Figure 1, made it possible both to observe and photograph the flame details from top and side views. These two possible photographic lines of sight are illustrated schematically in Figure 2. The fuel employed in all experiments was a hydrocarbon solvent, supplied in remarkably constant composition, containing approximately 30% naphthalenes, 65% paraffins and 5% aromatics.

Early investigations of the flame stabilization problem, e.g. references 3 and 4, concentrated attention on blowoff speed, that is the maximum gas speed

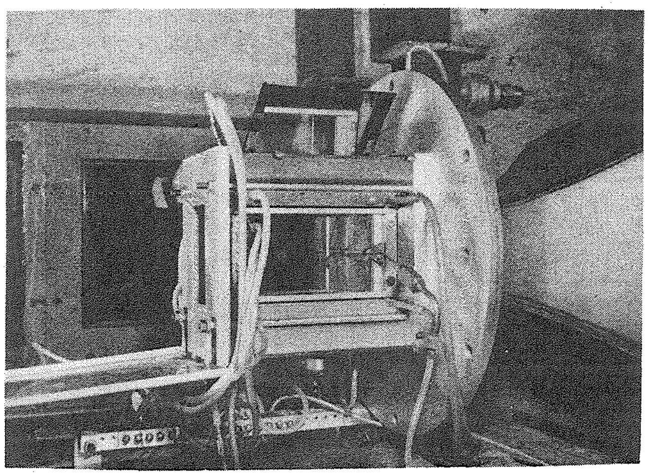

Figure 1. Photograph of combustion chamber and flame holder.

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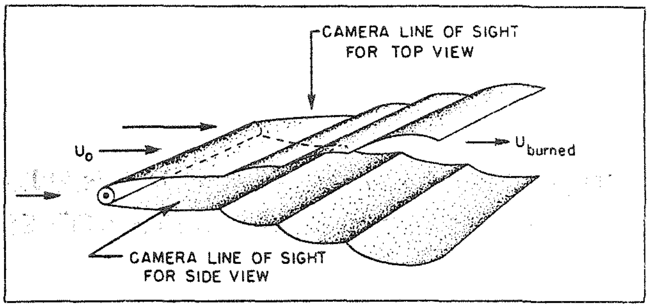


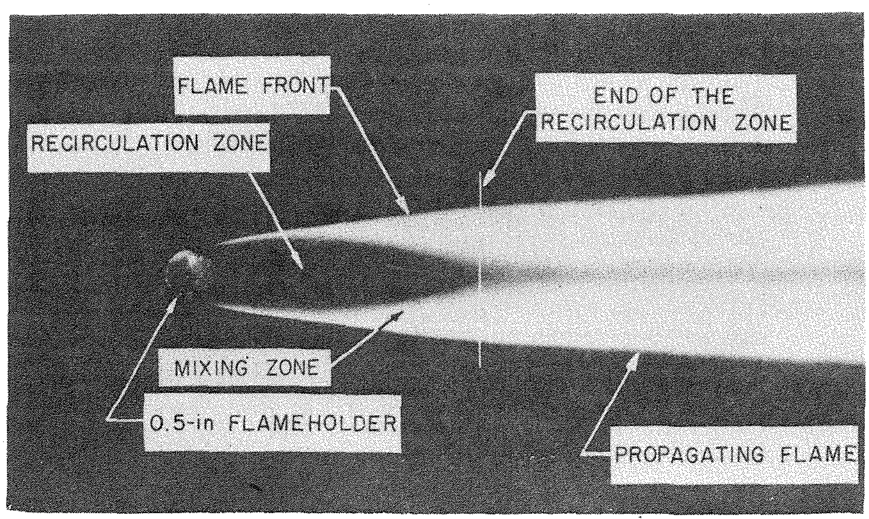
Figure 2. Schematic diagram indicating two photographic lines of sight

at which a given flame holder can support a flame in a stream of particular temperature and mixture ratio. A side view of a flame stabilized on a circular rod is shown in Figure 3. The dependence of such blowoff limits upon flame holder geometry, mixture ratio and temperature of the gas stream, and ambient pressure is quite complex and not at all transparent in the light of fluid mechanical and chemical fundamentals. This rather unsettled state of affairs was quite well described by J. P. Longwell in reference 5 where he showed the difficulties encountered in attempting to form a consistent picture from the information then available. A step in clarifying the situation occurred when detailed observations of the structure of stabilized flames, references 1 and 2, carried out in the present apparatus, revealed a transition phenomenon in the wake of the bluff body. Schlieren photographs of the flame surface, taken from the top view as shown in Figure 2, showed that as the Reynolds Number of the flow was increased, transition in the shear zone between wake and free stream moved from a point far downstream toward the separation point on the cylinder. This transition from laminar to turbulent shear zone is clearly illustrated by the sequence of schlieren photographs shown in Figure 4. The phenomen is similar when combustion is not present and was investigated, apparently for the first time, by L. von Schiller and W. Linke, reference 6. Now since the transport processes between the hot wake and the free stream are of prime importance in flame stabilization, it is to be expected that blowoff limits should behave differently for Reynolds Numbers below or above transition. As a result of this fact, discussed at length in reference 2, the present treatment is restricted to Reynolds Number values above transition, which is of somewhat more practical interest than low Reynolds Numbers.

GEOMETRY OF THE RECIRCULATING ZONE

It has often been conjectured, e.g. reference 3, that a more or less stable "recirculating zone" of combustion products exists in the flame holder wake immediately downstream of the flame holder. It was also supposed that this recirculation zone served as a source of heat and active chemical constituents to ignite the free stream flowing over it. The area of the recirculation zone, as it appears to the eye, is shown in Figure 3. Some exploratory work on the flow in the wake was performed by H. M. Nicholson and J. P. Fields, reference 7, using the characteristic light emitted by sodium vapor as a tracer. In the present experiments the technique introduced in reference 7 was refined to permit the locating of zone boundaries. A salt water solution was injected, from a very small tube and at low velocity into the wake; the resulting flow pattern was photographed and observed. Of particular interest in the present argument is the length L of the recirculating zone measured as indicated in Figure 3. The length could be defined with surprising accuracy considering the complexity and irregularity of the wake flow. If the salt solution was injected downstream of the end of the recirculating zone no luminous material appeared in the vicinity of the flame holder. If the point of injection was moved forward slightly the entire recirculation zone appeared luminous. In this manner the wake length could be defined within 5%.

Figure 3. Side view of flame stabilized on circular cylinder.



For a wide variety of cylinder diameters and flow speeds, the wake length varied as the square root of the characteristic flame holder dimension. The results of these measurements, shown in Figure 5, exhibit some velocity dependence but the relation between length and diameter is well established. The measurements shown are all at Reynolds Number values above the critical value mentioned previously. Wake length measurements were also made for another series of shapes consisting of cone-cylinder and wedge-plate combinations. This general geometry was suggested by a flame holder employed by J. P. Longwell to obtain some early flame blowoff results. For these flame holders the wake length was directly proportional to the characteristic flame holder dimension, Figure 6, and independent of the Reynolds Number. From the standpoint of turbulent spreading processes and turbulent wakes this linear dependence is to be expected rather than the square root dependence observed in the case of circular cylinders. An experiment in which boundary layer transition was induced on a cylinder demonstrated that, under these conditions, the wake length depended linearly upon size and was independent of Reynolds Number. Some more recent investigations have suggested that the square-root dependence of the cylinders, spheres and related shapes is due to the wake divergence resulting from boundary layer separation ahead of the diametral plane. This spreading tendency is Reynolds Number dependent and is influenced by blockage effects due to the finite size of the channel in which experiments were made. When boundary layer transition is induced on a cylinder the separation point moves rearward so that a more nearly parallel wake is formed. Clearly, the wake is always of this structure for the flame holder geometries of Figure 6.

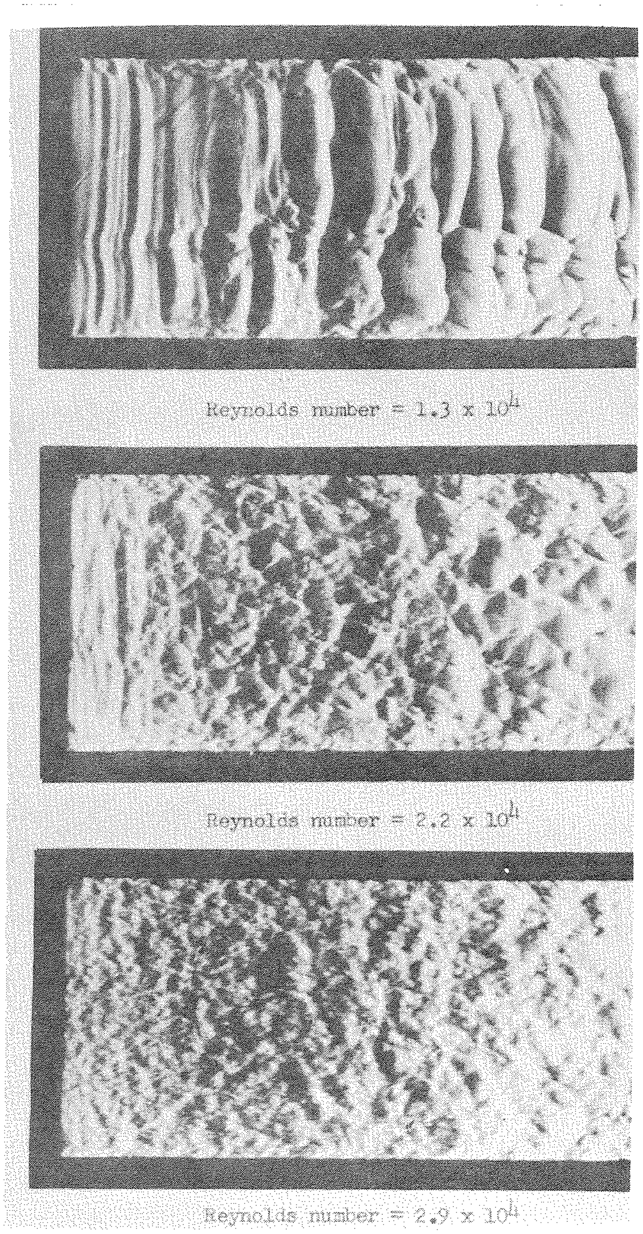


Figure 4. Schlieren photographs of transition in mixing zone.

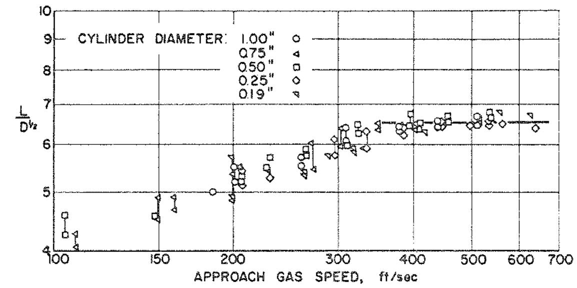


Figure 5. Length of recirculation zone for circular cylinders over a range of stream velocity.

These results are essentially independent of chemical influences of mixture, free stream temperature etc. and are very slightly influenced by changes in wake temperature that accompany changes in the mixture ratio. It may be assumed that, to a very good approximation, the wake geometry observed is governed by the fluid mechanics of the process and independent of the detailed chemistry.

TEMPERATURE OF THE RECIRCULATION ZONE

Since previous experiments, reference 2, have indicated that the mixture distribution of combustion products in the wake is essentially uniform, the variable of principal thermodynamic interest is the gas temperature. Direct methods of temperature measurement utilizing thermocouples or resistance thermometers are difficult because of the high temperatures involved and inaccurate because of the unknown and irregular velocities which exist in the recirculation zone. Optical

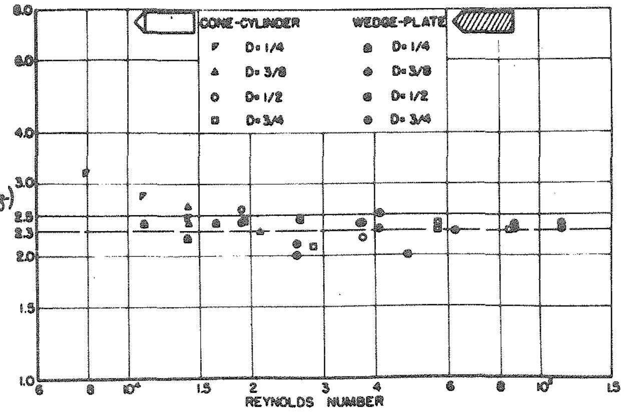


Figure 6. Length of recirculation zone for cone-cylinder flame holders over a range of Reynolds Numbers.

methods are therefore the most promising and consequently the well-known technique of sodium D-line reversal was employed. With the optical system employed the measurement had an uncertainty of at least 15° C so that together with the somewhat uncertain corrections for cool boundary regions in the optical path, the probable error was about 45° C. The cross section of the optical beam could always be made small in comparison with wake regions investigated so that the temperature measurement was truly a local one.

The wake temperature immediately downstream of a ½ inch diameter circular rod is shown in Figure 7 over the useful range of mixture ratios. The maximum temperature observed was 2170° K at an equivalence ratio of 1.07. The mixture dependence is very nearly that expected for combustion products of the fuel used except that the general level is about 10% below the calculated adiabatic flame temperature. Surveys downstream of the flame holder indicated that the temperature was uniform throughout the wake thus confirming

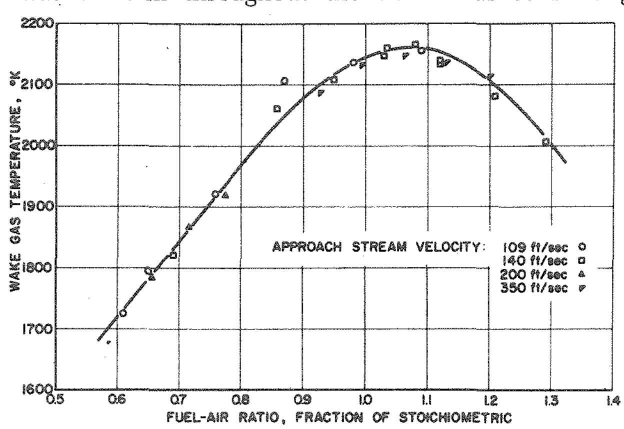


Figure 7. Wake gas temperatures measured ⅜ inch downstream from ½ inch cylindric rod for a range of mixture ratios and for various gas speeds.

the previous observations that no combustion process is active in the main portion of the wake. The discrepancy between measured and calculated flame temperatures, however, is far greater than attributable to exerpimental inaccuracies. Furthermore this temperature difference was not influenced by changes in flow velocity (and hence "residence time" in the wake) below blowoff. There is no question of simple lack of complete combustion because of too short a residence time. The reason for the observed difference is not clear at the present time.

Of particular interest to the present investigation is the variation of wake temperature as the gas stream velocity approaches the blowoff velocity for the flame holder in question. The results of extensive measurements on a wide variety of flameholder shapes are shown in Figure 8; the measurements were made at mixture

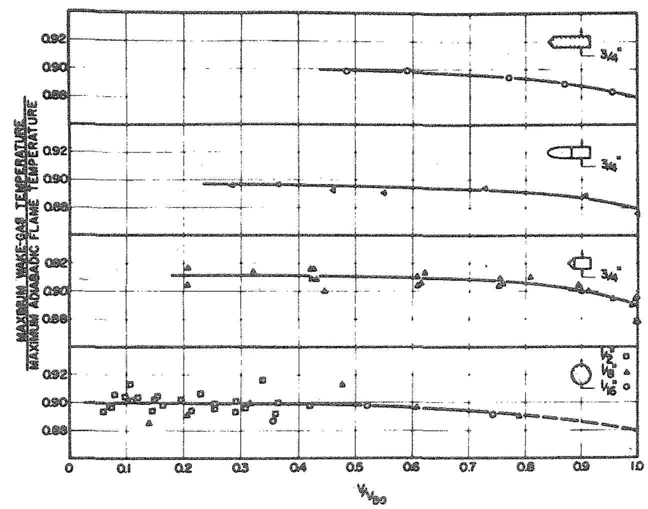


Figure 8. Wake gas temperatures for flame holders of different geometrics over a range of gas speed.

ratio giving the maximum wake temperature as indicated in Figure 7. Here the ratio of the wake temperature to maximum flame temperature is plotted against the velocity of the gas stream, measured as a fraction of the blowoff velocity. The temperatures measured were remarkably constant with the exception of a very slight drop in the immediate vicinity of blowoff. Furthermore this temperature pattern is independent of the flame holder geometry. The small temperature drop near blowoff is far too small to substantiate blowoff mechanisms which depend on temperature depression in the wake because of heat transfer to the free stream. In fact, the small temperature depression observed does not appear to result from heat transfer but from experimental error due to increased relative thickness, near blowoff, of cool boundary regions in the optical path.

THE IGNITION DELAY TIME

The foregoing experiments indicate that the recirculation zone consists of combustion products with no active combustion and that the temperature of the recirculation zone is determined by the mixture ratio and free stream temperature, independent of the gas residence time and detailed fluid dynamic processes. It is believed that the flame stabilization mechanism operative in all examples investigated is then the following.

Fresh gas from the free stream flows over the flame holder and mixes with hot combustion products in the narrow turbulent shear layer between the free stream and the recirculation zone. If the flame is stable, sufficient fresh gas has been ignited by the time the end of recirculation zone has been reached so that a propagating flame is established. In the recirculation zone all active combustion is restricted to the narrow shear layer at its boundary. A portion of this burned gas is recirculated to replenish the wake. The length of the recirculation zone is established fluid dynamically independent of the detailed chemistry. The wake temperature is established by the chemistry and free stream temperature, independent of the gross fluid dynamic features. The flame blows off when the time during which the fresh gas associates with the hot recirculation zone is too short for ignition to be accomplished. Thus it is the time which the fresh gas spends *in the shear layer* rather than the residence time in the wake which is important.

If V is the free stream velocity and L the length of the recirculation zone, then the ratio L/V is a measure of the time which the fresh gas spends in the neighborhood of the hot combustion products. In fact the

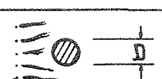
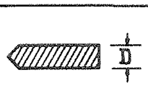
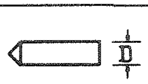
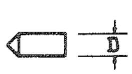
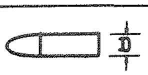
Flame Holder Geometry	D	$\hat{\tau}$
	1/8 inch 3/16 1/4	3.09×10^{-4} sec 2.35 2.80
 14 mesh screen	1/4	3.00
	1/4 3/8 1/2 3/4	2.38 2.70 2.65 2.58
	1/4 3/8 1/2 3/4	3.46 3.12 3.05 3.03
	3/4	3.05
	3/4	2.70

Chart I Minimum characteristic ignition times for several flame holder geometrics and sizes.

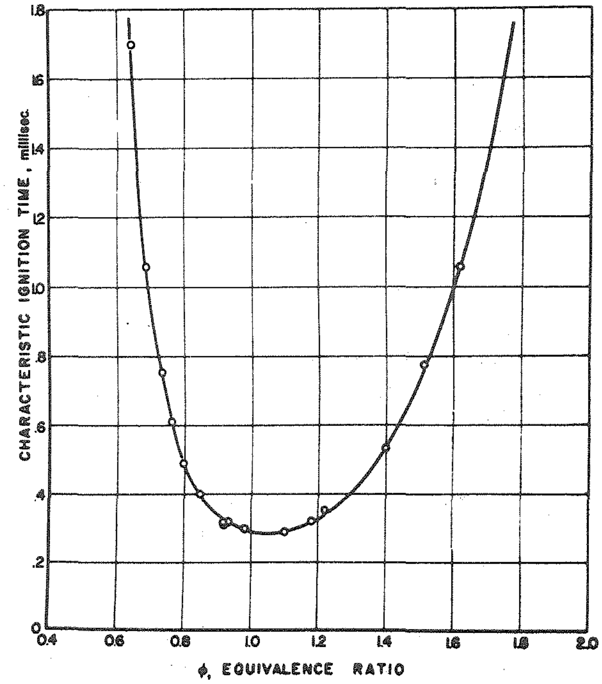


Figure 9. Characteristic ignition time for a cone-cylinder flame holder over a range of mixture ratios.

critical time τ required for ignition of the free stream is given by

$$\tau = L/V_{B.O.}$$

where $V_{B.O.}$ is the measured blowoff velocity.

If this point of view is correct the ignition delay time as defined above should not depend upon the particular flame holder employed. Chart I shows the remarkable constancy of this ignition delay time for a wide variety of flame holder geometries at the stoichiometric mixture ratio. Included also is the unconventional case where boundary layer transition was induced on a circular cylinder. The dependence of the ignition delay time upon mixture ratio is shown in Figure 9.

The ignition delay time thus defined seems to have a basic significance—it is related to the chemical process and independent of the gross fluid dynamic features. The similarity parameter describing the stabilization phenomenon is thus $V\tau/L$ and in particular the blowoff condition is described by the value

$$\frac{V_{B.O.}\,\tau}{L} = 1$$

The chemical and fluid dynamic effects are separated into τ and L respectively. The usual dependence of blowoff velocity on the flame holder size follows immediately from the behavior of L and hence is determined by the fluid dynamics.

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