Stable Combustion of a High-Velocity Gas in a Heated Boundary Layer†

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Summary

It is generally recognized that stable combustion processes in heated boundary layers may be achieved by either of two conceptual mechanisms. In one mechanism it is pictured that the heat transfer to the wall quenches the propagating flame at a certain distance from the surface. The equality between the flow velocity and the normal burning velocity at this quenching distance determines the position of the propagating flame. In the second mechanism it is conceived that the hot surface provides a continuous source of ignition in much the same manner that the hot recirculation zone of a bluff body flame holder provides continuous ignition to the gas flowing around it. In this case it is the characteristic time during which the gas must be heated that determines the position of the flame.

All experimental work reported to date has been concerned with conditions where the first picture has apparently been applicable. In the present paper, experiment and analysis are given that show under what conditions the continuous ignition mechanism provides the appropriate model and also how the two models are related. To differentiate the two mechanisms an experiment was set up to study flame stabilization in high-velocity boundary layers over a wall heated in the form of a step function. With a turbulent boundary layer and a wall temperature above 1,700°F., the characteristic time was found to be a systematic and reproducible variable. These observations led to the conclusion that a continuous ignition mechanism governs stabilization in heated turbulent boundary layers. A rational explanation is made for the transition from the low-speed mechanism known to be applicable in unheated turbulent boundary layers and heated laminar boundary layers to the ignition mechanism applicable in heated turbulent boundary layers.

As a further verification of the continuous ignition mechanism an apparent ignition energy was found. The logarithm of the heat added at the lower stability limit was found to be a linear function of the reciprocal of the limiting wall temperature. The activation energy derived from this Arrhenius type of relation agreed reasonably well with the estimated value for the fuel used.

Symbols

D_{tw} = diameter of the trip wire
D_1 = first Damkohler number (x/Ut)
d = length of the recirculation zone behind a bluff body
Q = heat transfer into the boundary layer from the flame holder wall up to the point of flame attachment, per unit width and time
R = Reynolds number (Ux/ν)
T_0 = free-stream temperature
T_w = flame holder wall temperature
T_{ws} = minimum wall temperature required for stabilization
t = characteristic time
t_1 = chemical time delay associated with bluff body flame stabilization
t_2 = chemical time delay associated with boundary-layer flame stabilization
U = velocity parallel to the flame holder wall
U_0 = free-stream velocity
U_τ = friction velocity $(\sqrt{\tau_w/\rho})$
x = coordinate parallel to the flame holder wall
x_f = position of flame attachment
y = coordinate normal to the flame holder wall
θ = momentum thickness
μ = absolute viscosity
ν = kinematic viscosity (μ/ρ)
ρ = density
τ_w = wall shearing stress
ϕ = fuel-air ratio, fraction of stoichiometric

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(1) Introduction

In terms of practical applications, flame stabilization is one of the most important branches of the combustion field. Because of the complex nature of the stabilization problems very little knowledge of the basic mechanisms has been available. As a result the designer of a combustion apparatus must rely upon his experience, or, at best, on semitheoretical, empirical relations.

For many years the study of flame stabilization in moving streams was restricted to low-velocity flows. The basic research tool was the simple Bunsen burner with the stability limits, flashback and blowoff, the subject of most interest. A good summary of the experimental results, and the attempts to correlate them, has been given by Lewis and von Elbe.[1] In particular, a mechanism explaining flashback was postulated in which the normal burning velocity was equated to the flow velocity at a distance from the wall called the quenching distance. Good correlation of the above mechanism with experiment was found. Attempts to develop a theory from the basic equations for conservation of momentum, energy, and chemical species were less successful.

With the advent of the continuous flow, airbreathing aircraft engine, it became necessary to stabilize flames in high-velocity flows. For this purpose can burners and bluff body flame holders were developed. It soon became apparent that the stability limits of the Bunsen burner type of problem were not applicable to the

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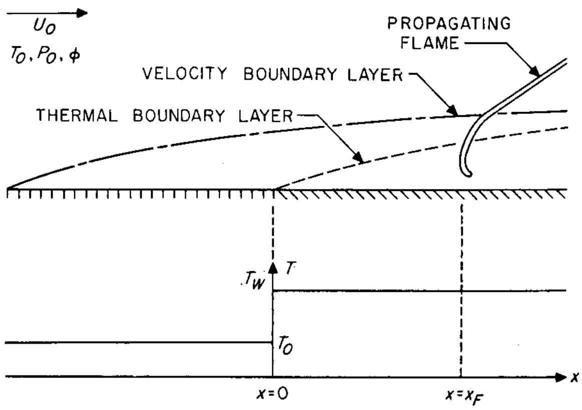

FIG. 1. Sketch of a flame stabilized in the boundary layer with the idealized wall temperature distribution.

high-velocity applications. In particular, the basic mechanism seemed to be different.

Since the bluff body flame stabilizer was relatively simple it became an important research tool. A significant parameter for correlating the data on blowoff limits was the chemical time delay given by

$$t_1 = \frac{d}{U_0} \tag{1}$$

where d is the length of the recirculation zone behind the bluff body and U_0 the free-stream velocity. This discovery led Zukoski and Marble[2] to hypothesize that the basic stabilization mechanism was one of continuous ignition. The hot gases in the recirculation zone continuously ignite the unburned gases in the mixing region. Since the fluid mechanics of flow behind a bluff body are not well understood even in an isothermal problem without combustion, detailed studies of the ignition mechanism were out of the question.

In order to obtain a better insight into the stabilization mechanisms simpler flow systems have been studied. Combustion in the turbulent mixing region between a cold combustible mixture and a hot inert gas has been investigated experimentally by Wright and Becker.[3] Unfortunately, stability problems made quantitative measurements difficult. Also the presence of both an initial and a propagating flame complicated the understanding of the mechanism. The problem of stabilization in a laminar boundary layer heated by a constant temperature flat plate has been investigated experimentally by Ziemer and Cambel.[4] These authors obtained a reasonably good correlation between their experiments and the Bunsen burner type mechanism previously discussed for wall temperatures between 1,500°F. and 2,000°F. Previously, the applicability of a Bunsen burner type mechanism to flame stabilization in the unheated laminar boundary layer on a flat plate had been verified by Hottel, Toong, and Martin.[5]

To provide the best differentiation between the two possible stabilization mechanisms, an experiment was set up to study flame stabilization in a turbulent boundary layer heated in the form of a step function. This thermal boundary condition eliminated the similarity between the velocity and temperature fields which would occur if a completely uniform wall temperature were maintained. The idealized experiment is illustrated in Fig. 1.

(2) The Experiment

The desired experiment would have a combustible mixture flowing over a flat plate with a wall temperature distribution in the form of a step function. A flame would be stabilized in the boundary layer some distance downstream from the step. Unfortunately, the strong temperature gradients in the region of flame attachment preclude any such steady-state experiment. No practical experimental apparatus could be expected to maintain a constant wall temperature through this region. In order to overcome this difficulty, a transient experiment was devised. The wall temperature distribution was first established, then the flame was allowed to stabilize in the boundary layer. Since the characteristic time associated with a change in wall temperature was large compared with the characteristic time in the combustion problem, significant measurements could be made before transient effects became important.

The experiments were carried out in a standard low-speed combustion tunnel. The air was first metered and then preheated. Most of the data were obtained at a mixture temperature of 300°F. The liquid fuel was injected and vaporized. A plenum chamber, screens, and a smoothly convergent section assured sufficient mixing and a good velocity distribution at the entrance to the test section. The test section had an area of 28.3 sq.in. The fuel used was commercial paint thinner composed of 95 per cent saturated hydrocarbons. For this gasoline type of fuel the stoichiometric ratio, fuel to air by weight, was 0.0674 and the average molecular weight was 93.

A cylindrical flame holder parallel to the flow was used to eliminate edge effects and simplify heating. The flame holder was a length of stainless steel pipe with an outer diameter of 1.825 in. and was cantilevered from the downstream end. With an ogive nose a flat plate boundary layer was formed on the flame holder

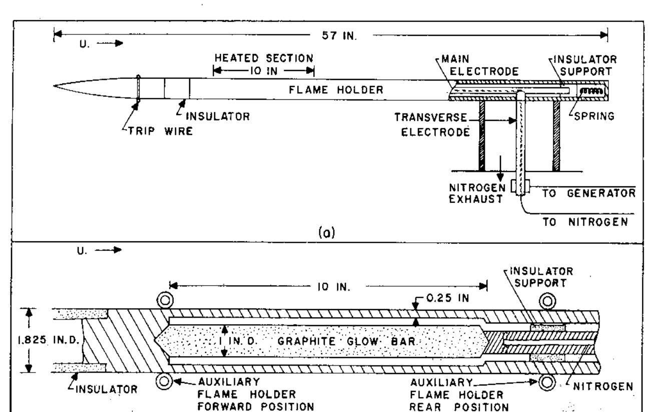

FIG. 2. Diagram of the flame holder. (a) Complete flame holder. (b) Heated section.

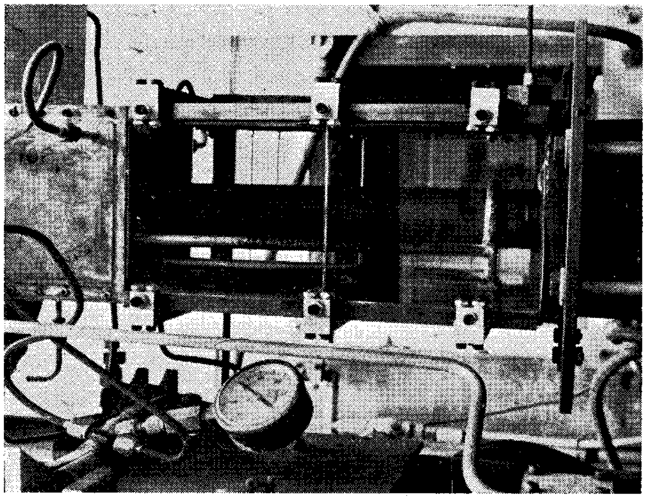

FIG. 3. Side view of the test section with auxiliary flame holder in its forward position.

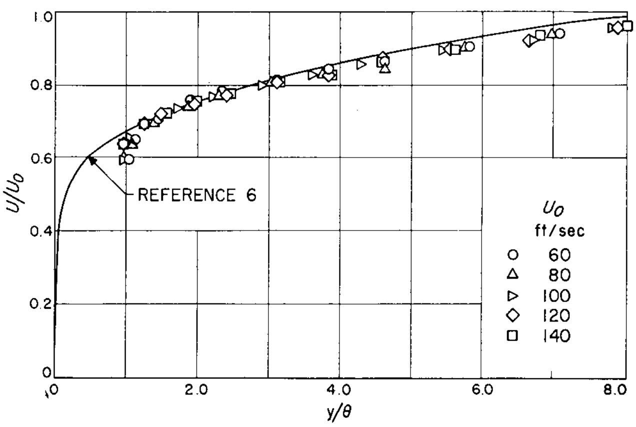

FIG. 4. Cold flow nondimensional boundary-layer velocity distributions at the upstream end of the heated section: T_0 = 200°F., D_{tw} = 0.0201 in.

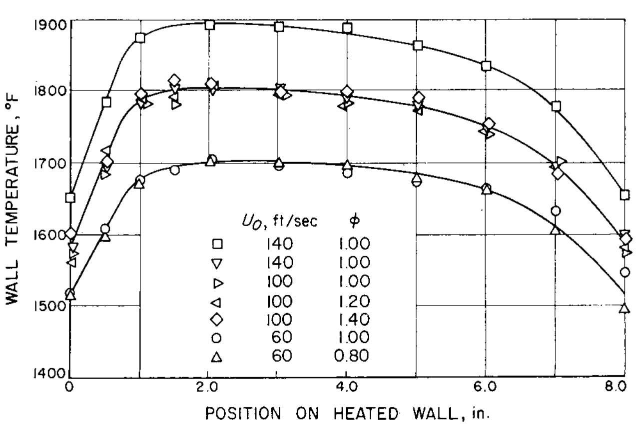

FIG. 5. Typical flame holder wall temperature distributions before the removal of the auxiliary flame holder: T_0 = 300°F.

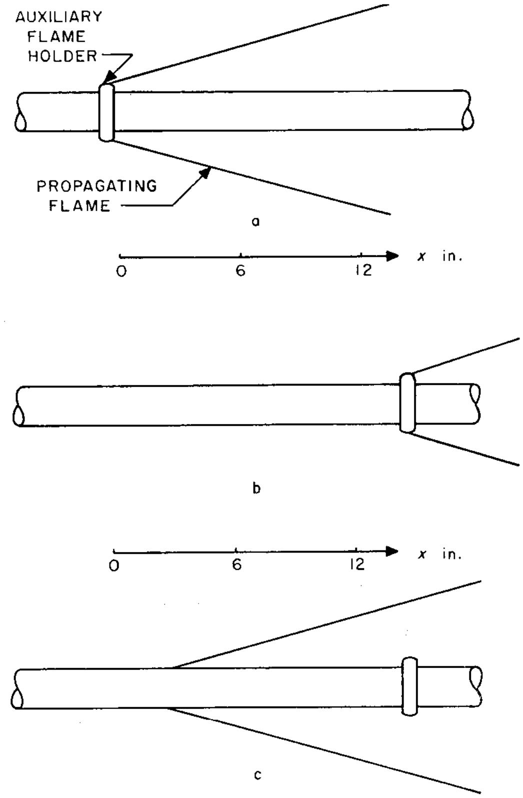

FIG. 6. Illustration of the experimental procedure: (a) flame holder in the forward position during heating, (b) flame holder in the rear position without boundary-layer flame stabilization, and (c) flame holder in the rear position with boundary-layer flame stabilization.

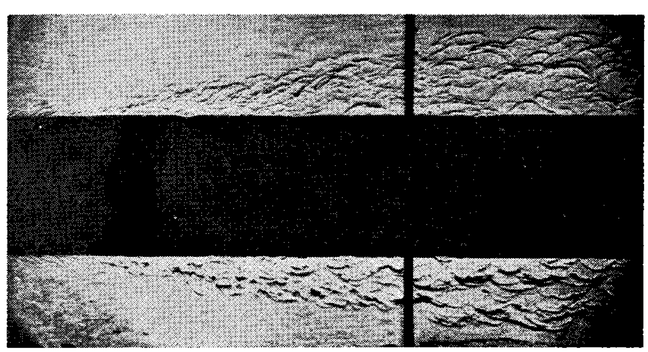

FIG. 7. Schlieren photograph of a flame stabilized in a turbulent boundary layer: T_w = 1,771°F., U_0 = 85 ft./sec., ϕ = 1.00, T_0 = 300°F., D_{tw} = 0.0201 in.

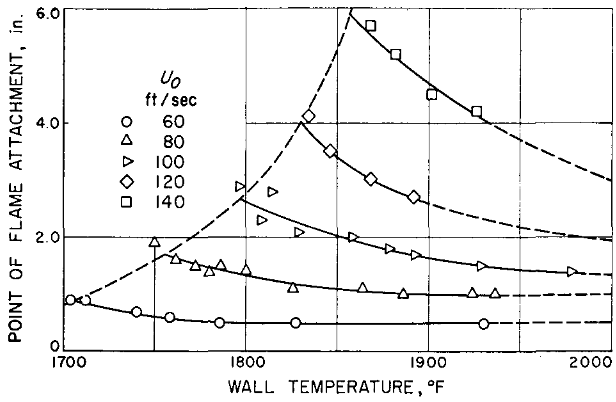

FIG. 8. Dependence of the flame attachment position on wall temperature: ϕ = 1.00, T_0 = 300°F., D_{tw} = 0.0201 in.

wall through the test section. For turbulent boundary layers a cylindrical wire was used as a tripping device. A diagram of the flame holder is given in Fig. 2. A photograph of the test section is given in Fig. 3. A set of cold flow turbulent boundary-layer velocity profiles measured at the upstream end of the heated section are shown in Fig. 4; they are compared with the measurements of Klebanoff and Diehl.[6] Other measurements showed that the boundary layer was axially symmetric and that the change in friction velocity over the length of the test section was less than 10 per cent. The profiles were used to determine the friction velocity through the empirical relation of Squire and Young.[7]

To study flame stabilization in a heated boundary layer, it was necessary to heat a section of the flame holder wall to temperatures of from 1,500° to 2,000°F. During the heating an auxiliary flame holder was used to stabilize the flame ahead of the section to be heated. The auxiliary flame holder acted as a bluff body stabilizer. The hot combustion gases heated the flame holder to about 1,500°F. Radiative heat losses kept this temperature from being higher. To increase the wall temperature to the desired level, a graphite glow bar coaxial with the flame holder was used; the radiation from the glow bar heating the flame holder wall. Nitrogen was used to cool the interior components. The details of the heater are shown in Fig. 2. Several typical wall temperature distributions are shown in Fig. 5. When the flame holder wall temperature reached the desired level, the auxiliary flame holder was removed, and the flame was allowed to stabilize in the boundary layer. With this procedure, the auxiliary flame holder acted as an ignition source. The initial point of flame attachment was the measured variable. The sequence of operations in the experimental procedure is illustrated in Fig. 6.

(3) Experimental Results

The quantitative study of flame stabilization in a turbulent boundary layer consisted of a determination of the point of flame attachment just after the removal of the auxiliary flame holder. Measurements were made for various values of the independent parameters. The independent parameters considered were the wall temperature, the free-stream velocity, the fuel-air ratio, the trip wire diameter, and the free-stream temperature. A schlieren photograph of a stabilized flame is shown in Fig. 7. The reference wall temperature was measured at x = 3 in.

Probably the most interesting independent parameter in the stabilization problem was the flame holder wall temperature. With all other variables fixed the dependence of the flame attachment position on wall temperature was found. For a sufficiently high wall temperature the flame would stabilize on the wall at a definite and repeatable position. As the wall temperature was decreased the length of heated wall upstream of the attachment point increased in a continuous manner. At a definite wall temperature this continuous relation ended abruptly. Below this stabilization limit the flame would not stabilize in the boundary layer. This was a true stabilization limit and not an ignition limit, since the experimental procedure provided a continuous source of ignition. The dependence of the flame attachment position on wall temperature for various free-stream velocities and a stoichiometric fuel-air ratio is given in Fig. 8. The stability limit is indicated with a dashed line. The scatter in the data was quite low; this can be attributed largely to the sta-

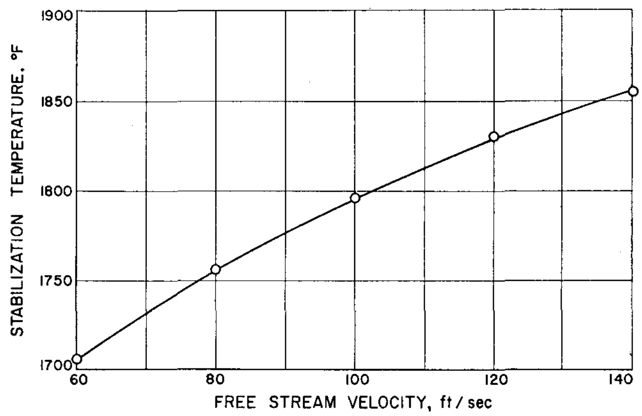

FIG. 9. Dependence of the minimum wall temperature required for stabilization on free-stream velocity: ϕ = 1.00, T_0 = 300°F., D_{tw} = 0.0201 in.

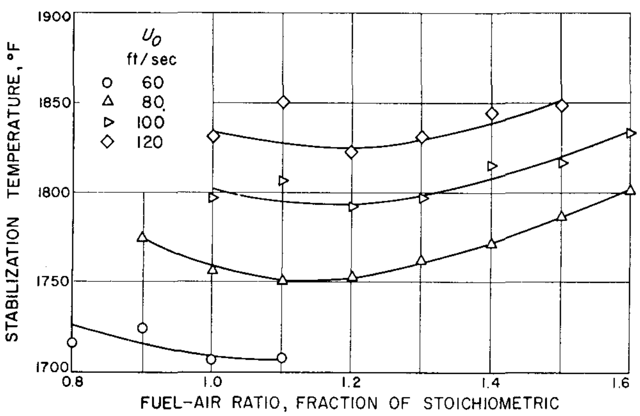

FIG. 10. Dependence of the minimum wall temperature required for stabilization on fuel-air ratio: T_0 = 300°F., D_{tw} = 0.0201 in.

bility of the flame attachment point. Although the propagating flame oscillated considerably, the point of attachment did not vary a visible amount. The minimum temperature required to stabilize a flame in the boundary layer had a definite measurable value. These values are plotted against velocity in Fig. 9 for a stoichiometric fuel-air ratio. In Fig. 10 the stability limit is plotted against fuel-air ratio for various velocities. Although the variation is not large, there seems to be a minimum stabilization temperature near ϕ = 1.20.

Any solution for the dependence of the flame position on wall temperature can be expected to be complicated due to the presence of the Arrhenius reaction rate term. For this reason the dependence of the flame position on free-stream velocity at constant wall temperature is important. In particular, one might expect that the dependence would be given by one of two similarity parameters—either the Reynolds number

$$R = U_0 x_f / \nu \qquad (2)$$

a significant parameter in boundary-layer problems, or the first Damkohler number

$$D_1 = x_f / U_0 t_2 \qquad (3)$$

a significant parameter in flow problems with chemical reaction. The dependence of the stability limit on velocity eliminates the possibility of similarity for constant values of wall temperature. To resolve this difficulty, the temperature difference between the wall temperature and the minimum wall temperature required for stabilization may be taken as the significant temperature variable. In Fig. 11 the flame position is plotted against velocity for constant values of this temperature difference. The curves exhibit some degree of similarity. For plots requiring a fixed temperature, a constant value of $T_w - T_{ws}$ would seem to be the most logical choice. An arbitrary value of 50°F. has been selected.

The dependence of flame position on fuel-air ratio is given in Fig. 12 for various free-stream velocities and $T_w - T_{ws}$ = 50°F. Again a shift of the minimum stabilization distance to rich mixture ratios is observed. Such a shift would be expected at or near a stoichiometric fuel-air ratio since the heat release from combustion would be at a maximum. However, if differential diffusion were involved, the actual concentration near the flame holder wall might be different from that of the free stream. Since the average fuel molecular weight is approximately three times larger than the average molecular weight of air, this shift can be explained from a consideration of differential molecular diffusion. The oxygen molecules would diffuse toward the wall more rapidly than the fuel molecules; therefore, if combustion were occurring, the mixture ratio would be less than in the free stream. This type of molecular diffusion would only be of importance in a laminar regime. Therefore, the experiments indicate that the mechanism governing stabilization in a turbulent

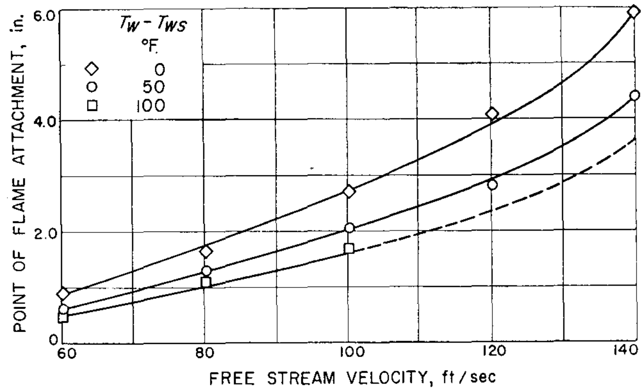

FIG. 11. Dependence of the flame attachment position on free-stream velocity: ϕ = 1.00, T_0 = 300°F., D_{tw} = 0.0201 in.

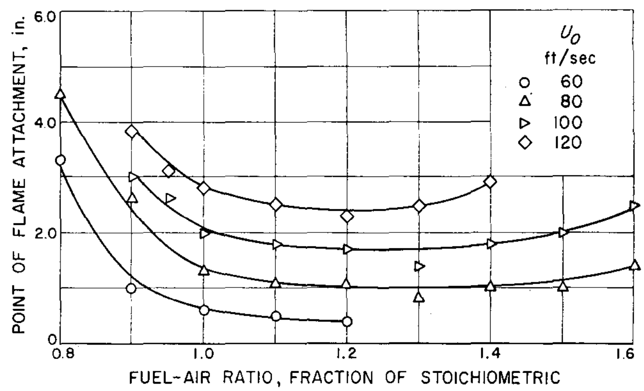

FIG. 12. Dependence of the flame attachment position on fuel-air ratio: $T_w - T_{ws}$ = 50°F., T_0 = 300°F., D_{tw} = 0.0201 in.

boundary layer is a laminar phenomenon and, hence, is confined to the region very near the wall.

(4) Stabilization Mechanism

In an isothermal laminar boundary layer, a flame should stabilize by a mechanism similar to that governing flashback in Bunsen burners. This Bunsen burner mechanism requires that the flame speed shall equal the flow velocity at a distance from the wall called the quenching distance. The cool wall acts as a heat sink that quenches the end of the propagating flame. The validity of this mechanism in the isothermal laminar boundary layer has been demonstrated by Hottel, Toong, and Martin.[5] The form of this flame is illustrated in Fig. 13(a).

In order to understand what the stabilization mechanism might be in a heated boundary layer, consider what change would be expected in the Bunsen burner mechanism as the wall temperature is increased. For the purpose of this intuitive discussion, assume that the wall velocity gradient increases with the wall temperature to keep the propagating flame stabilized at the same point. As the temperature increases chemical reaction begins to occur near the flame holder wall; this is illustrated in Fig. 13(b) with the two regions of strong chemical reaction shaded. The end of the propagating flame is still quenched by the wall. However, the heat released through chemical reaction near the wall pro-

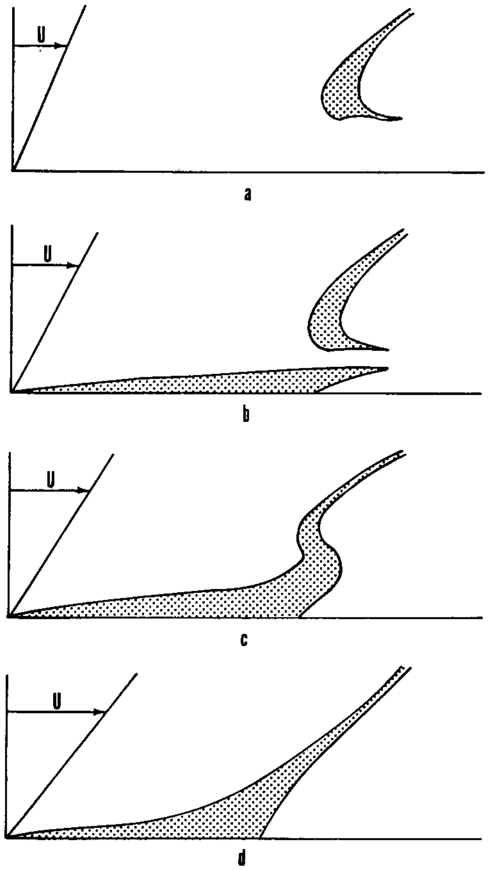

FIG. 13. Illustration of the change in stabilization mechanism with increasing wall temperature.

vides thermal shielding to the heat-transfer process in the quenching region; the temperature distribution in the region between the end of the propagating flame and the wall may no longer be approximated by a linear relation, and the heat loss from the end of the flame to the wall is reduced. As the wall temperature is increased further the two regions of chemical reaction will join; this is illustrated in Fig. 13(c). The high wall temperature and the thermal shielding by the reaction near the wall prevent true quenching. Now consider what might happen if the wall temperature and wall velocity gradient were increased even more. The expected form of the flame is illustrated in Fig. 13(d). The flame is anchored to the wall; the flame thickness depends on the distance from the wall. The important heat transfer is now from the heated plate into the combustible mixture. The heat ignites the mixture on the plate and a propagating flame is formed. The chemical reaction in the region near the wall completely shields the rest of the propagating flame; no quenching occurs. The flow velocity is greater than the normal flame speed all through the boundary layer, and no remnant of the Bunsen burner mechanism remains. This new mechanism will be referred to as a continuous ignition mechanism. It should be noted that this discussion is based on essentially a thermal concept of flame stabilization. If the wall has an appreciable catalytic or absorptive effect on the active particles the picture could be appreciably different.

Data on flame stabilization in heated laminar boundary layers have been obtained by Ziemer and Cambel.[4] A comparison was made by these authors with a Bunsen burner mechanism; fair agreement was obtained. Although some of the empirical extrapolations used in the comparison might be questioned, the choice of stabilization mechanism seems valid at least for the lower temperatures. Apparently the picture of the mechanism given in either Fig. 13(b) or in Fig. 13(c) is applicable in the heated laminar boundary layer.

The present experiments can be evaluated in terms of the above discussion without going into the details of an exact solution. Some features of the two mechanisms can be deduced and compared with the observed features of stabilization in heated turbulent boundary layers. First, the continuous ignition mechanism will be considered. With the flame anchored on the wall, as illustrated in Fig. 13(d), the visible point of flame attachment should be stable; this was observed experimentally. In the ignition problem the chemical time delay is known to be an important variable. From Eq. (1) this time delay can be related to the length of heated wall required for stabilization. Experimentally this was found to be an important and reproducible variable. The visible point of attachment is the position where the region of chemical reaction emerges from the very thin sublayer region to form the propagating flame.

If, instead, the Bunsen burner mechanism were applicable, the important parameters would be the quenching distance, the normal flame speed, and the wall velocity gradient. However, along the heated wall these are nearly constant in turbulent flow. The velocity gradient is nearly constant due to the nature of the experiment. The temperature distribution is weakly dependent on x a short distance downstream of the step increase due to the nature of turbulent heat transfer. And the quenching distance depends upon the temperature distribution. Therefore, the length of heated wall up to the point of stabilization would not be a significant variable. If stabilization occurred anywhere along the heated surface, the flame would be expected to propagate upstream through the boundary layer to the upstream end of the heated section, the change in quenching distance with wall temperature would prevent a further movement. This property of the Bunsen burner mechanism has also been discussed by Toong.[8]

The observed systematic dependence of the flame attachment position on the independent variables and the stability of the attachment point indicate the validity of a continuous ignition mechanism in turbulent boundary-layer stabilization. This is further verified by the laminar nature of the phenomenon. The question now arises as to why the mechanism applicable in heated laminar boundary-layer stabilization does not apply in heated turbulent boundary layers. The answer can be seen in the discussion of Fig. 13. One of the key variables was the wall velocity gradient. But the most significant change that occurs when a boundary layer becomes turbulent is the increase in the wall shearing stress; and this is directly proportional to the velocity gradient at the wall. Therefore the change in mechanism follows directly from the discussion. The observed stability limit can also be explained qualitatively. Below the minimum stabilization temperature, the heat released by the chemical reaction at the wall is conducted away so rapidly that a propagating flame cannot be established before the reaction dilutes the reactive species near the wall.

It seems reasonable to conclude that, while the Bunsen burner mechanism is applicable in laminar boundary layers, the continuous ignition mechanism governs stabilization in heated turbulent boundary layers. This is not to predict that the correspondence is generally valid. In a very thick turbulent boundary layer with a low wall temperature a Bunsen burner mechanism would certainly be applicable. Also, if the wall temperature were sufficiently high, an ignition mechanism might be applicable in the laminar boundary-layer problem.

In general, it might be said that the mechanism which gives the minimum stabilization distance is the applicable mechanism in a particular case. However, in some cases an interaction between the two mechanisms might occur. A heated wall might cause a dilution in the combustible mixture near the wall affecting the quenching distance in such a manner that a flame would not stabilize anywhere along the flat plate.

(5) Discussion of Results

If the continuous ignition mechanism is applicable, the heat input required for stabilization should be an important parameter. In particular, the heat input at the stability limit might correspond to a minimum ignition energy. The heat transfer from the wall was measured experimentally without combustion. Since the combustion in the boundary layer should have an appreciable effect on the heat-transfer rate only near the point of flame attachment, this approximation should provide a satisfactory estimate. For the details of the method the complete report of the present work[9] may be consulted.

In Fig. 14 the dependence of the heat-transfer rate at the stability limit on reciprocal wall temperature is shown for the various trip wires and free-stream temperatures considered. Changing the trip wire diameter changed the boundary-layer thickness over the heated section. An empirical equation is plotted for comparison in the form

$$Q(\text{B.t.u./ft. hr.}) = 2.22 \cdot 10^{15}\, e^{-[33{,}600/T_{ws}\,(°\text{K.})]} \quad (4)$$

The dependence of the heat required for stabilization on an Arrhenius relation provides an opportunity for determining the activation energy of the fuel used. The calculated activation energy of 66,800 calories is fairly close to the best available estimate for the fuel used which is 40,000 to 50,000 calories. The dependence of

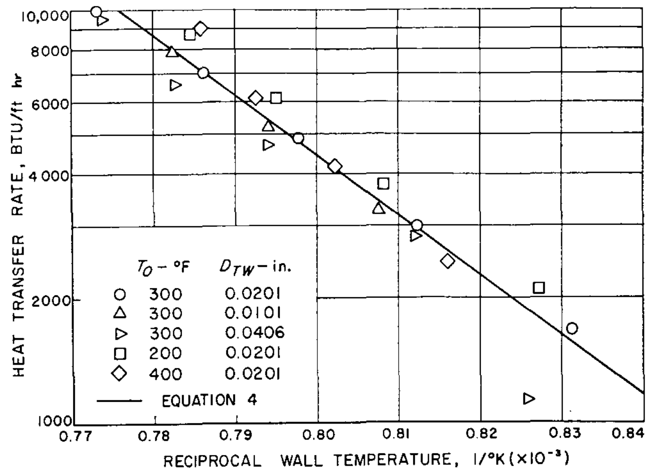

FIG. 14. Dependence of the heat-transfer rate at the stability limit on the reciprocal wall temperature: $\phi = 1.00$.

this apparent ignition energy on an Arrhenius rate law tends to substantiate the validity of a continuous ignition mechanism.

(6) Concluding Remarks

Flames were successfully stabilized in the heated boundary layer of a high-velocity combustible mixture. The visible point of attachment of the propagating flame was a well-defined measurable quantity. Data were obtained for dependence on wall temperature, free-stream velocity, fuel-air ratio, boundary-layer thickness, and free-stream temperature. A stability limit was also found—a wall temperature below which stabilization was not possible.

The observed features of the stabilization indicated that the governing mechanism originated in the laminar sublayer of the turbulent boundary layer. The length of heated wall upstream of the flame attachment point was a significant variable and the point of attachment was particularly stable. These observations led to the conclusion that the stabilization was governed by a continuous ignition type mechanism. The flat plate served as an ignition source. This conclusion was further substantiated by the dependence of the rate of heat transfer into the boundary layer at the stability limit on the wall temperature according to an Arrhenius rate law. The activation energy agreed fairly well with the estimated value for the fuel used.

A rational picture is given of the relation between the continuous ignition mechanism in the high velocity boundary-layer flows and the Bunsen burner mechanism in low-velocity flows. The applicability of the continuous ignition mechanism in turbulent boundary layers seems to offer the best possibility for a comparison between an ignition theory and experiment. This would be particularly true if the important features of the stabilization mechanism can be restricted to the laminar sublayer region of the turbulent boundary layer.

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