NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3977

FURTHER EXPERIMENTS ON THE STABILITY OF LAMINAR AND TURBULENT HYDROGEN-AIR FLAMES AT REDUCED PRESSURES

By Burton Fine

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

LIBRARY COPY

APR 11 1957

LANGLEY AERONAUTICAL LABORATORY
LIBRARY, NACA
LANGLEY FIELD, VIRGINIA

WASHINGTON

NOT TO BE TAKEN FROM THIS ROOM
FURTHER EXPERIMENTS ON THE STABILITY OF LAMINAR AND
TURBULENT HYDROGEN-AIR FLAMES AT REDUCED PRESSURES

By Burton Fine

SUMMARY

Stability limits for laminar and turbulent hydrogen-air burner flames were measured as a function of pressure, burner diameter, and composition. The average pressure exponent of the critical boundary velocity gradient for turbulent flashback was 1.31, which is not significantly different from the laminar value. The use of a simple flame model and measured turbulent flame speeds indicated that turbulent flashback could involve a smaller effective penetration distance than laminar flashback. Turbulent blowoff velocity was nearly independent of pressure and varied about as the inverse square root of the burner diameter. Of several recent theoretical treatments, none satisfactorily predicts the observed dependence of blowoff on pressure and burner diameter. Extrapolation of stability loops to the quenching point showed that the quenching pressure was inversely proportional to burner diameter. The actual pressures were higher than those obtained by other quenching measurements.

INTRODUCTION

Relatively little attention has been paid to the stability limits of turbulent burner flames as a function of pressure. Reference 1 (p. 82) reports data on the flashback of unpiloted turbulent propane-air flames at pressures above 1 atmosphere. It was observed that the critical boundary velocity gradient was several times higher than that for corresponding laminar flames at the same pressure and composition. Reference 2 presents blowoff and flashback data for acetylene flames at low pressures; these data extend into the turbulent region. However, data in the higher Reynolds number region are not discussed in detail.

The present study is concerned with the stability of unpiloted turbulent hydrogen-air flames at subatmospheric pressures and extends, into the turbulent region, previous work done on properties of laminar
hydrogen-air flames at subatmospheric pressures (ref. 3). Turbulent flashback was studied at various pressures, equivalence ratios, and burner diameters. Results are compared with results in the laminar region. A possible explanation of the results based on the extension of the laminar model to the case of turbulence is offered. Blowoff in the turbulent region was studied at various pressures and burner diameters at equivalence ratios of 1.1 and 1.5. The results are compared with predictions of several recent theoretical treatments, none of which give satisfactory predictions.

Several stability loops were obtained. These permitted an estimation of the dependence of quenching distance on pressure. The results were in reasonable agreement with those obtained by more direct measurements of flame quenching (ref. 4).

SYMBOLS

A, C  dimensionless coefficients  
D  burner diameter, cm  
g  critical boundary velocity gradient, sec$^{-1}$  
k  pressure exponent, dimensionless  
l  thickness of laminar sublayer, cm  
M  molar weight, g  
m  diameter exponent, dimensionless  
n  pressure exponent of burning velocity, dimensionless  
P  ambient pressure, cm Hg  
q  quenching point, dimensionless  
R  gas constant, cal/(mole)(°K)  
r  radial distance, cm  
Re  Reynolds number, dimensionless  
S  flame surface, sq cm  
T  temperature, °K  
U  velocity, cm/sec  
$\bar{U}$  mean stream velocity, cm/sec
\( V \) volume flow, cm\(^3\)/sec

\( \beta' \) stability parameter, dimensionless

\( \delta \) penetration distance, cm

\( \mu \) viscosity, poises

\( \nu \) kinematic viscosity, cm\(^2\)/sec

\( \phi \) equivalence ratio, fuel-air ratio divided by fuel-air ratio for stoichiometric mixture

Subscripts:

- \( av \) average
- \( b \) burning
- \( bo \) blowoff
- \( cr \) critical for laminar-turbulent transition
- \( f \) flashback
- \( p \) constant pressure
- \( q \) quenching
- \( t \) turbulent
- \( w \) wall

Superscript:

- \( o \) determined at calibration conditions (near 1 atm) or initial conditions

**APPARATUS AND PROCEDURE**

The apparatus used was that described in reference 3. It is shown schematically in figure 1. Burner flames were established within a chamber whose pressure was regulated by a vacuum pump and manual air bleed. The pressure within the chamber was read on a manometer. The burner itself was 50 inches long and about 3/4 inch in diameter and was water cooled near the lip. Tubular inserts of about 4/10 and 5/8 inch were used. Tank hydrogen (98 to 99 percent hydrogen) and tank compressed
air (water-pumped) were used without further purification. The combustible mixture was prepared by metering fuel and air separately through calibrated critical-flow orifices and mixing several feet upstream of the burner inlet.

For measuring stability limits a stable flame was established at some pressure. Then the pressure was slowly increased or decreased at constant mass flow until the flame flashed back or blew off. The average stream velocity at which flame loss occurred was obtained as a function of ambient pressure, burner diameter, and nominal volume flow rate at the calibration pressure (about 1 atm) by the expression

\[
\bar{U}_f \text{ (or } \bar{U}_{bo}) = \frac{4v^O P^O}{\pi D^2 P}
\]  

(1)

This procedure is essentially that described in reference 2. Near the quenching point flames did not flash back sharply, but rather moved slowly back into the tube. Often this movement was asymmetric and resulted in tilted flames (ref. 5). In this region, the flashback pressure was taken as the pressure at which a portion of the flame first dropped below the level of the burner rim.

Turbulent flame speeds were measured by the method of reference 6. Flames were photographed, and the mean flame surface was obtained from measurement of the visible image. With simple photographic means, measurable images were obtained down to pressures of about 0.3 atmosphere. The flame speeds were then obtained by the relation

\[
U_{b,t} = \frac{v^O P^O}{S_m P}
\]  

(2)

No correction was made for the effect of flame-front curvature on the apparent mean flame surface. All measurements were made on a 4/10-inch (1.016-cm) burner at a Reynolds number of about 3500.

RESULTS AND DISCUSSION

Flashback

The flashback of a laminar burner flame is generally described by a critical boundary velocity gradient. This gradient is related to other flame properties by the expression

\[
\varepsilon_f = U_b/5
\]  

(3)
where $\delta$ is the penetration distance, the smallest distance from a cold wall at which the burning velocity attains its normal value (ref. 7, p. 285). If it is assumed that some similar model applies to the flashback of turbulent flames, equation (3) may be written as

$$g_{f,t} = \frac{U_b}{\delta_t}$$  \hspace{1cm} (4)

where turbulence may affect $U_b$ and $\delta$.

**Calculation of velocity gradients.** - For a flame on a cylindrical burner with fully developed laminar pipe flow, the expression

$$g_r = \frac{(dU)}{dr} \mid_w = \frac{8U_f}{D}$$  \hspace{1cm} (5)

is a good approximation provided it is assumed that $\delta/D$ is small. This is equivalent to the assumption that the burner diameter is much larger than the quenching distance at a given pressure.

For turbulent pipe flow, the expression for the boundary velocity gradient (based on the existence of a laminar sublayer near the wall) given by reference 7 (p. 285) is

$$g_t = 0.023 \, \text{Re}^{0.8} \frac{U}{D}$$  \hspace{1cm} (6)

where Reynolds number is defined as

$$\text{Re} = \frac{UD}{\nu}$$  \hspace{1cm} (7)

At flashback equation (6) takes the form, in terms of convenient laboratory variables,

$$g_{f,t} = 0.023 \left(\frac{\mu RT}{M}\right)^{-0.8} \, p^{0.8} \frac{U^{1.8} D^{-0.2}}{\nu}$$  \hspace{1cm} (8)

For the present study the gases were assumed ideal; thus the molecular weight was additive in the mole fraction. The mixture viscosity $\mu$ was obtained by an approximation given in reference 8. It was found that, within experimental accuracy, the viscosity for mixtures containing between 25 and 50 percent hydrogen by volume could be assumed constant and equal to 0.000179 poise. The same value of $\mu$ was used for the few data points obtained outside the composition range given above, at 17 and 56 percent hydrogen. The error is not significant.
Experimental results for flashback are shown in figure 2 and tables I and II. Values of laminar and turbulent critical boundary velocity gradients were calculated by equations (5) and (6), respectively. Most of the data in the laminar region are from reference 3. However, points in the quenching region for D = 1.016 centimeters, $\phi = 1.1$ and 1.5 for D = 1.459 centimeters, $\phi = 1.1$ are new. Some of the new data are used in both figures 2 and 5, the rest in figure 5 only.

The derivation of the expression for $g_{f,t}$ involves an empirical friction factor which applies only in the region of fully developed turbulence and not in the region of laminar-turbulent transition. Experimental data on pipe friction (e.g., ref. 9, p. 402) indicate that the transition region lies between Reynolds numbers of 2200 and 3200. However, flashback data of figure 2 indicate that the transition region, taken to be that region where the ambient pressure at flashback is independent of the critical stream velocity for a given burner, lies between Reynolds numbers of 1500 and 2500. That is, the transition region is displaced by a Reynolds number of 700. Below $Re = 1500$, equation (5) correlates the data. Above $Re = 2500$, equation (6) gives a good correlation. Because of the displacement of the transition region, no attempt was made to obtain a friction factor for that region from pipe friction data. Instead, flashback velocity gradients were calculated by the laminar expression (eq. (5)) up to the point where the flames appeared visibly and steadily turbulent and the pressure at flashback was no longer independent of Reynolds number. Since the pressure remained constant in the transition region, a more sophisticated calculation would not have altered the curve in any way but would merely have shifted data points along the curves to slightly higher values of $g_f$. Qualitative measurement of longitudinal velocity fluctuation with a hot-wire anemometer showed that, in the absence of a flame, the flow at the center of the tube mouth (for D = 1.89 and 1.459 cm) was laminar below a Reynolds number of about 1500. Between Reynolds numbers of 1500 and 2500 the flow was generally laminar but showed an increasing frequency of turbulent pulsations with increasing Reynolds number. Above $Re = 2500$, the flow was steadily turbulent. Thus the cold-flow behavior correlated well with the flame behavior. This showed that the apparent displacement of the laminar-turbulent transition was characteristic of the tube and was probably not a flame-induced effect.

Effect of pressure and tube diameter. - Figure 2 shows that between equivalence ratios of 0.80 and 2.25 (25 and 48 percent-hydrogen) the pressure exponent of the critical boundary velocity gradient for flashback in the turbulent region $\delta \log g_{f,t}/\delta \log P$ varies in the range 1.22 to 1.44, the variation with composition being random. The average value is 1.31. Since the pressure exponent of the critical boundary velocity gradient for the laminar flames was $1.35 \pm 0.08$ (ref. 3), the
pressure exponents for the laminar and turbulent case are the same, within experimental error. This is to be expected if the boundary velocity gradient at flashback is proportional to a reaction rate (ref. 10).

Experimental results indicate that the average stream velocity at flashback is correlated by a relation of the form

\[ \bar{U}_f = \bar{U}_f^0 k_f D^{m_f} \]  

(9)

where \( \bar{U}_f^0 \) represents the average flashback velocity at 1 atmosphere for a burner 1 centimeter in diameter. Equation (8) may be combined with equation (9) to give

\[ g_{f,t} = 0.023 \bar{U}_f^{0.8} \left( \frac{\mu_k T}{M} \right)^{-0.8} p (0.8 + 1.8 k_f) D (-0.2 + 1.8 m_f) \]  

(10)

which expresses the pressure and diameter dependence of the critical boundary velocity gradient in terms of the pressure and diameter dependence of the critical mean stream velocity. By equations (9) and (10)

\[ \frac{\partial \log g_{f,t}}{\partial \log P} = 0.8 + 1.8 \frac{\partial \log \bar{U}_f}{\partial \log P} \]  

(11)

Since the left side of equation (11) equals about 1.31, the pressure exponent of the critical turbulent flashback velocity is about 0.28.

In a similar fashion, the diameter dependence of the critical flashback velocity and boundary velocity gradient are related by the expression

\[ \frac{\partial \log g_{f,t}}{\partial \log D} = -0.2 + 1.8 \frac{\partial \log \bar{U}_f}{\partial \log D} \]  

(12)

which shows that if the flashback velocity gradient is independent of burner diameter (as seems to be the general case in fig. 2) then the critical mean stream velocity will also be nearly independent and \( \frac{\partial \log \bar{U}_f}{\partial \log D} \) will have a value of about 0.1 at the most.

At an equivalence ratio of 3.00 only a few points could be obtained in the turbulent region. These gave \( \frac{\partial \log g_{f,t}}{\partial \log P} = 1.26 \), a value in good agreement with the general result. At the lean extreme of the composition range covered, \( \Phi = 0.50 \), a much lower value of \( \frac{\partial \log g_{f,t}}{\partial \log P} \) was obtained, about 0.87. Because of the unreliability of the data in this region, no interpretation is put on that result.
Effect of composition. - In reference 3 it is shown that the mean critical laminar flashback velocity and, therefore, the critical laminar boundary velocity gradient, peaked at about \( \Phi = 1.5 \). In the turbulent region, however, the critical velocity peaked at about \( \Phi = 1.8 \), while the boundary velocity gradient peaked, again, near \( \Phi = 1.5 \). The dependence of \( \varepsilon_{f,t} \) on composition at constant pressure is shown in figure 3. Since the viscosity of hydrogen-air mixtures is very nearly constant between \( \Phi = 0.8 \) and \( 2.4 \) and enters into equation (8) only to the 0.8 power (ref. 8), it appears that the difference in peak composition shown between the critical mean stream velocity and the critical boundary velocity gradient does not depend on the viscosity but depends on the density, or, in terms of equation (8), on the pressure and molecular weight. The fact that critical flashback gradients for both laminar and turbulent flames peak at the same equivalence ratio is consistent with the concept that the critical boundary velocity gradient for flashback is proportional to a reaction rate.

Comparison of laminar and turbulent flashback. - Since, within experimental error, the pressure exponents for laminar and turbulent flashback are the same over a range of composition, the relation between laminar and turbulent flashback may be expressed as

\[
\frac{\varepsilon_{f,t}}{\varepsilon_f} = A
\]  

(13)

where \( A \) has a value of about 2.8 and is independent of pressure, burner diameter, and composition. The result represented by equation (13) is similar to that reported in reference 1 (p. 82) for unpiloted turbulent-propane-air flames at pressures greater than 1 atmosphere. In reference 3 laminar flashback velocity gradients for hydrogen-air flames are correlated by the relation

\[
\varepsilon_f = 2.6 \frac{U_b}{D_q}
\]  

(14)

Combination of equations (13) and (14) gives, in the turbulent region,

\[
\varepsilon_{f,t} = 7.3 \frac{U_b}{D_q}
\]  

(15)

Equations (13) and (15) may be explained in terms of the penetration of the flame into the laminar sublayer. Measurements of transverse velocity profiles in pipes have shown that the velocity profile in the sublayer is very nearly linear with radial distance. An empirical expression of the thickness of this sublayer is given in reference 9 (p. 407). In terms of the friction factor given in reference 7, it may be expressed as

\[
l = 33DRe^{-0.9}
\]  

(16)
Velocity-profile measurements show that the laminar sublayer does not merge sharply with the fully turbulent region. Rather, there is a large range of \( \frac{l}{D} \) values which correspond to a region of transition between laminar and turbulent friction. It is quite possible that there should exist a range of values of \( l \) greater than that given by equation (16) over which the turbulent contribution would not be significant. Thus, the coefficient 33 in equation (16) is somewhat arbitrary and seems to give a minimum value for the effective thickness of the laminar sublayer. An alternate expression for \( l \), which is given in reference 11, has the same form as equation (16) but uses a coefficient of 66. Since the velocity profile in the sublayer is linear with radial distance, the boundary velocity gradient may be written as

\[
\alpha_t = \frac{U_{cr}}{l}
\]  

(17)

If equations (6) and (16) are combined with equation (17), an expression is obtained which relates \( U_{cr} \) to the mean flow

\[
U_{cr} = 0.75 \frac{\bar{U}}{Re^{0.1}}
\]  

(18)

Thus \( U_{cr} \) is nearly proportional to \( \bar{U} \). In the presence of a flame which is about to flashback

\[
U_{cr,f} = 0.75 \frac{\bar{U}_f}{Re^{0.1}}
\]  

(18a)

and equation (16) can be combined with equations (14) and (4) to give

\[
\alpha_{f,t} = \frac{(U_b/8)_t}{U_{cr,f}} = \frac{U_{cr,f}}{l}
\]  

(17a)

If the flame penetrates into the laminar sublayer, \( \alpha \) will be less than \( l \). In that case, \( U_b \) must be less than \( U_{cr} \) at flashback. For a Reynolds number of 5000, equation (18a) shows that a minimum value of \( U_{cr} \) is about 0.3 \( \bar{U} \). Thus, if the normal burning velocity is less than 0.3 \( \bar{U} \) at a given pressure, it will be possible for a flame near flashback to penetrate into the laminar sublayer. Since the maximum burning velocity of hydrogen-air flames is about 300 centimeters per second at 1 atmosphere (refs. 3 and 12) and decreases with decreasing pressure, the condition for penetration into the laminar sublayer at flashback will be met as long as the critical average flashback velocity is not much smaller than 1000 centimeters per second.
Table I shows that this condition is generally met. The following is an example based on data of table I:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number, Re</td>
<td>5540</td>
</tr>
<tr>
<td>Average flashback velocity, $\bar{U}_f$</td>
<td>1335</td>
</tr>
<tr>
<td>Critical velocity, $U_{cr}$</td>
<td>422</td>
</tr>
<tr>
<td>Burning velocity (ref. 3), $U_b$</td>
<td>270</td>
</tr>
<tr>
<td>Ambient pressure, $P$, cm Hg</td>
<td>52.5</td>
</tr>
</tbody>
</table>

It appears then, that the burning velocity governing flashback is the laminar burning velocity.

Turbulent and laminar burning velocities shown in figure 4 suggest another interesting point. These data show that $U_{b,t}/U_b \leq 1.30$. Thus, regardless of whether flashback is governed by a laminar or turbulent burning velocity, the threefold increase in the critical boundary velocity gradient with turbulence cannot be ascribed to an increase in burning velocity. By equation (4), then, turbulence must lead to a smaller penetration distance. If turbulent flashback is governed by a laminar burning velocity, it follows from equations (4) and (13) that

$$\delta_t = (1/2.8)\delta$$

Thus, the estimate that the quenching distance between parallel plates should be about twice the penetration distance from a single wall holds only for laminar flow. According to present results, this estimate does not apply to pipe turbulence with a laminar sublayer. As long as the increase in flashback velocity gradient cannot be explained by an increase in flame speed, it seems necessary to assume a smaller penetration distance for the turbulent case, even though it is not easy to imagine why this should be so.

**Blowoff**

Description of results. - Blowoff data are shown in figures 5 to 8. These were obtained at $\Phi = 1.1$ and 1.5, values which correspond, respectively, to conditions of maximum flame temperature and maximum chemical reactivity based on flashback (ref. 3). Since both conditions were richer than stoichiometric, it was desirable to examine the effect of the atmosphere near the flame base. Several check points were run with the flame surrounded by a mantle of inert gas. A low annular flow of carbon dioxide was used, which was just sufficient so that the pink tinge which normally surrounds a hydrogen-air flame disappeared near the flame base. In the laminar region no effect on blowoff limits was observed. In the turbulent region blowoff limits were slightly reduced; that is, the blowoff pressure increased slightly for a given mass flow.
This is attributed to the greater sensitivity of turbulent flames to the cooling effect of a secondary jet. The absence of an effect in the laminar region indicated that the dimensions of the combustion chamber were such that the atmosphere near the flame base was inert and that blowoff was not affected by diffusion of secondary air into the flame base.

In figure 5 are shown stability loops for burners 1.016 and 1.459 centimeters in diameter. These include flashback data previously discussed. Figure 6 shows blowoff curves, incomplete in the low flow region, for two smaller burners, 0.546 and 0.311 centimeter in diameter. Because of unusually smooth inlet conditions, flow in the 0.546-centimeter burner did not become turbulent until a Reynolds number of about 6000 was reached. In order to obtain a larger experimental region of turbulent blowoff, the burner inlet was very loosely packed with steel wool. This procedure induced steady turbulence at a Reynolds number of about 3000. Data for both conditions are shown in figure 6. It should be noted that the blowoff curve in the turbulent region is independent of the Reynolds number at which steady turbulence is achieved. That is, above \( \text{Re} = 6000 \) blowoff data from the disturbed and undisturbed 0.546-centimeter burner lie in a single curve. With the smallest burner (0.311-cm diam.) the onset of steady turbulence was accompanied by the discontinuity in the blowoff curve at a Reynolds number of about 3000 that is shown as a dashed line in figure 6.

The general blowoff curve may be divided into several regions with increasing Reynolds number. (In figs. 5 and 6 a line of constant Reynolds number is represented by \( \text{Pu} = \text{constant} \).) First, there is a region of partial wall quenching where \( \frac{\partial \log \tilde{U}_{bo}}{\partial \log P} \) is negative (\( \alpha \) of fig. 5(d)). Second, there is a region of normal laminar blowoff where \( \frac{\partial \log \tilde{U}_{bo}}{\partial \log P} \) is infinite and then positive (\( \beta \) of fig. 5(d)). Third, there is a region of laminar-turbulent transition. This region corresponds, in terms of Reynolds number, to the transition region for flashback, but effects on the blowoff curve are not at all pronounced (\( \gamma \) of fig. 5(d)). Finally at a critical Reynolds number (in fig. 5 about 2500) the curve breaks sharply upward so that \( \frac{\partial \log \tilde{U}_{bo}}{\partial \log P} \) approaches zero. At some mass flow rate a velocity is reached above which a flame cannot exist for a given equivalence ratio and burner diameter. The blowoff curve may even bend backward so that \( \frac{\partial \log \tilde{U}_{bo}}{\partial \log P} \) assumes a negative value at high mass flow rates.

In the low-flow region it is possible, by extrapolation of blowoff and flashback data to a point (\( q \) of fig. 5), to estimate a quenching pressure and the pressure dependence of quenching diameter. Actual quenching pressures obtained in this way are considerably higher than
those predicted in reference 4 (perhaps because of uncertainty intro-
duced by the long extrapolation imposed by restrictions on the appara-
tus). However, the quenching diameter obtained in this way is very
nearly inversely proportional to pressure; this result is in agreement
with reference 4.

The region of normal laminar blowoff (as distinguished from the re-
gion of partial quenching) may be taken to be bounded on the low-flow
side by the point at which $U_{bo}$ goes through a minimum and on the high-
flow side by the point at which flames assume a nearly steady turbulent
appearance. For the two larger burners this coincides roughly with the
point at which the curves break sharply upward. Thus, a large portion
of the transition region is considered as included in the laminar region.
This may be justified by the fact that the blowoff curve throughout most
of the transition region is a smooth continuation of the normal laminar
curve.

**Effect of pressure and tube diameter.** - In the past, the blowoff of
laminar and turbulent burner flames has been successfully correlated as
a function of burner diameter and equivalence ratio by a boundary veloc-
ity gradient $g_{bo}$ (ref. 13). In practice, this has been calculated in
exactly the same way as the boundary velocity gradient for flashback.
Thus, in the laminar region

$$g_{bo} = \frac{8U_{bo}}{D} \quad (20)$$

and in the turbulent region

$$g_{bo} = 0.023 \left( \frac{Re^{0.8} U_{bo}}{D} \right) \quad (21)$$

It is difficult to relate the observed correlation to a detailed mech-
anism because of two experimental complications. First, if conditions
are close to blowoff, a flame will be stabilized at some distance above
the burner rim; this distance will be a function of pressure, stream
velocity, and initial mixture (ref. 1, p. 80). Therefore, the flame
will be stabilized in the mixing region of the free jet so that a model
based on wall friction within a pipe may not be valid. Second, the burn-
ing velocity at the base of the flame will not correspond to the burning
velocity of the initial mixture because of diffusion near the base of
the free jet. This will be particularly important for rich flames burn-
ing in secondary air. In general, then, if a critical boundary velocity
gradient for blowoff is described as

$$g_{bo} = \frac{U_b}{\delta_{bo}} \quad (22)$$
both $U_b$ and $g_{bo}$ will be uncertain, and the degree of uncertainty will be a function of pressure, stream velocity, and initial mixture. Since, in spite of this uncertainty, a critical boundary velocity gradient has served to correlate blowoff data at constant pressure, it was of interest to examine the effect of pressure and burner diameter for a constant initial mixture. For data plotted in the form of figures 5 and 6, three conditions must be met in order that the velocity gradient model be successful. First, large portions of the laminar and turbulent blow-off curves should be described by straight lines if log $P$ is plotted against log $U_{bo}$ at constant $D$. Second, $g_{bo}$ and $g_{bo,t}$ should be proportional to $g_f$ and $g_{f,t}$, respectively. This means that the pressure and diameter dependence of the critical gradients should be the same for blowoff and flashback. Third, the critical boundary velocity gradient for blowoff should be independent of burner diameter. In the turbulent region, this condition implies that the critical mean blowoff velocity should also be nearly independent of burner diameter, since an equation of the form of equation (11) should hold for blowoff.

Figures 5 and 6 show that the first condition is not met. Even if the region of partial wall quenching is not considered, the laminar blowoff curve shows considerable curvature. The turbulent portion is more nearly linear, but is not entirely free from curvature.

The second condition is not met either. Figure 7 shows a log-log plot of $g_{bo}$ against pressure. Data are taken from the "normal laminar" portions of figures 5 and 6. Any reasonable average value for the pressure dependence of $g_{bo}$ would be two or three times larger than the value for $g_f$ and thus would have no meaning in terms of the simple model. With regard to the turbulent region, the proportionality of $g_{bo,t}$ and $g_{f,t}$ implies that the blowoff curve (log $U$ plotted against log $P$) should break sharply upward with the onset of turbulence in a fashion similar to the behavior of the flashback curve. This is actually observed in figures 5 and 6; however, results are not sufficiently consistent to warrant quantitative discussion.

Figure 7 also shows that $g_{bo}$ is somewhat dependent on burner diameter, particularly for smaller burners. Furthermore, in the turbulent region the critical mean blowoff velocity is rather strongly dependent on burner diameter. If observed or estimated values for this maximum over-all blowoff velocity are plotted against burner diameter, the observed value of the pressure exponent is about $-0.5$. This is shown in figure 8. This result indicates that increasing burner diameter will actually decrease the stability of a burner flame to blowoff. Thus, the third condition is satisfied in neither laminar nor turbulent regions.
Generally, it must be concluded that the velocity gradient model does not explain the dependence of either laminar or turbulent blowoff on pressure and burner diameter.

Recently two rather limited theoretical treatments have been offered which lead to explicit expressions for the pressure dependence of critical blowoff velocity. In one treatment (ref. 14) it is assumed that blowoff occurs because of the interruption of flame propagation caused by a high velocity gradient near the flame base. In the other treatment (ref. 15, p. 182) blowoff is assumed to occur simply because the mass flow rate through the burner exceeds a critical mass reaction rate. Both treatments concern piloted turbulent burner flames. However, since neither treatment considers any specific effects which a pilot might have on flame stability, it is of interest to see how well each of them describes the blowoff of turbulent flames stabilized without a pilot.

In reference 14 it is shown that a high boundary velocity gradient near the base of a turbulent flame could induce instability by reducing the local flame speed. A relation is derived which may be expressed as

$$\beta' \propto U^{7/8} D^{-1/8} P^{-(1/8+n)}$$

(23)

The condition for the interruption of the flame propagation was that $\beta'$ assume a critical value. Setting $\beta' = \text{Constant}$ and using $n = 0.23$ (ref. 3) give

$$U_{bo} \propto P^{0.41} D^{0.125}$$

(24)

By reference to figures 5 and 8, it may be seen that equation (24) does not adequately describe blowoff results, particularly with regard to the dependence of blowoff velocity on burner diameter.

Reference 15 (p. 182) also derives an expression for the critical blowoff velocity of piloted turbulent burner flames. In this case the criterion for flame extinction is that the mass flow rate exceed the total mass reaction rate. This leads to an expression

$$U_{bo} \leq \frac{\delta_{U_b}}{D FU_b^2} \times \text{Constant}$$

(25)

Since most combustion systems follow an equation of the form

$$U_b = U_b^{CP^n}$$

(26)
equation (25) may be written as

\[ \overline{U_{BO}} \leq D_p^{2n+1} \times \text{Constant} \]  \hspace{1cm} (27)

For hydrogen-air flames, this becomes

\[ \overline{U_{BO}} \propto p^{1.46}D \]  \hspace{1cm} (28)

Both pressure and diameter exponents are very much larger than those actually observed. This may be due to the exceedingly simple model of turbulent flame stabilization adopted in reference 15, which would predict much higher values of \( \overline{U_{BO}} \) than are actually observed. The inequality sign in equation (27) may serve to represent the fact that real burner flames are much more sensitive to external disturbances than the model of reference 15 would predict.

Although neither treatment can be considered satisfactory, equation (24) represents the data more closely than equation (28) with respect to both pressure and burner diameter. It appears that whatever weaknesses may be involved in the model of reference 14, a consideration of shear near the base of a turbulent flame appears to give somewhat closer agreement with experiment than a consideration of mass flow and mass reaction rates only.

**SUMMARY OF RESULTS**

Stability limits of laminar and turbulent hydrogen-air burner flames were measured over a range of subatmospheric pressures. The following results were obtained:

1. The pressure exponent for the critical flashback boundary velocity gradient was the same for both laminar and turbulent flames. The composition at which it peaked was also the same.

2. The turbulent-to-laminar ratio of critical flashback boundary velocity gradients was 2.8. The difference between the gradients was not caused by an increased burning velocity for the turbulent case, but rather implied that the penetration distance for turbulent flashback was about \( 1/3 \) of the penetration distance for the laminar case.

3. Turbulent blowoff velocity was nearly independent of pressure and varied approximately with the inverse square root of burner diameter. None of the current mechanisms of flame blowoff predict these results.
4. Extrapolation of stability loops to the quenching point showed that the quenching pressure was inversely proportional to burner diameter. The actual pressures obtained were higher than those obtained by other methods.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 29, 1957

REFERENCES


TABLE I. FLASHBACK OF HYDROGEN-AIR FLAMES

<table>
<thead>
<tr>
<th>Ambient burner diameter, d, cm</th>
<th>Equivalence ratio, φ</th>
<th>Average flame velocity, (\frac{V}{d}), cm/sec</th>
<th>Critical boundary velocity for laminar flashback, (V_b), cm/sec</th>
<th>Critical boundary velocity for turbulent flashback, (V_t), cm/sec</th>
<th>Reynolds number, (Re)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70.7</td>
<td>1.016</td>
<td>0.50</td>
<td>317</td>
<td>6,530</td>
<td>23.2</td>
</tr>
<tr>
<td>50.8</td>
<td>1.149</td>
<td>0.50</td>
<td>937</td>
<td>5,580</td>
<td>26.5</td>
</tr>
<tr>
<td>47.9</td>
<td>1.210</td>
<td>0.50</td>
<td>470</td>
<td>5,480</td>
<td>27.5</td>
</tr>
<tr>
<td>46.9</td>
<td>1.210</td>
<td>0.50</td>
<td>523</td>
<td>4,620</td>
<td>30.4</td>
</tr>
<tr>
<td>46.2</td>
<td>1.150</td>
<td>0.50</td>
<td>462</td>
<td>5,760</td>
<td>26.7</td>
</tr>
<tr>
<td>45.0</td>
<td>1.016</td>
<td>0.60</td>
<td>722</td>
<td>6,530</td>
<td>23.2</td>
</tr>
<tr>
<td>47.9</td>
<td>1.210</td>
<td>0.50</td>
<td>842</td>
<td>6,850</td>
<td>23.6</td>
</tr>
<tr>
<td>45.0</td>
<td>1.016</td>
<td>0.60</td>
<td>510</td>
<td>5,760</td>
<td>26.7</td>
</tr>
<tr>
<td>45.0</td>
<td>1.016</td>
<td>0.60</td>
<td>722</td>
<td>6,530</td>
<td>23.2</td>
</tr>
<tr>
<td>47.9</td>
<td>1.210</td>
<td>0.50</td>
<td>842</td>
<td>6,850</td>
<td>23.6</td>
</tr>
<tr>
<td>52.6</td>
<td>1.150</td>
<td>0.50</td>
<td>944</td>
<td>11,100</td>
<td>36.9</td>
</tr>
<tr>
<td>52.8</td>
<td>1.150</td>
<td>0.50</td>
<td>944</td>
<td>11,100</td>
<td>36.9</td>
</tr>
<tr>
<td>53.1</td>
<td>1.210</td>
<td>0.50</td>
<td>722</td>
<td>6,530</td>
<td>23.2</td>
</tr>
<tr>
<td>46.2</td>
<td>1.150</td>
<td>0.50</td>
<td>944</td>
<td>11,100</td>
<td>36.9</td>
</tr>
<tr>
<td>47.9</td>
<td>1.210</td>
<td>0.50</td>
<td>842</td>
<td>6,850</td>
<td>23.6</td>
</tr>
<tr>
<td>52.6</td>
<td>1.150</td>
<td>0.50</td>
<td>944</td>
<td>11,100</td>
<td>36.9</td>
</tr>
<tr>
<td>52.8</td>
<td>1.150</td>
<td>0.50</td>
<td>944</td>
<td>11,100</td>
<td>36.9</td>
</tr>
<tr>
<td>53.1</td>
<td>1.210</td>
<td>0.50</td>
<td>722</td>
<td>6,530</td>
<td>23.2</td>
</tr>
</tbody>
</table>

Notes: 
- Critical boundary velocity for laminar flashback, \(V_b\), is determined using the correlation given in the paper.
- Critical boundary velocity for turbulent flashback, \(V_t\), is derived from empirical data.
- Reynolds number, \(Re\), is calculated based on the average flame velocity and burner diameter.
TABLE II. - FLASHBACK OF TURBULENT HYDROGEN-AIR FLAMES

<table>
<thead>
<tr>
<th>Equivalence ratio, $\phi$</th>
<th>$\frac{\partial \log g_{f,t}}{\partial \log P}$</th>
<th>$\left(\frac{g_{f,t}}{g_f}\right)_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.87</td>
<td>\text{--------}</td>
</tr>
<tr>
<td>.80</td>
<td>1.44</td>
<td>2.5 to 3.3</td>
</tr>
<tr>
<td>.95</td>
<td>1.22</td>
<td>2.5 to 2.9</td>
</tr>
<tr>
<td>1.20</td>
<td>1.38</td>
<td>\text{--------}</td>
</tr>
<tr>
<td>1.50</td>
<td>1.28</td>
<td>2.6</td>
</tr>
<tr>
<td>1.80</td>
<td>1.34</td>
<td>2.7</td>
</tr>
<tr>
<td>2.25</td>
<td>1.23</td>
<td>3.2</td>
</tr>
<tr>
<td>3.00</td>
<td>1.26</td>
<td>\text{--------}</td>
</tr>
</tbody>
</table>
Figure 1. - Combustion apparatus.
Figure 2. - Flashback of laminar and turbulent hydrogen-air flames.
Figure 2. - Continued. Flashback of laminar and turbulent hydrogen-air flames.
Figure 2. - Continued. Flashback of laminar and turbulent hydrogen-air flames.
(g) Equivalence ratio, 2.25 (mixture 48.4 percent hydrogen); $\partial \log g_f/\partial \log P$, 1.35; $\partial \log g_{f,t}/\partial \log P$, 1.23.

(h) Equivalence ratio, 3.00 (mixture 55.5 percent hydrogen); $\partial \log g_{f,t}/\partial \log P$, 1.26; burner diameter, 1.890 centimeters.

Figure 2. - Concluded. Flashback of laminar and turbulent hydrogen-air flames.
Figure 3. - Turbulent flashback velocity gradient as function of composition at constant pressure.
Figure 4. - Laminar and turbulent burning velocity for hydrogen-air flames as function of pressure. Equivalence ratio, 1.8.
Figure 5. - Stability loop for hydrogen-air flames.
(d) Burner diameter, 1.469 centimeters; equivalence ratio, 1.50 (mixture 38.4 percent hydrogen).

Figure 5. - Concluded. Stability loop for hydrogen-air flames.
Figure 6. - Blowoff of hydrogen-air flames from small burners. Equivalence ratio, 1.10.
Figure 7. - Comparison of data from figures 5 and 6 for blowoff of laminar hydrogen-air flames. Equivalence ratio, 1.10.
Figure 8. - Dependence of turbulent blowoff velocity on burner diameter. Equivalence ratio, 1.1; diameter exponent at blowoff, $m_{bo}$, -0.47.