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Conceptual Model of Turbulent Flameholding for Scramjet Combustors

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SUMMARY

Concepts which are believed applicable to the basic understanding of the pertinent flow processes involved in turbulent flameholding and flamespreading have been reviewed with an interest in their application to design of scramjet combustors. As a result, some new concepts have been generated and some new approaches to modeling of these extremely complex processes have been suggested.

For flameholding, these new concepts include

1. Blowoff is caused by the flame inside the recirculation zone failing to reach the dividing streamline at the rear stagnation zone rather than from heat-flow divergence ($K \geq 1$) in the shear layer outside the dividing streamline. When this happens, "cold" mixture enters and "snuffs out" the flame in the recirculation zone and the external "held" flame breaks off.

2. Increased turbulent exchange across the dividing streamline helps flameholding due to forward movement of the flame anchor point inside the recirculation zone rather than from increased heat flow to the outer shear layer. The increased mixing thickness in the outer flow helps the initial flamespreading.

3. Modeling of the blowoff phenomenon is based on the concept that the time required for a flow element of reactants to travel along the dividing streamline is equal to the time required for a flame element to travel across the recirculation zone.

For flamespreading, it is believed that the idea that laminar flame concepts do not relate to high-shear flames is true only for the case of fast chemistry, where the turbulent fluid parcels are effectively consumed as fast as generated by shear. For slow chemistry (low p, T, ϕ, or high u) the smaller parcels of reactants will burn faster than the larger ones, but overall combustion may be retarded.

The scale required to achieve flameholding in a scramjet combustor has been calculated using the present model. The results show a strong adverse effect of low p and low ϕ on flameholding with some adverse effect of increased M_∞, which is opposite to that for self-ignition. There was little effect due to change of recovery factor F_R, again, different from self-ignition.

Based on these results, recommendations are made for needed research efforts to reduce some of the uncertainties associated with the model concepts and to increase confidence in the ability to design a combustor for high-speed air-breathing vehicles. It is recommended that main fuel injection not be coincident with the flameholder and that the flameholder be independently fueled, either by premixing an upstream flow layer or by adding fuel (and oxygen) directly into the recirculation zone. It is also recommended that ignition be accomplished with a separate ignitor, rather than depend on self-

ignition. A hot-gas pilot is recommended as a superior ignitor-flameholder. Combustor design should be based on flamespread angle and not simply on mixing-spread angle.

INTRODUCTION

Combustion in air-breathing propulsion devices for hypersonic vehicles must occur at supersonic velocities in order to avoid the high T, p, and heat transfer rates that result when the flow is decelerated to subsonic speeds (ref. 1). At supersonic speeds, the injection, mixing, ignition, and combustion times must be very short (total time must be less than 1 ms) to avoid excessively long combustion chambers and the attendant problems of increased weight, drag, and heat loss.

For optimum propulsion performance over a flight Mach number range, the heat release must be distributed along the combustor (cross-sectional area) in a prescribed manner at each Mach number. A unique and convenient way to accomplish this is proposed in reference 1 and involves the use of a mixed-mode fuel-injection concept. With this concept the mixing lengths are tailored with flight speed by variation of the split between two modes of fuel injection. These modes are transverse injection for shorter mixing lengths and streamwise injection for longer mixing lengths.

Success of this concept, or any concept based on a prescribed heat-release distribution, requires that the ignition and flameholding processes occur at prescribed locations in the combustor. For hydrogen fuel in air, the self-ignition process is very temperature dependent (ref. 2) so that significant variation of self-ignition delay (hence flame position) might be expected to occur with changes in M_∞, altitude (p), and fuel-air ratio (ref. 2). In view of the need for positive ignition control at all flight speeds, and the fact that self-ignition is not reliable at the lower speeds, a separate ignition source may therefore be required and is desirable in ground tests where test conditions are frequently changed.

For positive control of the flame position, a flameholder or pilot flame is required, or a staged fuel injection scheme might be used to provide a flame-holding separated-flow region. Which method is more suitable depends on the particular configuration, type of fuel used, gas flow conditions, and control systems available.

With the ignition and flame anchor point established, the release of heat occurs through transverse propagation of the flame from the anchor point across the combustor flow. For premixed fuel and air, the rate at which the flame propagates transversely (flamespreading) is a complex combination of the chemical chain-reaction system and the turbulence generated in the flow and at the flame front. For diffusion flames, the flamespreading rate may also depend on the turbulent mixing rate, if reaction chemistry is fast relative to mixing.

In this paper the basic concepts relating to the fluid mechanical and thermochemical processes involved in flamespreading and flameholding will be reviewed for application to scramjet combustor design. It is not intended to

be a general survey or critique of work relating to these processes, but rather to provide a brief restatement of concepts pertinent to the understanding of the scramjet problem. This review then serves as a background or starting point for development of new approaches to the understanding and modeling of some of these processes as well as to the delineation of needed areas of research.

A conceptual model of flameholding is presented which can be used to predict the parametric dependency and approximate magnitude of the bluff-body scale required to achieve flameholding. Since the model is developed based primarily on subsonic concepts, it is recognized that compressibility effects, including shocks and expansions, in supersonic flow may alter somewhat the assumed structure of the separated flow region.

SYMBOLS AND ABBREVIATIONS

a,d	flame dimensions, streamwise and normal to flow
BO	blowoff
b	base height
C_p	specific heat at constant pressure
c	mass fraction
DS	dividing streamline
F_R	recirculation-zone temperature recovery factor
H	enthalpy
h	step height
K	Karlovitz number (flame-stretch parameter), equation (2)
k	thermal conductivity
L	length of dividing streamline along recirculation-zone boundary
ℓ	flow length
M_∞	flight Mach number
N_D	Damkohler number
p	pressure
S_T, S_L	flame speed, turbulent and laminar
T	temperature

u, u'	flow velocity, turbulent velocity fluctuation
x	distance along flow direction
y	distance normal to flow direction
Δ_r	transverse distance from flame anchor point to dividing streamline
η_o	flame thickness parameter
ρ	density
τ	time
ϕ	fuel equivalence ratio
ψ	flame tilt angle (relative to perpendicular to the local flow)

Subscripts:

ahead	ahead of flame in shear layer
b	burned
comb	combustion products
e	edge of shear layer
f	fuel
max	maximum
mix	premixed fuel and air
R	recovery
u	unburned

Superscripts:

o	at 1 atm pressure (1 atm = 101.3 kPa)
^	at anchor point in recirculation zone, partial pressure
n	exponent on pressure
*	along dividing streamline
—	integrated average, mean

PREMIXED VERSUS DIFFUSION FLAMES

Before discussing the mechanics of flamespreading and flameholding, it is well to consider similarities and differences in these processes for the cases of premixed reactants versus mixing reactants (diffusion flames). On a local scale, of course, the reactants are premixed in both cases before reaction can take place. For the diffusion flame the reaction cannot occur faster than the mixing, so in this case it is mixing controlled. However, reaction can certainly occur slower than the mixing (for finite-rate kinetics), so in this case the combustion is reaction rate controlled. Therefore, at conditions where the reaction rates are of the same order as the mixing rates there is little basic difference between the mechanism of flame propagation in premixed and diffusion flows.

The parameter used to determine if finite-rate kinetics are important is the Damköhler first number, defined as the ratio

$$N_D = \frac{\text{Reaction rate}}{\text{Mixing rate or flow rate}}$$

where

$$\text{Reaction rate} \propto Tp^n$$

$$\text{Flow rate} \propto \frac{u}{\ell} \propto \frac{1}{\text{Flow time}}$$

Note that the reaction rate system is not strongly dependent on ϕ as long as ϕ is not greatly different from 1.0. Therefore, within this constraint,

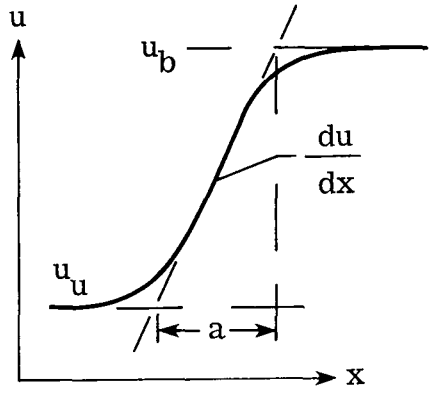
$$N_D \propto \frac{\ell T p^n}{u} \tag{1}$$

For $N_D \gg 1$, the chemistry is considered fast and equilibrium can be assumed; for $N_D \ll 1$, the chemistry is frozen (no reaction). However, when $N_D = O(1)$ finite-rate kinetics must be considered. For supersonic combustion problems, with low T, p, and high u, finite-rate kinetics must be considered over a significant part of the flight regime. For the purpose of this review, therefore, it is deemed appropriate in the following discussion to apply the characteristics of flamespreading and flameholding in premixed flows to the modeling

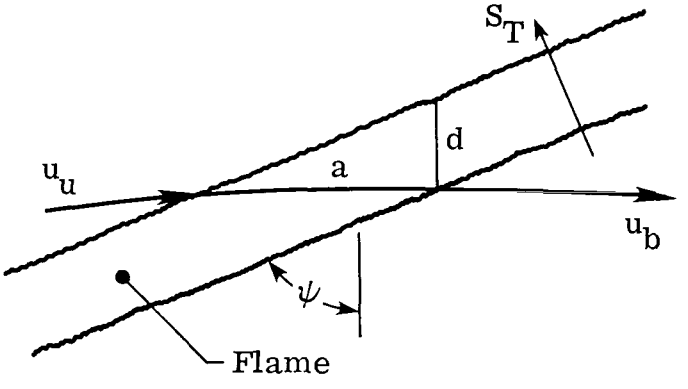
of scramjet combustor flows. In some scramjets, good flameholding and flame-spreading depend on obtaining sufficient heat release in the flameholding region so the p and T of the main flow are increased enough for reaction and heat release to occur in relatively short distances.

TURBULENT FLAMESPREADING

Flamespreading is the propagation of the flame from the anchor point across the combustor flow. In scramjet combustors, flamespreading involves high flame-generated shear and strong shear-generated turbulence which are primarily due to the high combustor velocity and large flame tilt angle (the latter is also caused by the high combustor velocity). This can be seen with the help of the following sketches of an idealized flame in uniform flow:



Streamwise velocity increase through flame



Increased shear due to flame tilt

The velocity gradient normal to the stream direction is then

$$\frac{du}{dy} = \frac{du}{dx} \tan \psi$$

and for large tilt angles the shear-producing velocity gradient $\frac{du}{dy}$ may be 10 or more times the streamwise gradient. This flame-generated shear $\left(\frac{d(\rho u)}{dy}, \right.$ or $\left. \rho \frac{du}{dy} \text{ in the region of the flame front} \right)$ increases as u_u, ψ, and $\Delta H(\phi)$ increases.

In the region of strong interaction (strong flame-generated turbulence) those properties which can greatly influence laminar flame propagation (as well as lower-shear turbulent flames) have been found to have no significant influ-ence on the high-shear propagation, at least for fast chemistry. These proper-ties include fuel type, ϕ, T_u, and initial turbulence, as shown in refer- ences 3 and 4 (for subsonic flow). It might be expected that at ϕ's well removed from 1.0 (low temperature rise, hence low Δu) there would be some influence.

The propagation is apparently accomplished almost entirely by the shear generation of turbulence, with the flame front being a conglomeration of "par-cels" of either reactant mixture surrounded by burned gas, or vice versa (fig. 1). At no instant in time or space does the front show a smooth steady transition from unburned to burned gas with associated smooth changes in T, u, etc. The parcels are continuously generated by shear and preferentially consumed by reaction and/or accelerated by pressure fields. (See refs. 5 to 11 and T. Y. Toong's comment in ref. 4.)

In the presence of a streamwise pressure gradient, the hot-gas parcels are differentially accelerated, with respect to the cold gas flow, in a direction depending on the pressure gradient so that the turbulent combustion phenomenon can be quite different in a ducted flow from that in a free-jet configuration. Of course, for finite-rate chemistry, both laminar and turbulent combustion can be different for the case of ducted versus unducted flow due to pressure effects on kinetics.

The reactant-mixture parcels ignite and are burned in random sporadic fashion (on a local scale) but the net effect of the combined heat release is to produce an average temperature rise, which in the laminar flame concept leads to heat-conduction propagation. However, for turbulent flames the shear gener-ated by the u increase due to added heat leads to a propagation rate more dependent on shear-generated turbulence of the flame than on laminar conduction. Therefore, unless the temperature rise is quite low, preventing rapid parcel ignition (low ϕ, or high inert gas dilution), the flamespreading process is fairly insensitive to the laminar parameters ϕ, fuel type, and T_u, or to ini-tial turbulence since the parcels are ignited and burned about as fast as they are formed. Furthermore, it is interesting that when u_u is increased the shear is increased (which increases the formation and consumption of the par-cels) such that the increased propagation rate is about the same as the velocity increase and ψ does not change much (refs. 3 and 4). Apparently the only way to change ψ is to change the shear without changing the approach velocity. The implication is that none of the above parameter changes does this.

When chemical kinetics becomes important (due to low ϕ, low p, or high u_u) then the flame propagation rate should become sensitive to the laminar flame parameters because the reactant-mixture parcels will not be consumed as fast as formed. Note that almost all of the flamespread studies reported in the liter-ature have been at subsonic speeds and atmospheric pressure, so that the effects of high velocity, low pressure p^n, and compressibility, which would increase the importance of kinetics, have not been observed.

Therefore, in the gross sense, scramjet flamespreading is a shear-generated-turbulence process, although in the microscopic sense the parcels are burned by the usual laminar conduction process.

FLAMEHOLDING

A flameholder is a scheme (either aerodynamic or geometric or both) to provide a region of low velocity in a high-velocity combustible mixture, where the flame can be stabilized (anchored). Flame velocities are characteristically very low in comparison with most aerodynamic flows (except the very low subsonic) and the flame will blow off unless the basic criteria for flame stabilization are met. The first criterion is that, somewhere in the flow, the local flow velocity is equal to the local flame velocity. Other criteria, such as boundary velocity gradient or flame stretch, must also be met to prevent the anchored flame from breaking off or being quenched. The most common form of flameholder is the separated flow region behind a step or bluff body (e.g. ref. 12).

Step and Bluff Body

The principal features of the flameholding region behind a step or bluff body are shown schematically in figure 2. The shear layer (i.e. detached boundary layer of the approaching flow) and the dividing streamline start at the point of boundary-layer separation from the body and continue until reattachment of the layer at the rear stagnation zone. The dividing streamline represents the boundary between gases which are recirculating at low velocity within the separated region, and the high velocity shear-layer gases which have sufficient momentum to negotiate the pressure rise at the reattachment point and continue on. Although there is no net flow across the dividing streamline, there is some turbulent exchange of gases across it such that the flow of recirculating gases out of the recirculation zone is balanced by the flow of shear-layer gases into the recirculation zone. The mixing layer represents the extent of this exchange; it starts at the separation point with zero thickness and grows in thickness on either side of the dividing streamline.

In the preceding case of flamespreading, the high-shear condition was flame generated. This shear led to strong turbulence which was the "flame-driving mechanism" which, in turn, resulted in the generation of shear, and so on. For the case of flameholding behind a bluff body, the aerodynamically generated shear layer (due to flow separation behind the bluff body) is also high shear. However, when a flame is present in the recirculation region next to the aerodynamic shear layer, the shear is reduced due to the higher recirculation velocity at the higher temperature of the combustion products (ref. 13). Furthermore, the high shear is not maintained along the separated layer (as it is along the high-shear flame) but decreases with distance behind the separation point due to viscous spreading of the layer.

The turbulent exchange of mass, momentum, and energy across the dividing streamline (and the resulting mixing layer) is of utmost importance to the

flameholding process. This is the means through which reactant-mixture gas is supplied to the recirculation zone to maintain combustion there, and through which hot combustion products, including chain carriers from the recirculation zone, are supplied to the shear-layer flow outside the dividing streamline to heat this layer and promote the initial flamespreading. The greater the turbulent exchange across the dividing streamline, the better the flameholding and initial flamespreading, as will be described.

As depicted in figure 2, the flame originates from an anchor point in the inner, low velocity part of the recirculation zone where local u = local S_T, and where the velocity gradient $\frac{du}{dy}$ ahead of the flame is not so large that the flame is "stretched" beyond a critical value. The concept of flame stretch refers to the fractional area increase incurred by propagation of a curved flame front, where the curvature is due to propagation through a nonuniform flow region such as a shear layer. An indication of this fractional area increase is given by the flame-stretch parameter

$$K = \frac{du}{dy} \frac{k}{C_p \rho} \frac{1}{u S_T} \tag{2}$$

which is also called the Karlovitz number (ref. 14). From the anchor point, the flame propagates out toward the dividing streamline with $\frac{du}{dy}$, u, and ρ increasing. The variation of S_T is nonmonotonic (see fig. 3) and will be discussed later. The combination must be such that $K \leqq 1$ or the flame will self-quench, resulting in blowoff. This self-quenching results from the divergence of the conduction heat flow from the burned gases behind the flame to the unburned gases ahead (ref. 12). For a plane flame front, $\frac{du}{dy} = 0$, $K = 0$, and no quenching occurs.

Figure 3 illustrates the nature of the variation of T_u, S_T, and c_{mix} across the mixing layer ahead of the flame. Note that $y = 0$ is the flame anchor point near the inner edge of the mixing layer, and $y = \Delta_r$ is the dividing streamline. At the outer edge of the layer $\left(\text{at some } \frac{y}{\Delta_r} > 1.0\right)$ the conditions are no longer affected by the exchange process. It is seen that S_T is higher than $S_{T_{mix}}$ over the outer portion of the mixing layer and lower over the inner portion. This nonmonotonic behavior results from two opposing effects; the temperature increases toward the inner portion of the layer, which tends to increase S_T, but the decreasing value of c_{mix} lowers S_T due to the lower partial pressure of the unburned mixture.

It should be noted that the shape of the c_{mix} profile (fig. 3) was arrived at in a somehwat arbitrary manner, however, the general features including c_{mix} values at the end points and at Δ_r are correct.

Note that for the previous flamespreading case, the flame was propagating into a uniform stream so that the concept of flame stretch does not need to be considered, even if it were a laminar concept. However, laminar concepts do (at least partially) apply to the flame within the recirculation region and for some distance into the shear layer. As the flame propagates out into the shear layer (usually aft of the recirculation zone) where u and ψ are higher, the flame becomes more like the high flame-generated shear case for flamespreading (with high flame-generated turbulence). Therefore, the flame is more a heat-conduction flame (laminar concept) when inside the recirculation zone and becomes a high-shear-turbulence flame after it leaves the recirculation zone and goes into the flamespreading mode.

As indicated in figure 2, a recycling and exchange of the outer part of the gases in the recirculation zone occurs. The process proceeds as the reactant mixture, which has crossed the dividing streamline, mixes with recirculating burned products in the inner mixing layer and is burned in the recirculation-zone flame. Those gases recirculating inside the flame anchor point region (i.e. region bounded by gases flowing through the flame anchor point, as shown in fig. 2) are not exchanged much (there is some turbulent exchange) but remain as essentially trapped products. Reference 15 reports that near-theoretical flame temperatures have been measured in the recirculation zone.

Better flameholding capability means that the flame can be anchored at higher approach velocities, and improved flameholding results when the exchange rate across the dividing streamline increases. The resulting increase in mixing-layer thickness (penetrating farther into the recirculation zone) allows the flame to move further forward, and hence permits a higher flow velocity before the flame crosses the dividing streamline near the rear stagnation zone.

It is interesting to note that an increase in the oncoming stream turbulence was observed to increase the exchange across the dividing streamline (for both flame and no flame, ref. 13). This increase in exchange could possibly be due to transition of the separated flow occurring sooner, or due to the strong aerodynamically generated shear acting to amplify any upstream turbulence. Furthermore, it was found that increasing the oncoming boundary-layer thickness also increased the exchange $\left(\text{even though } \frac{du}{dy} \text{ is thereby decreased for a given total } \Delta u\right)$ since there is more total turbulence due to the increased boundary-layer mass involved, and a larger scale of turbulence. Scramjet flameholding may not necessarily be better with a thicker boundary layer, because the larger T defect in the cold-wall boundary layers that are usually present in scramjets may have a detrimental effect on S_T.

An increase of temperature in the mixing layer also helps flameholding and initial flamespreading. The accompanying increase in S_T due to increased reaction rates and production of chain carriers results in a lower value of ψ and a forward movement of the anchor point, both of which allow for higher

approach velocity before blowoff. The turbulent exchange is somewhat reduced due to the higher mixing layer T and higher u, but apparently the reduction is not too detrimental to flameholding since it has been observed in reference 15 that flameholding is best when $\phi \approx 1$ inside the recirculation zone.

A large additional gain in flameholding and flamespreading ability can be realized by bleeding additional fuel (and oxygen) into the recirculation zone since the T will be significantly increased over that for air, and the "effective" exchange is also greatly increased.

Blowoff.- In the stable flameholding condition, all the fresh mixture entering the recirculation zone across the dividing streamline is burned by the flame inside the recirculation zone (the gas temperature in the recirculation zone was found to be close to the theoretical flame temperature for the mixture (ref. 15)). Figure 4 shows a schematic of a flameholder at a velocity below that of blowoff. The processes leading up to the blowoff condition are as follows:

As the oncoming stream velocity is increased, the anchor point of the flame moves closer to the $u = 0$ line to maintain local $u = S_T$ and moves farther aft where $\frac{du}{dy}$ is lower, and the flame propagates at a more inclined trajectory (ψ increases). As the blowoff condition is approached, the point where the flame crosses the dividing streamline is very near the rear stagnation zone as shown in figure 2. When the velocity is further increased, the flame does not cross the dividing streamline at the rear of the recirculation zone but remains inside; the connection to the outer "held" flame is broken so that it blows off, allowing some of the cooler unburned gas mixture to enter the recirculation zone. The mixture ahead of the recirculation-zone flame then becomes cooler, S_T decreases further, and the flame falls further below the dividing streamline. The process rapidly quenches the flame in the recirculation zone; of course, the flamespreading had already ceased.

It should be pointed out that the flame-stretch parameter K is most likely highest inside the recirculation zone at the flame anchor point where u is very low, S_T is low, and $\frac{k}{C_p\rho}$ is very high. As the flame propagates out toward the dividing streamline and into the shear layer, the stretch factor decreases substantially, but probably not monotonically. The high $\frac{du}{dy}$ right at the dividing streamline may result in a localized increase of K in this region, but not above the critical value. The blowoff condition, therefore, results from a failure of the flame to reach the dividing streamline at the rear of the recirculation zone, thereby resulting in quenching due to the entering cold flow (more like "snuff out"). Note that this concept is different from the commonly used concept (e.g. refs. 12, 13, and 16) that at blowoff the critical value of the flame-stretch parameter is reached near the rear of the recirculation zone, at the dividing streamline, which causes the held flame to blow off and cold mixture to then enter and quench the recirculation-zone flame.

This is not believed to be the sequence, or an accurate description, of the actual blowoff mechanism for the following reasons:

(1) In order for K to be greater at the aft dividing-streamline point than at the anchor point of the recirculation flame, $\frac{du}{dy}$ has to be greater there by a very large factor, since fairly large changes in each of the other parameters act in combination to greatly lower K, except right at the rear stagnation point where u drops to zero. (See eq. (2).)

(2) Since the flame does not blow off at approach velocities lower than the blowoff velocity, acceptance of the previous concept means that K must be less at the more forward crossing point (at the lower velocity) than it is at the rear crossing point at blowoff (where K is allegedly greater than 1.0). Such a relationship is not at all likely based on consideration of the change in u along the dividing streamline and of changes in $\frac{du}{dy}$ and u which occur when approach velocity is lowered (note that the parameters $\frac{k}{c_p\rho}$ and S_T will not change much along the dividing streamline since this is a constant 50-50 mixture of outgoing hot flame products and incoming cold fuel-air mixture). For K to be lower at the forward crossing point (when approach velocity is reduced) means that $\frac{du}{dy}$ must be lower by a larger factor than that by which u is lower. The opposite is much more realistic since the velocity gradients are relatively steeper further forward where the turbulent exchange is less and the mixing layer is thinner. Therefore, even though the overall shear intensity is about proportional to approach velocity, there is a decreasing shear intensity toward the rear so that a shift of the crossing point forward is to make $\frac{du}{dy}$ proportionately increase (therefore an increase in K). Additionally, the value of u along the dividing streamline increases toward the rear (refs. 17 and 18) at a given approach velocity (again, except right at the rear stagnation point), which would act to further increase K in the forward position.

Based on the present concept, therefore, blowoff is related to the flame trajectory inside the recirculation zone (i.e. u and S_T) rather than to critical flame stretch K in the outer region of the mixing layer. Accordingly, if the flame can be maintained in the recirculation zone then the outer held flame will be maintained; likewise, the inner flame should not be dependent upon the products of the held flame as suggested in reference 16. Furthermore, it is believed that the improved flameholding observed when a fuel-air mixture is injected into the recirculation zone (ref. 16) is due to an increase in the "exchange" rate resulting in a forward movement of the flame anchor point.

Effect of slow chemistry.- When the reaction rate is no longer much faster than the mixing rate or flow rate ($N_D = O(1)$, or less) due to lower p, T,

ℓ, or higher u, the flameholding process departs from an equilibrium chemistry case. If laminar flame concepts applied throughout the flameholding region, the first place where the effects of slow chemistry would be seen would be in the flame propagation in the outer shear layer where u is higher and T is lower. Since this is the high-flame-generated-shear flamespreading condition where laminar flame concepts do not strongly apply (see flamespreading section), the finite-rate chemistry effects may not be so evident except when p is low and/or when ϕ is well away from 1.0, in which case the reaction rate decrease might lower the parcel consumption rate in the shear layer, and S_T in the recirculation zone.

Hot-Gas Pilot as an Ignitor-Flameholder

A hot-gas pilot can serve as an alternate to the step or bluff-body flameholder. The pilot (see fig. 5) acts as an ignitor-flameholder by providing a continuous supply of high temperature, high chain-carrier gases contiguous with the main-stream mixture. The transfer of heat and chain carriers from the pilot gases to the mixture ignites the mixture at some downstream point in the mixing layer near the hot-gas boundary where temperature is high, but not so near the boundary that dilution by the products lowers the reactant concentration too much. Although the pilot may act as a flameholder by providing continuous ignition of the mixture (from which the flame may, or may not, spread), it is not a true flameholder in the classical sense (local u = local S_T, at the ignition point) since both streams may be at quite high velocity relative to S_T. Therefore, if the pilot is turned off the flame may go out unless the configuration is such that a proper size recirculation region occurs for flameholding in the area from which the pilot stream was issuing. Note that the conditions are less favorable for such a flameholding action as the main stream departs from $\phi \approx 1.0$ (refs. 19 to 21).

Whether or not ignition will occur in a given situation depends primarily upon the requirement that the ignition delay length be less than the available mixing length (refs. 20 and 21). The ignition delay length decreases as T and p increase, and the mixing length increases as the pilot size increases.

Whether the flame will spread from the ignition point or break off, depends on the critical flame-stretch parameter K because the flame is not yet in the high-flame-generated-shear turbulent condition, since the boundary layers initially bounding the mixing layer provide a region of lower flow velocities and lower values of $\frac{du}{dy}$. Since laminar flame propagation concepts at least partially apply here, there is a beneficial effect on the flame-stretch parameter and ignition, due to the preheating and production of chain-carrier species in the mixing layer gases ahead of the flame (fig. 5). As was the case with the bluff-body flameholder, it is desirable that the hot-gas pilot be at as high a temperature as possible since it is beneficial to both the ignition process (exponential dependence of ignition kinetics) and to the initial flamespreading process (higher S_T). It is possible, depending on the above conditions, that one could have ignition without flamespreading. If flamespreading does occur, the flame will soon leave the immediate region of the pilot and become a high-

flame-generated-shear case where it is no longer based on laminar flame concepts. Depending on the relative velocities of stream and pilot, there may be large aerodynamically generated shear and turbulence to promote exchange across the dividing streamline. In any case, the flame will be anchored at the most upstream point (beyond the ignition delay distance) where $K \lesssim 1.0$.

It should also be pointed out that one can have anything between a true flameholder and a true pilot, depending on whether there is no fuel and oxidant added to the recirculating flow, or such a large amount added that there is no separation and recirculation. Recirculation will cease at approximately that condition where the pilot total p is greater than 12 percent of the mainstream total p, assuming the splitter plate lip is thin (ref. 20). The advantages of a pilot are that it works over a wide range of main mixture ϕ's, has less drag and blockage, and provides dependable ignition and flame stability. The disadvantages are that separate fuel, oxidant lines, and controls are required, and it requires a higher degree of cooling.

SIMPLE ANALYTICAL MODEL OF FLAMEHOLDING

The flow processes in the flameholding region behind bluff bodies were conceptually discussed in a previous section. Because of the complexity of this flow region, it would be extremely difficult to compute the quantitative details of these processes. Therefore a simple representation of the major aspects is made. In reference 15 it was observed experimentally that for a bluff-body flameholder in turbulent flow with a fixed point of separation and at a given premixed ϕ, the flow time past the recirculation region was constant at the blowoff condition. This result means that irrespective of body scale and approach velocity, the time for a free-stream flow element to traverse the length of the separated zone was constant at the blowoff condition. The traverse time, however, was found to be a strong function of the mixture parameters that affect the local flame speed, such as ϕ, T, fuel, initial turbulence, etc. The blowoff velocity was a maximum when the flame speed was a maximum. In reference 12, Lewis and Von Elbe made a simple flame calculation which suggested that for a flame in the recirculation zone, the time required to propagate transversely from the anchor point to the edge of the shear layer was about the same (within a factor of two for a range of mixture parameters and flow conditions) as the traverse time of the free-stream flow at blowoff.

The present model is based on a similar concept, which assumes that the flame travel time equals the flow travel time, where the flame traverse distance is from the anchor point to the dividing streamline rather than to the shear layer edge, and the flow time depends on the velocity along the dividing streamline rather than on the approach velocity. Figure 6 illustrates the concept of the present model for a bluff-body flameholder at the blowoff condition. Recall that at blowoff, the flame reaches the dividing streamline at the rear stagnation zone. At the blowoff condition, the flame travels a distance Δ_r transversely at velocity $\bar{S}_T$ and the flow element travels a distance L along the dividing streamline at velocity u*. Equating these times gives

$$\tau = \frac{L}{u^*} = \frac{\Delta_r}{\bar{S}_T} \tag{3}$$

where $\bar{S}_T$ is the mean flame speed which varies nonmonotonically (starts at a value of $\hat{S}_T$ at the anchor point) over the transverse distance to the dividing streamline (fig. 3). In essence, the concept of this model is to say that during traverse of a flame element across the recirculation zone, that amount (mass) of mixture is burned which entered the recirculation zone during the traverse of a flow element along the recirculation boundary (that same amount also leaves the recirculation zone).

Following reference 12, the flame-stretch parameter K (see eq. (2)) is rearranged and integrated as follows:

$$\frac{du}{u} = K \frac{C_p \rho}{k} S_T \, dy$$

$$\int_{u=\hat{S}_T}^{u=u^*} \frac{du}{u} = K \int_{y=0}^{y=\Delta_r} S_T \frac{C_p \rho}{k} \, dy = K \, \Delta_r \int_0^1 S_T \frac{C_p \rho}{k} \frac{dy}{\Delta_r} \tag{4}$$

where K is assumed to be constant. Integration gives

$$\ln \frac{u^*}{\hat{S}_T} = K \, \Delta_r \left(\overline{S_T \frac{C_p \rho}{k}} \right) \tag{5}$$

Substituting equation (3) into (5), letting $L = 3h$ (this has been observed experimentally), and solving for h gives

$$h = \frac{1}{3K} \frac{1}{\left(\overline{S_T \frac{C_p \rho}{k}} \right)} \frac{u^*}{\bar{S}_T} \ln \frac{u^*}{\hat{S}_T} \tag{6}$$

From graphical integration of profiles, such as shown in figure 3, for a few typical cases with mixture ϕ's of 0.5 and 1.0, the following approximate relations are obtained and assumed for the model:

$$\left(\overline{S_T \frac{C_p\rho}{k}}\right)_{\phi=1} \approx 0.182\left(S_T \frac{C_p\rho}{k}\right)_{mix} \qquad \left(\overline{S_T \frac{C_p\rho}{k}}\right)_{\phi=0.5} \approx 0.43\left(S_T \frac{C_p\rho}{k}\right)_{mix} \tag{7}$$

$$\left(\bar{S}_T\right)_{\phi=1} \approx 0.91 S_{T_{mix}} \qquad \left(\bar{S}_T\right)_{\phi=0.5} \approx 1.13 S_{T_{mix}} \tag{8}$$

$$\left(\hat{S}_T\right)_{\phi=1} \approx 0.57 S_{T_{mix}} \qquad \left(\hat{S}_T\right)_{\phi=0.5} \approx 0.88 S_{T_{mix}} \tag{9}$$

where the subscript "mix" denotes conditions at the outer edge of the mixing layer where there are no combustion products present. Putting equations (7), (8), and (9) into equation (6) and assuming that $K \approx 1$ and $u^* \approx 0.5u_e$ (u_e is the free-stream flow velocity at the edge of the shear layer) the equations for the flameholding model are obtained; for $\phi = 1.0$,

$$h \approx \frac{1.01}{\left(S_T \frac{C_p\rho}{k}\right)_{mix}} \frac{u_e}{S_{T_{mix}}} \ln\left(0.88 \frac{u_e}{S_{T_{mix}}}\right) \tag{10a}$$

and for $\phi = 0.5$,

$$h \approx \frac{0.35}{\left(S_T \frac{C_p\rho}{k}\right)_{mix}} \frac{u_e}{S_{T_{mix}}} \ln\left(0.57 \frac{u_e}{S_{T_{mix}}}\right) \tag{10b}$$

In evaluating these parameters in equations (7) to (9), it has been assumed that the velocity is low in the mixing layer so that the recovery temperature of reference 2 based on F_R and T_f can be applied throughout the mixing layer. In order to find the gas properties across the mixing layer ahead of the flame for evaluating equations (7) to (9), the following procedure was used.

It was first assumed that the recirculation zone consisted of unburned mixture at $T_{R_{mix}}$, where $T_{R_{mix}}$ is the recovery temperature based on a given set of assumed flow conditions, F_R, T_f, ϕ, and M_∞. The burned gas conditions in the recirculation zone (at T_{comb}) were then found by using hydrogen-air flame charts $\left(\text{i.e. } \frac{T_b}{T_u} \text{ vs } \phi, T_u, \text{ where } T_{R_{mix}} = T_u \text{ and } T_{comb} = T_b\right)$. These combustion products in the recirculation zone then mix with incoming reactant mixture $T_{R_{mix}}$ in various proportions across the mixing layer so that the flame

in the recirculation zone encounters different initial conditions as it traverses the recirculation zone starting from the anchor point. It should be noted that the use of a constant value of T_{comb} for this calculation is reasonable since the $\frac{T_b}{T_u}$ ratio starts (at the anchor point) at low values and increases, and T_u starts at high values and decreases such that their product is about constant. The temperature ahead of the flame is found from the following simple approximate relation which assumes that C_p for the mixture and products is about the same and that no reaction occurs:

$$T_{ahead} = c_{mix}T_{mix} + c_{comb}T_{comb} \tag{11}$$

where $c_{mix} + c_{comb} = 1.0$ and both vary from 0 to 1.0 across the layer. Values of C_p, ρ, and k are taken from reference 22 for hydrogen and hydrogen-oxygen products, and from reference 23 for air, as functions of p and T. Properties of the mixtures of hydrogen, air, and combustion products are determined by using the usual relationships for gas mixtures.

Propagation of Flame Through Mixing Layer

Having established approximate conditions for the gas mixture in the mixing layer, the flame propagation speed can now be found. Consider that if the gas ahead of the flame in the recirculation zone is all products ($c_{comb} = 1$) then there would be no propagation (no flame). If the gas ahead of the flame is all fresh mixture ($c_{mix} = 1$) at $T_{R_{mix}}$, then the flame would propagate according to the $T_{R_{mix}}$, ϕ, and p of that gas. Since the mixture ($c_{mix} + c_{comb}$) is composed of a reactive part (c_{mix}, capable of propagation) and an inert part (c_{comb}, which is incapable of propagation) one can treat the case as one of a reactive gas at T_{ahead} and ϕ, but at a pressure equal to the partial pressure of the reactant mixture, $\hat{p} \approx pc_{mix}$* (note that c_{mix} should be mole fraction, but mass fraction is not very far wrong in these cases). From the literature values of S_T vs p (there is not a great deal available) (e.g. ref. 24) it looks like the following relation is reasonable for pressures on the order of 1 atm (1 atm = 101.3 kPa):

$$\hat{S}_T(\text{at } \hat{p}) = S_T^o(\hat{p})^{0.42} \tag{12}$$

where $\hat{p}$ is in atm and S_T^o is at $p = 1$ atm.

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*Note that this is equivalent to assuming that the diluent gas has no effect on propagation when based on the reactive gas at $\hat{p}$. In essence, this then assumes that the effect of energy absorption by the diluent gas (lowers T_b) is offset by the effect of density increase of the mixture so as to maintain about the same propagation.

Values of $S^{o}_{T_{mix}}$ as a function of $T_{R_{mix}}$ and ϕ, for use in evaluating equations (10), were obtained from a plot of available literature values along with an approximate method which was employed for extrapolation of these values over a wider range of conditions (fig. 7). The plot was obtained in the following manner: Available laminar and turbulent flame speed data for hydrogen-air at p = 1 atm (most literature is at this p) (e.g. refs. 24 to 28) was plotted as a function of T and ϕ. Note that the maximum flame speeds are at $\phi \approx 1.8$ and all increase with T. Using equation (13) from reference 14, and equation (14) from reference 12, the following expression for $S_{T_{max}}$ given by equation (15) was obtained:

$$\frac{S_T}{S_L} = 1 + \sqrt{\frac{2u'}{S_L}} \tag{13}$$

$$\frac{u'_{max}}{S_L} = \frac{1}{\sqrt{3}}\left(\frac{\rho_u}{\rho_b} - 1\right) \tag{14}$$

$$\frac{S_{T_{max}}}{S_L} = 1 + \sqrt{1.15\left(\frac{T_b}{T_u} - 1\right)} \tag{15}$$

Note that equation (15) is an approximate relation for the maximum effects of flame generated velocity fluctuations u'_{max} and does not account for temperature fluctuations or for any turbulence which may already be in the unburned flow. The values of S_L shown in figure 7 were increased by the ratio $\frac{S_{T_{max}}}{S_L}$ and are shown as $S_{T_{max}}$ on the plot. The available turbulent flame data is seen to be higher than the maximum flame-generated turbulent result, which is in agreement with subsonic results for bluff-body flameholders which show that flame generated turbulence is subordinate to aerodynamically generated turbulence (ref. 13). However, the $S_{T_{max}}$ curves can at least serve as useful guides to extrapolation of the turbulent data. As a result, the two uppermost extrapolated curves on figure 7 were used for S_T for $\phi = 1.8$ and 1.0, respectively, and the laminar $\phi = 1.8$ curve was used for S_T for $\phi = 0.5$, since it bears about the same relation to the $S_{T_{max}}$ curve for $\phi = 0.5$.

Using these values of S_T from figure 7 $\left(\text{read at } T_{R_{mix}}\right)$, computed values of $\left(\frac{c_p \rho}{k}\right)_{mix}$ at $T = T_{R_{mix}}$, and values of u_e for typical scramjet combustor entrance conditions from reference 2 (as a function of M_∞), equations (10) were

evaluated over a range of M_∞ from 4 to 7 for ϕ = 0.5, 1.0, and 1.8; p = 0.3 and 1.0 atm; and F_R = 0.4 and 0.6. The results are plotted in figure 8.

Discussion of Model

The simplifying assumptions of K = Constant in integrating equation (4) and the use of K = 1 in obtaining equations (10a) and (10b) from equation (6) are made recognizing that K is not actually constant in the mixing layer, but cannot be computed without knowledge of the u profile through the recirculation zone. The value of K will decrease from 1.0 or less at the anchor point to lower values as the flame travels toward the outer edge of the mixing layer (see previous blowoff section). The use of a constant $u^* = 0.5u_e$ is also questionable since u^* may well be somewhat below that value, although the heating of the recirculating gases will increase it over the cold flow case. However, the errors caused by these two effects are partially compensating in evaluating equations (10a) and (10b). Certainly the extrapolation of S_T° to values of $T_{R_{mix}}$ much higher than the data (fig. 7) and to much lower pressures than the data (eq. (12)) is also arbitrary but is about the best that can be done simply, lacking pertinent experimental measurements of S_T.

Several interesting conclusions can be drawn from inspection of the results shown in figure 8. First, the required flameholder size is very sensitive to the mixture pressure. This sensitivity is a result of a first power dependence of ρ on pressure and the dependence of S_T on pressure, in equation (12), which is approximately squared in equations (10). It is seen from figure 8 that flameholder size varies approximately with p^2. Second, there is a fairly strong dependence of flameholder scale on the equivalence ratio when ϕ goes below 1.0. This dependence is primarily due to the strong influence of ϕ on S_T° (fig. 7) which, again, is approximately squared. Third, the influence of Mach number is fairly strong for the high ϕ cases, but is in a direction opposite to that for self-ignition (ref. 2) where Mach number increase promoted self-ignition. The M_∞ influence on scale in equations (10) is primarily due to the effect of temperature on ρ, since the effect of temperature on S_T is nearly balanced by the effect of the u_e change.

It is also very interesting to note that the effects of F_R on flameholder scale are negligible at the higher ϕ's and weak at the lower ϕ, so that recovery T and fuel cooling are not very influential, again, quite different than for self-ignition.

Finally, it must be reiterated that the model presented herein is based on many crude assumptions and simplifications of the processes involved in a very complex phenomenon. Although the quantitative predictions of required flameholder size may be questionable, it is hoped that the parametric dependencies shown are reasonably good in quality and magnitude. Obviously, experimental data is needed before these uncertainties can be reduced and the utility of the model assessed. Some confidence that the model has about the right parametric form is gained by comparison of equation (6) with the form of the Damköhler first number

$$N_D = \frac{\text{Reaction rate}}{\text{Flow rate}} = \frac{\tau_{flow}}{\tau_{flame}}$$

where

$$\tau_{flow} = \frac{L}{u^*}$$

$$\tau_{flame} = \frac{\eta_o}{S_T} = \frac{1}{S_T^2 \frac{C_p \rho}{k}}$$

where

$$\eta_o = \frac{k}{C_p \rho S_T} \approx \text{Flame thickness}$$

Equating τ_{flow} to τ_{flame}, letting $L = 3h$, and solving for h gives

$$h = \frac{N_D}{3} \frac{1}{S_T \frac{C_p \rho}{k}} \frac{u^*}{S_T}$$

which is very similar to equation (6) except for the factor $\ln \frac{u^*}{\hat{S}_T}$. Note that $N_D \approx K \approx 1$. Also, some confidence in the quantitative aspects of the model is gained by noting that the step size found in reference 29 to produce successful flameholding is about that predicted from the model.

CONCLUDING REMARKS

Concepts which are believed applicable to the basic understanding of the pertinent flow processes involved in turbulent flameholding and flamespreading have been reviewed with an interest in their application to design of scramjet combustors. As a result, some new concepts have been generated and some new approaches to modeling of these extremely complex processes have been suggested.

For flameholding, these new concepts include

1. Blowoff is caused by the flame inside the recirculation zone failing to reach the dividing streamline at the rear stagnation zone rather than from heat-flow divergence ($K \geq 1$) in the shear layer outside the dividing streamline. When this happens, "cold" mixture enters and "snuffs out" the flame in the recirculation zone and the external "held" flame breaks off.

2. Increased turbulent exchange across the dividing streamline helps flameholding due to forward movement of the flame anchor point inside the recirculation zone rather than from increased heat flow to the outer shear layer. The increased mixing thickness in the outer flow helps the initial flamespreading.

3. Modeling of the blowoff phenomenon is based on the mass conservation concept which says that during the traverse of a flame element across the recirculation zone, that amount of reactants is burned which entered the recirculation zone during the traverse of a flow element along the recirculation-zone boundary (the dividing streamline).

For flamespreading, it is believed that the idea that laminar flame concepts do not relate to high-shear flames is true only for the case of fast chemistry, where the turbulent fluid parcels are effectively consumed as fast as generated by shear. For slow chemistry (low p, T, ϕ, or high u) the smaller parcels of reactants will burn faster than the larger ones, but overall combustion may be retarded.

The scale required to achieve flameholding in a scramjet combustor has been calculated using the present model. The results show a strong adverse effect of low p and low ϕ on flameholding with some adverse effect of increased M_∞, which is opposite to that for self-ignition. There was little effect due to change of recovery factor F_R, again, different from self-ignition.

Based on these results, it is believed there are certain research efforts needed to reduce some of the uncertainties associated with the model concepts and to increase confidence in the ability to design a combustor for high-speed air-breathing vehicles. It is recommended that main fuel injection not be coincident with the flameholder and that the flameholder be independently fueled, either by premixing an upstream flow layer or by adding fuel (and oxygen) directly into the recirculation zone. It is also recommended that ignition be accomplished with a separate ignitor, rather than depend on self-ignition. A hot-gas pilot is recommended as a superior ignitor-flameholder. Combustor design should be based on flamespread angle and not simply on mixing-spread angle.

In order to determine the quantitative and parametric behavior of flameholding and flamespreading under specified ranges of conditions, experiments can be carried out in direct-connect facilities with simple geometry. For flamespreading, the possible influence of finite-rate chemistry should be explored by lowering p, T, and ϕ and increasing u. It is important that the study be made in a ducted flow wherein the streamwise pressure gradients

are similar to those in the engine, since the controlling phenomenon is one of shear and turbulence generation with strong density variations.

Since flameholding is subject to laminar flame concepts, even for equilibrium chemistry, the study should include all the parametric variations, or duplication of all flow conditions of the engine. The flameholding will likely be influenced by finite-rate chemistry (worsened as p, T, ϕ, and scale are lowered and u increased). These factors all strongly suggest the work be done at as near engine conditions as possible. Because of turbulence and finite-rate effects, ducted tests are desirable but care should be taken in any unducted tests that the pressure fields at the flameholder are similar to the engine case. However, it should be remembered that the flamespreading behind the flameholder will not be duplicated for this unducted case.

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August 19, 1980

REFERENCES

1. Henry, John R.; and Anderson, Griffin Y.: Design Considerations for the Airframe-Integrated Scramjet. NASA TM X-2895, 1973.

2. Huber, Paul W.; Schexnayder, Charles J.; and McClinton, Charles R.: Criteria for Self-Ignition of Supersonic Hydrogen-Air Mixtures. NASA TP-1457, 1979.

3. Williams, G. C.; Hottel, H. C.; and Scurlock, A. C.: Flame Stabilization and Propagation in High Velocity Gas Streams. Third Symposium on Combustion and Flame and Explosion Phenomena, Williams & Wilkins Co., 1949, pp. 21-40.

4. Wright, F. H.; and Zukoski, E. E.: Flame Spreading From Bluff-Body Flameholders. Eighth Symposium (International) on Combustion, Williams & Wilkins Co., 1962, pp. 933-943.

5. Howe, N. M., Jr.; and Shipman, C. W.: A Tentative Model for Rates of Combustion in Confined, Turbulent Flames. Tenth Symposium (International) on Combustion, Combustion Inst., 1965, pp. 1139-1149.

6. Cushing, B. S.; Faucher, J. E.; Gandbhir, S.; and Shipman, C. W.: Turbulent Mass Transfer and Rates of Combustion in Confined, Turbulent Flames. II. Eleventh Symposium (International) on Combustion, Combustion Inst., 1967, pp. 817-824.

7. Spalding, D. B.: The Spread of Turbulent Flames Confined in Ducts. Eleventh Symposium (International) on Combustion, Combustion Inst., 1967, pp. 807-815.

8. Spalding, D. B.: Mixing and Chemical Reaction in Steady Confined Turbulent Flames. Thirteenth Symposium (International) on Combustion, Combustion Inst., 1971, pp. 649-657.

9. Bray, K. N. C.; and Libby, Paul A.: Interaction Effects in Turbulent Premixed Flames. Phys. Fluids, vol. 19, no. 11, Nov. 1976, pp. 1687-1701.

10. Libby, Paul A.; and Bray, K. N. C.: Variable Density Effects in Premixed Turbulent Flames. AIAA J., vol. 15, no. 8, Aug. 1977, pp. 1186-1193.

11. Libby, Paul A.; Bray, K. N. C.; and Moss, J. B.: Effects of Finite Reaction Rate and Molecular Transport in Premixed Turbulent Combustion. Combust. & Flame, vol. 34, no. 3, 1979, pp. 285-301.

12. Lewis, Bernard; and Von Elbe, Guenther: Combustion, Flames and Explosions of Gases. Second ed. Academic Press, Inc., 1961.

13. Winterfeld, G.: On Processes of Turbulent Exchange Behind Flame Holders. Tenth Symposium (International) on Combustion, Combustion Inst., 1965, pp. 1265-1275.

14. Karlovitz, Bela; Denniston, D. W., Jr.; and Wells, F. E.: Investigation of Turbulent Flames. J. Chem. Phys., vol. 19, no. 5, May 1951, pp. 541-547.

15. Zukoski, Edward E.; and Marble, Frank E.: Experiments Concerning the Mechanism of Flame Blowoff From Bluff Bodies. Proceedings of the Gas Dynamics Symposium on Aerothermochemistry, Donald K. Fleming, ed., Northwestern Univ., 1956, pp. 205-210.

16. Filippi, F.; and Fabbrovich-Mazza, L.: Control of Bluff-Body Flameholder Stability Limits. Eighth Symposium (International) on Combustion, Williams & Wilkins Co., 1962, pp. 956-963.

17. Dewey, C. Forbes, Jr.: Near Wake of a Blunt Body at Hypersonic Speeds. AIAA J., vol. 3, no. 6, June 1965, pp. 1001-1010.

18. Reeves, Barry L.; and Lees, Lester: Theory of Laminar Near Wake of Blunt Bodies in Hypersonic Flow. AIAA J., vol. 3, no. 11, Nov. 1965, pp. 2061-2074.

19. Schetz, Joseph A.; and Jannone Joseph: The Ignition of Flowing Hydrocarbon/Air Mixtures by a Hydrogen Pilot Flame. Pyrodynamics, vol. 2, no. 1, Jan. 1965, pp. 1-14.

20. Bray, Kenneth N. C.; and Fletcher, Ronald S.: Ignition of a High Speed, Cold, Combustible Flow by Means of a Hot, Turbulent Jet. AIAA Paper No. 70-148, Jan. 1970.

21. Kay, I. W.; McVey, J. B.; Kepler, C. E.; and Chiappetta L.: Hydrocarbon-Fueled Scramjet. Volume 8: Piloting and Flame Propagation Investigation. AFAPL-TR-68-146-VOL-8, U.S. Air Force, May 1971. (Available from DTIC as AD 883 264L.)

22. Svehla, Roger A.: Thermodynamic and Transport Properties for the Hydrogen-Oxygen System. NASA SP-3011, 1964.

23. Hansen, C. Fredrick: Approximations for the Thermodynamic and Transport Properties of High-Temperature Air. NASA TR R-50, 1959. (Supersedes NACA TN 4150.)

24. Drell, Isadore L.; and Belles, Frank E.: Survey of Hydrogen Combustion Properties. NACA Rep. 1383, 1958. (Supersedes NACA RM E57E24.)

25. Slutsky, S.; Tamagno, J.; and Fruchtman, I.: An Analysis of Hydrocarbon-Air Combustion Flames. AIAA Paper No. 66-573, June 1966.

26. Anderson, Griffin Y.; and Vick, Allen R.: An Experimental Study of Flame Propagation in Supersonic Premixed Flows of Hydrogen and Air. NASA TN D-4631, 1968.

27. Agnone, A. M.; and Anderson, G. Y.: Premixed Flame Propagation Characteristics in a Supersonic Airstream. AIAA J., vol. 15, no. 5, May 1977, pp. 749-751.

28. Agnone, A. M.; and Sanlorenzo, E.: Pre-Mixed-Scramjet-Engine Development. New York University Report DAS 77-15, NASA Grant NGR 33-016-131, June 1977.

29. Kepler, C. E.; and McFarlin, D. J.: Mach 5 Test Results of Hydrogen Fueled Variable Geometry Scramjet. AFAPL-TR-68-116, U.S. Air Force, Oct. 1968. (Available from DTIC as AD 393 374L.)

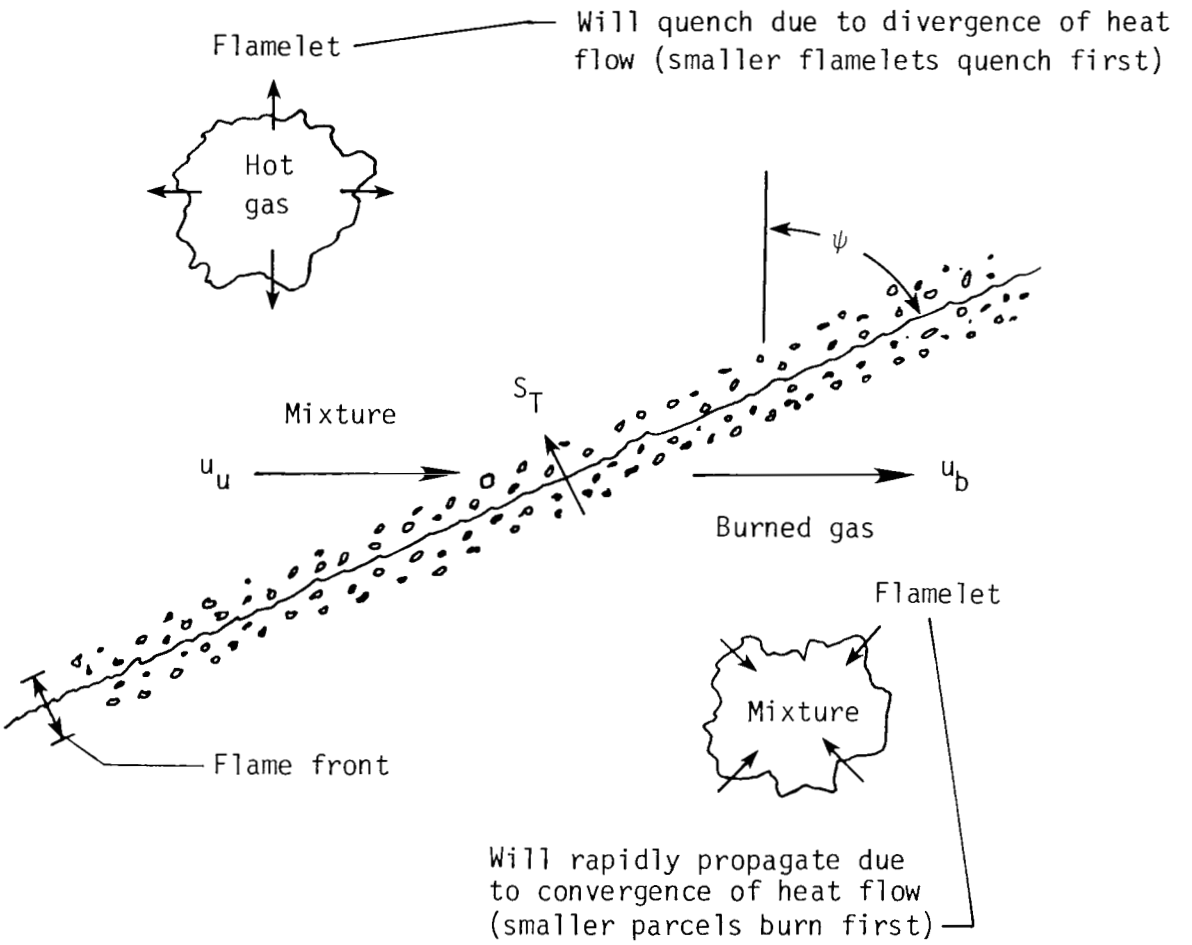

Figure 1.- Preferential quench and consumption of small parcels.

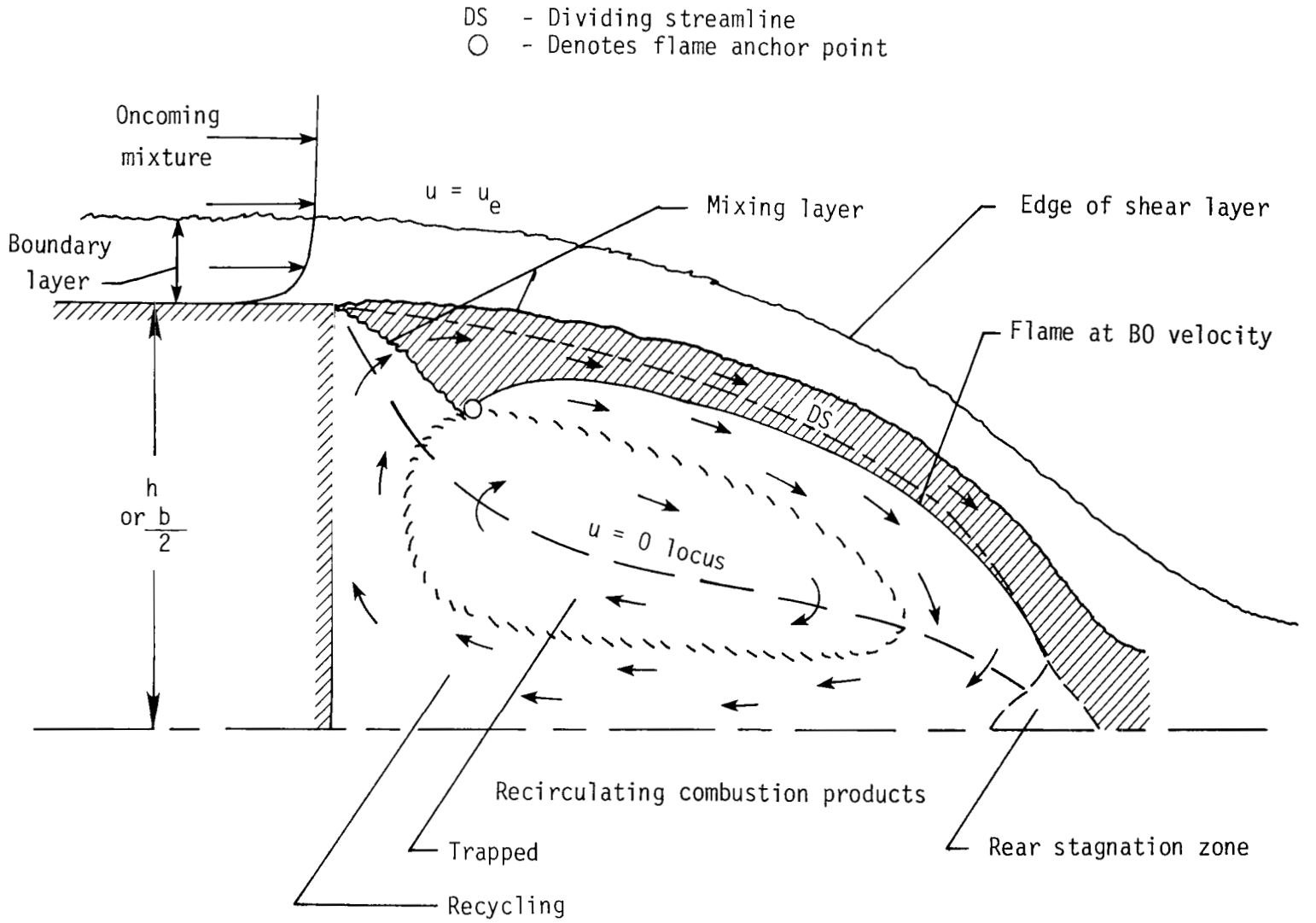

Figure 2.- Schematic of flameholding region behind step or bluff body (shown at blowoff condition).

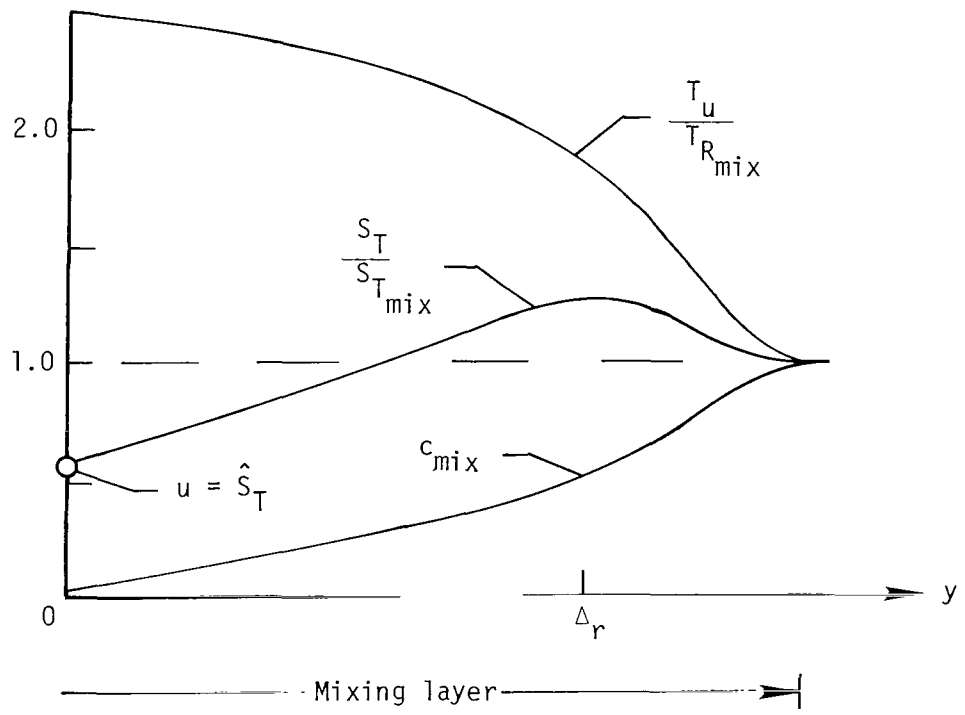

Figure 3.- Nature of variation of properties across mixing layer.

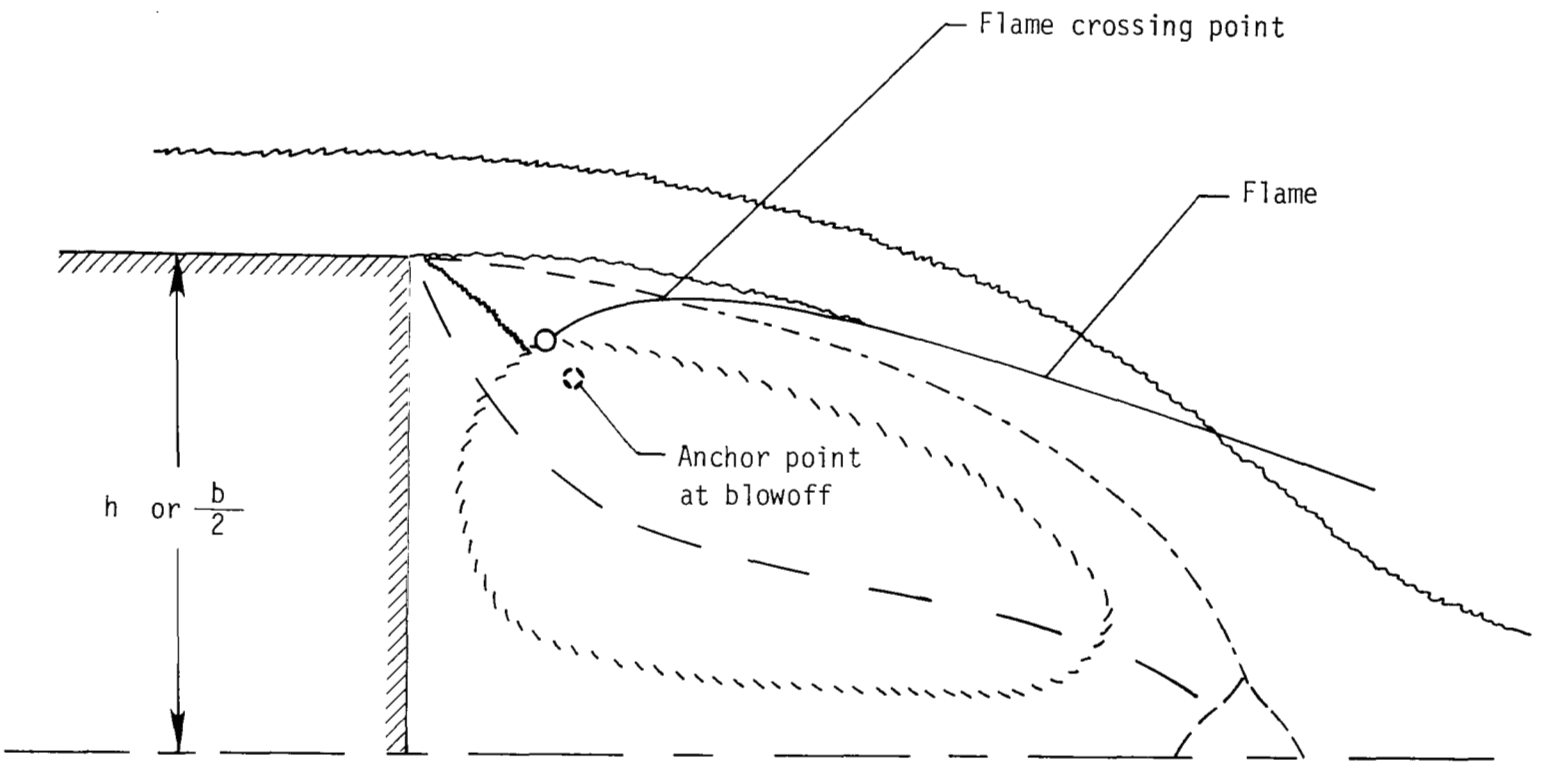

Figure 4.- Schematic of flame position at velocity below blowoff (see fig. 2 for other details).

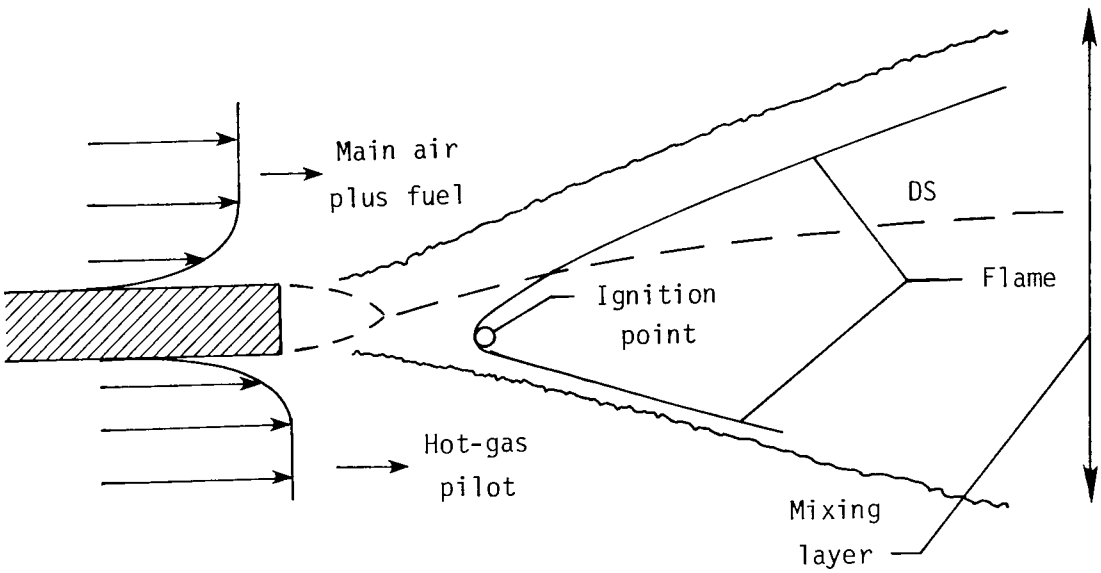

Figure 5.- Hot-gas pilot as ignitor-flameholder.

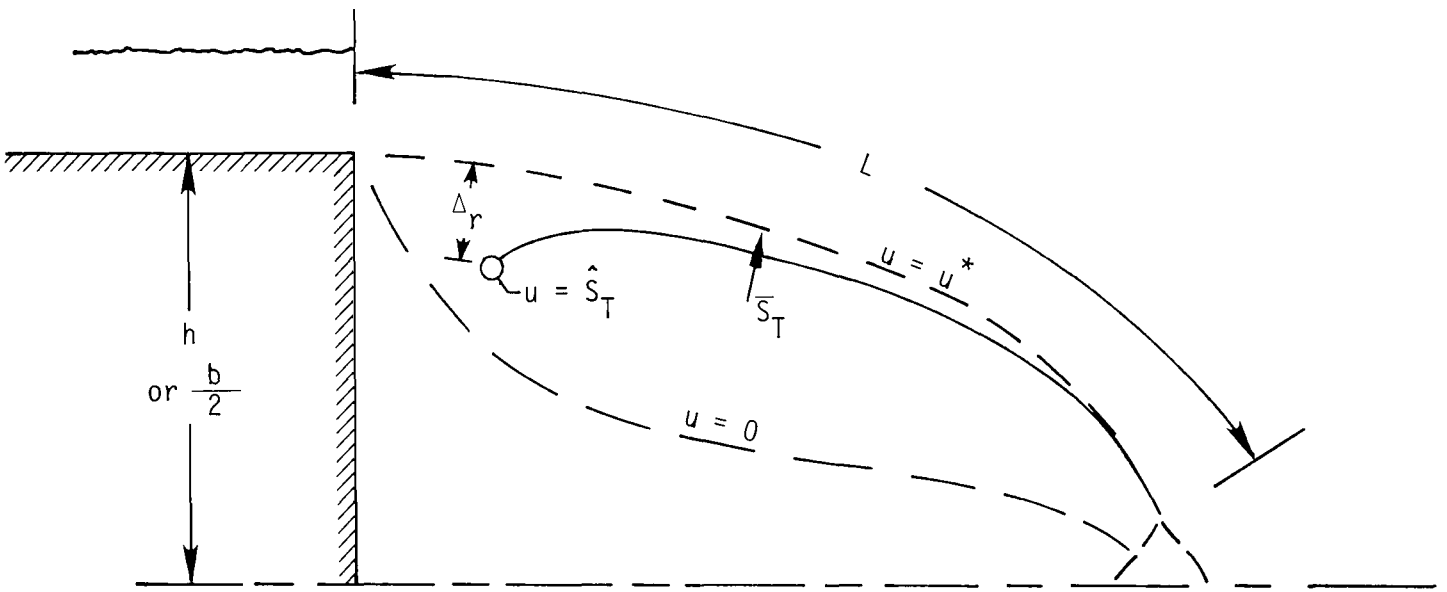

Figure 6.- Model concept; Flame travel time = Flow travel time $\left(\text{at blowoff, } \frac{\Delta_r}{\bar{S}_T} = \frac{L}{u^*} = \tau_{travel}\right)$.

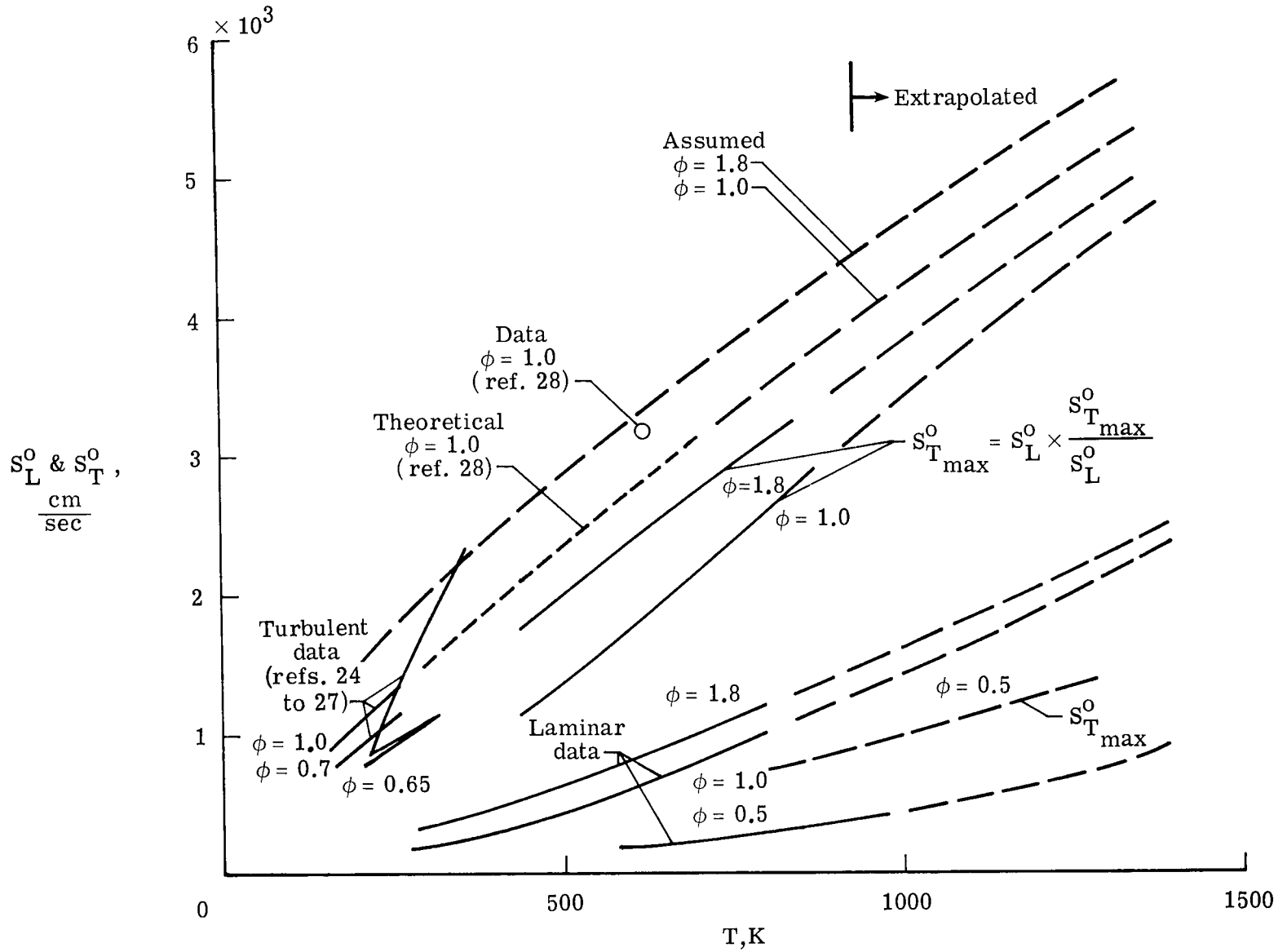

Figure 7.- Turbulent flame velocities assumed in model.

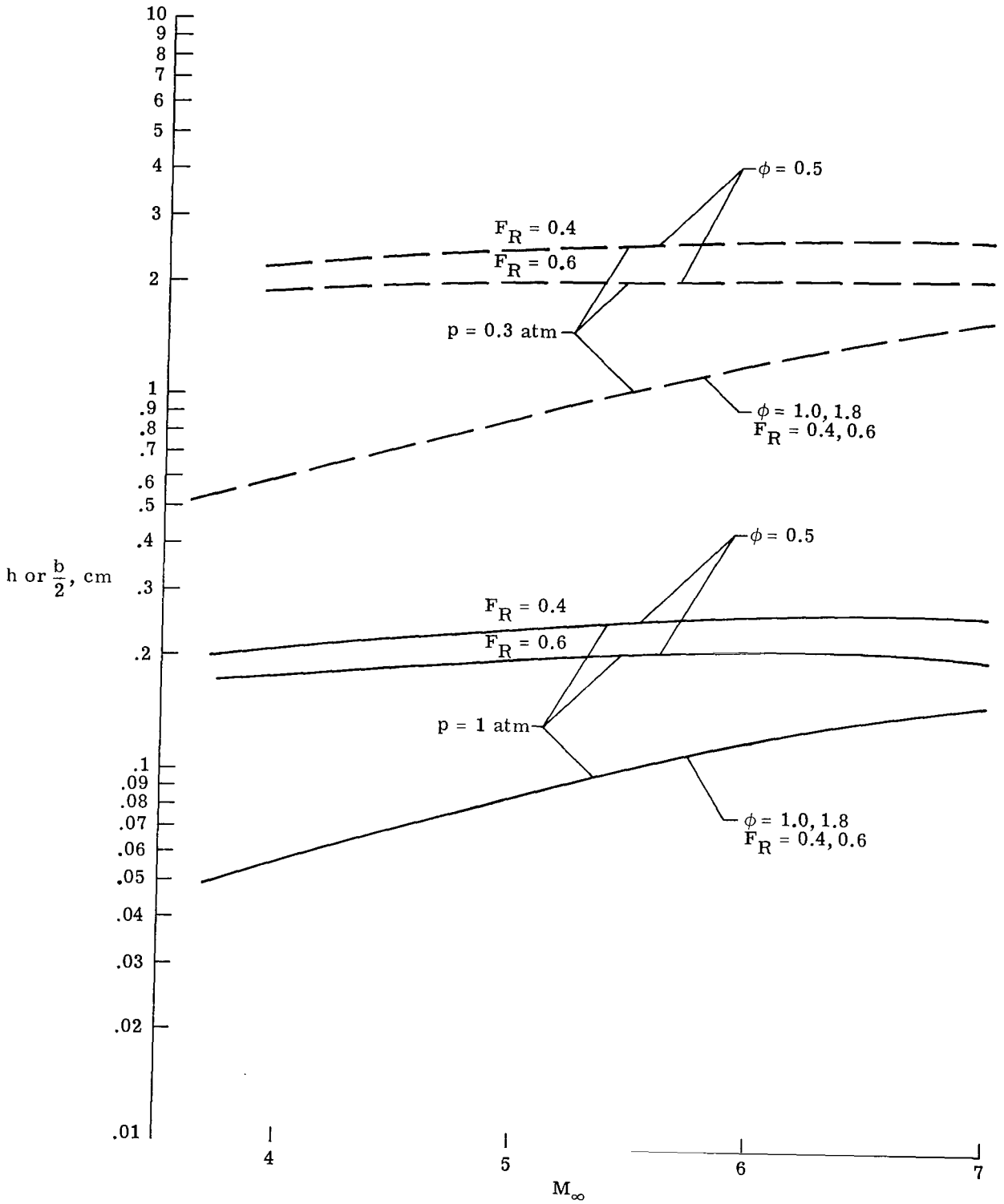

Figure 8.- Step-base scale for flameholding (premixed hydrogen-air).

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16. Abstract

Review of the basic processes involved in turbulent flameholding and flamespreading has led to the generation of some new concepts and approaches to scramjet-combustor design.

New concepts for flameholding include

1. Blowoff is from failure of the recirculation-zone (RZ) flame to reach the dividing streamline (DS) at the rear stagnation zone.

2. Increased turbulent exchange across the DS helps flameholding due to forward movement of the flame anchor point inside the RZ.

3. Modeling of the blowoff phenomenon is based on a mass conservation concept involving the traverse of a flame element across the RZ and a flow element along the DS.

4. The scale required to achieve flameholding, predicted by the model, shows a strong adverse effect of low pressure and low fuel equivalence ratio, moderate effect of flight Mach number, and little effect of temperature recovery factor.

Possible effects of finite-rate chemistry on flameholding and flamespreading in scramjets are discussed and recommendations for approaches to engine combustor design as well as for needed research to reduce uncertainties in the concepts are made.

17. Key Words (Suggested by Author(s))

Flameholding
Supersonic combustion
Scramjet engines
Flamespreading
Turbulent flames

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