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RECENT RESULTS ON STANDING DETONATION WAVES

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ABSTRACT

The method of establishing a hydrogen-air standing detonation wave (SDW) at The University of Michigan is reviewed briefly. Some recent experimental results are presented and interpreted in the light of theoretical treatment made here and elsewhere.

The SDW is generated by mixing cold hydrogen with hot air supersonically, letting the mixture expand in the open jet of an underexpanded nozzle, and achieving combustion downstream of the normal shock which is characteristic of such jets. To assess the results, the shock Mach number, the stagnation temperature of the mixture, the mixture composition, and the pressure at the region of interest were determined. The results indicated that a one-dimensional treatment of the flow field near the wave is adequate.

The experimental results consistently revealed a separation between the shock wave and the combustion zone. This is explained as an ignition time delay which can be deduced from consideration of the elementary chemical reactions and rates involved as shown in Reference 5. The experimental results are compared with theory, and the agreement is quite good. This confirms the utility of the SDW method as a tool in the experimental study of chemical kinetics.

Aerodynamic and chemical criteria important to establish and identify standing detonation waves are described. The aerodynamic criterion arises from the jet structure and the scale of the experiment, while the chemical criterion is based primarily on the temperature with its attendant relation to the explosion limit and ignition time delay. Consideration of these criteria allows identification of the waves as to strength. It is concluded that some strong detonation waves have been observed, but in most cases only a portion of the potential energy release influenced the shock wave.

Some basic differences between the experimental results of Reference 3 and those presented here are noted. For example, no separation between shock and combustion zone was observed in Reference 3, and the suggestion was made that the transport properties were influential. On the basis of the studies reported here, this effect should be very small. The results presented here are consistent with the physical considerations of the problem with no allowance made for the transport terms.

OBJECTIVE

The objective of this report is to present the aerodynamic and chemical criteria important to the establishment of standing detonation waves, and to present some recent experimental data.

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INTRODUCTION

In recent years there has been considerable interest in standing gaseous detonation waves. This interest relates to the opportunity of proving that such waves (Chapman-Jouguet as well as strong) are possible, to the possible application to hypersonic ramjets, and to the potential use as an experimental tool in the study of chemical kinetics. At the Seventh Combustion Symposium, Nicholls, Dabora, and Gealer[1] reported on experiments in an underexpanded free jet at The University of Michigan, wherein stable shock-combustion waves of hydrogen and air were realized. While some question existed about the proper identification of these waves, further consideration[2] indicated that some waves corresponded to standing detonation waves while others would be more appropriately called cases of shock ignition.

Recent results obtained at The University of Michigan pertain to the hydrogen-air ignition delay zone, the interpretation of the observed wave phenomenon, and the consideration of transport processes within the wave as they relate to wave structure. Gross[3] has reported on the attainment of standing detonation waves in a supersonic wind tunnel. His results differ from those reported here in two ways: first, he observes no ignition time delay and second, a so-called hysteresis effect has been detected. These apparent discrepancies will be discussed in the light of our results.

The Michigan experimental facility was described in Reference 1 but for the sake of continuity a brief description will be given here. High-pressure air is heated to a high temperature by blowing down through a pebble-bed heat exchanger. The air is then introduced into an axisymmetric convergent-divergent nozzle. Unheated hydrogen is injected at the throat of this nozzle by means of a small needle located on the nozzle centerline. The gases mix at supersonic velocities in the divergent part of the nozzle. Because of the short residence time within the nozzle and the rapid drop in temperature, no combustion occurs. The nozzle is operated highly underexpanded (exit pressure much greater than the receiver pressure) so that further expansion takes place in the open jet. As shown in Fig. 1, such jets are characterized by a complex shock-wave structure consisting of an intercepting shock surface, a Mach disc (approximately a normal shock surface), and a reflected shock surface. The region bounded by the nozzle exit, the intercepting shock, and the Mach disc is one of isentropic expansion. The increase in Mach number and decrease in static pressure in this region in the flow direction along the jet centerline are indicated in Fig. 1. The normal shock serves to increase the static temperature of the mixture to a value close to the stagnation temperature. At sufficiently high temperatures a flame front will be established some distance downstream of the shock wave, this distance representing the ignition time delay and varying with mixture ratio, temperature, and pressure.

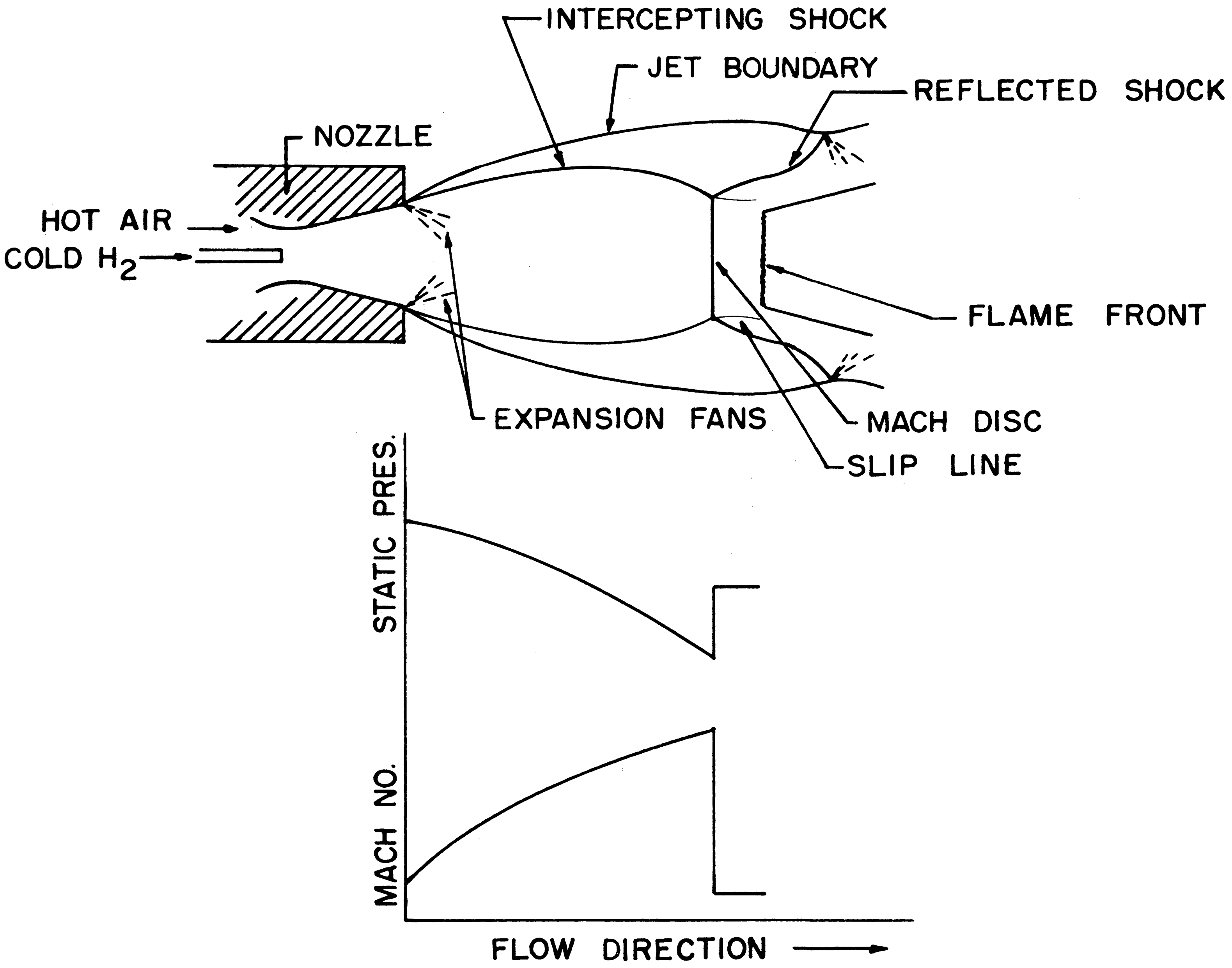


Fig. 1. Schematic of nozzle and jet structure.

Thus the advantages that accrue from the study of stationary phenomena can be realized in a facility of this type. However, it is now necessary to measure carefully the free-stream conditions into the wave. Consequently, the first portion of this paper is devoted to a description of measurements made in the jet.

JET MEASUREMENTS

In an experiment of this type the test section is that zone around the Mach disc. Consequently, it is essential that the hydrodynamic and thermodynamic variables upstream of the shock be determined. These variables would include Mach number, stagnation pressure, stagnation temperature, and composition. All these should be determined for different radial positions into the disc to determine the departure from one-dimensional flow. Some preliminary measurements were reported in our earlier paper,[1] but these have now been greatly extended and an improved nozzle has been employed. Measurements have been made at elevated temperatures with and without hydrogen, limited to temperatures below that leading to combustion. The small scale of the experiment precludes the use of water-cooled probes which would be required in the presence of the flame. Consequently, it has been necessary to extrapolate the calibration measurements and trends up to the operating range. The Mach number distribution can be evaluated from the measured pressure. The stagnation pressure behind a normal shock at the nozzle exit along with the static pressure at that point were measured, allowing the exit Mach number (M_N) and stagnation pressure loss through the nozzle to be determined. This information in addition to other stagnation pressure measurements along the centerline of the open jet provided a basis for determining the Mach number variation shown in Fig. 2. It is to be noted that the hydrogen introduces relatively small changes and that the experimental results compare quite well with the theory of underexpanded air jets.[4]

The stagnation pressure and hydrogen distribution downstream of the Mach disc were measured at different radial positions. The measurements were made for three different air temperatures. The hydrogen distribution was determined by sampling the flow with a probe and evaluating the samples by a mass spectroscope. Figures 3 and 4 show the pressure and the hydrogen distribution, and as can be seen, the distribution is reasonably flat. It is concluded, therefore, that one-dimensional theory is applicable near the Mach disc. However, it is known, even for no combustion, that the downstream subsonic flow accelerates to supersonic velocities. Thus combustion processes occurring too far downstream would not be described accurately with one-dimensional theory. More will be said on this point in a subsequent section.

Accurate determination of the stagnation temperature into the disc is especially important. As brought out earlier, only the air is heated. Consequently, the stagnation temperature of the mixture at the Mach disc is lower than the air stagnation temperature as a result of heat transfer to the hydrogen. The magnitude of this heat transfer has been assessed by many experiments employing a thermocouple with known aerodynamic and radiation characteristics. The results of these experiments led to a means of evaluating

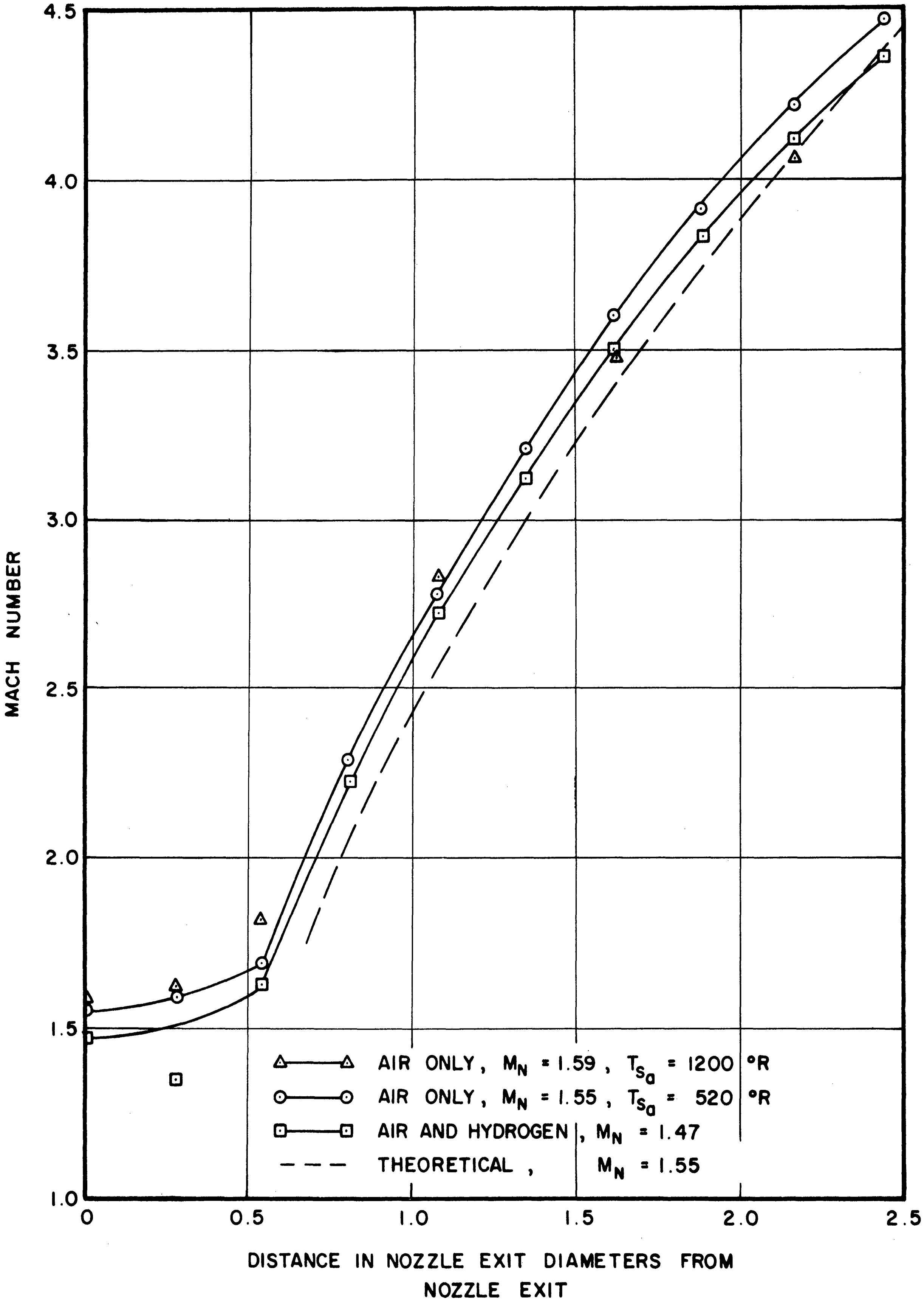


Fig. 2. Mach number variation along jet axis.

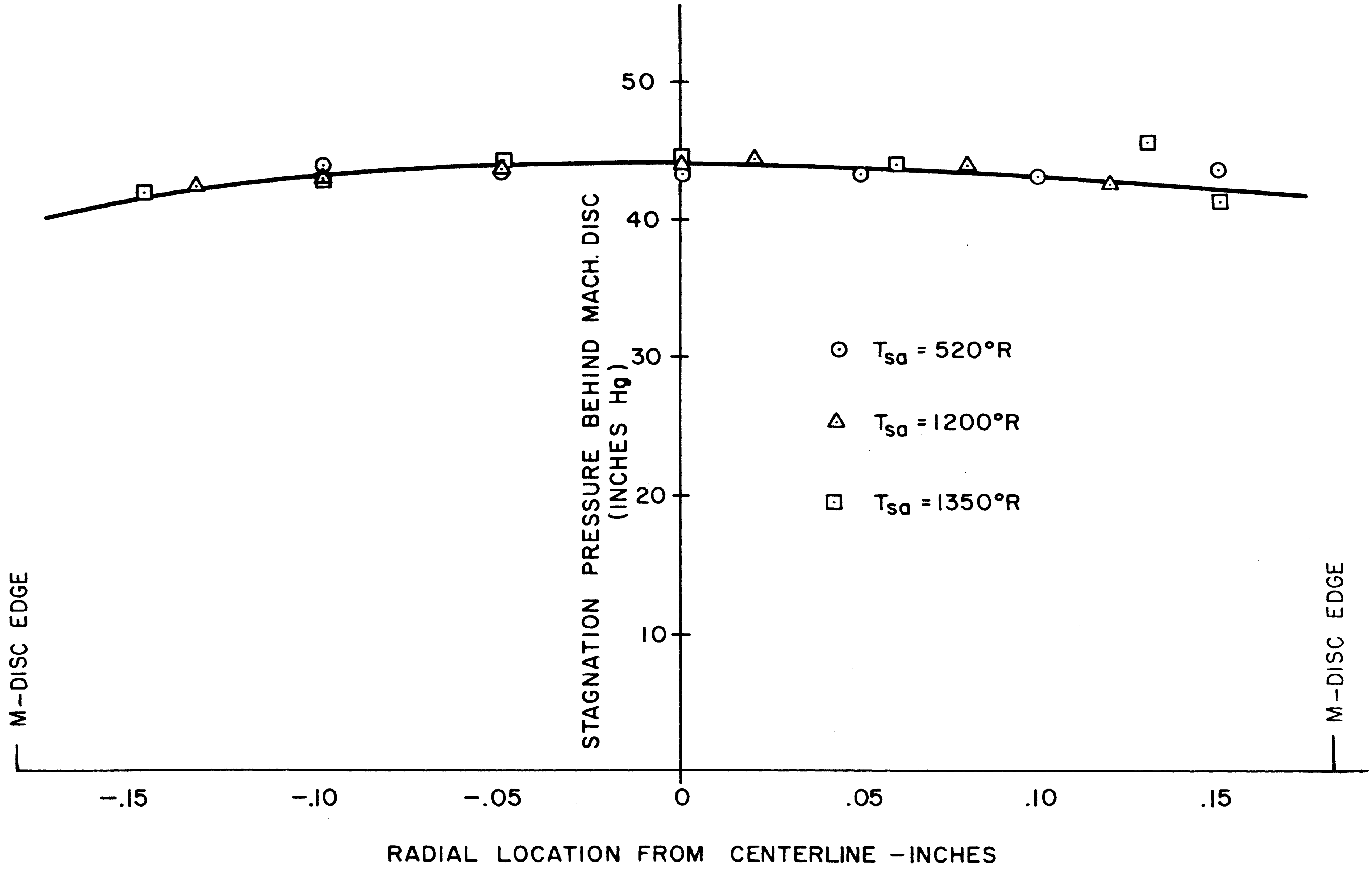


Fig. 3. Stagnation pressure behind Mach disc.

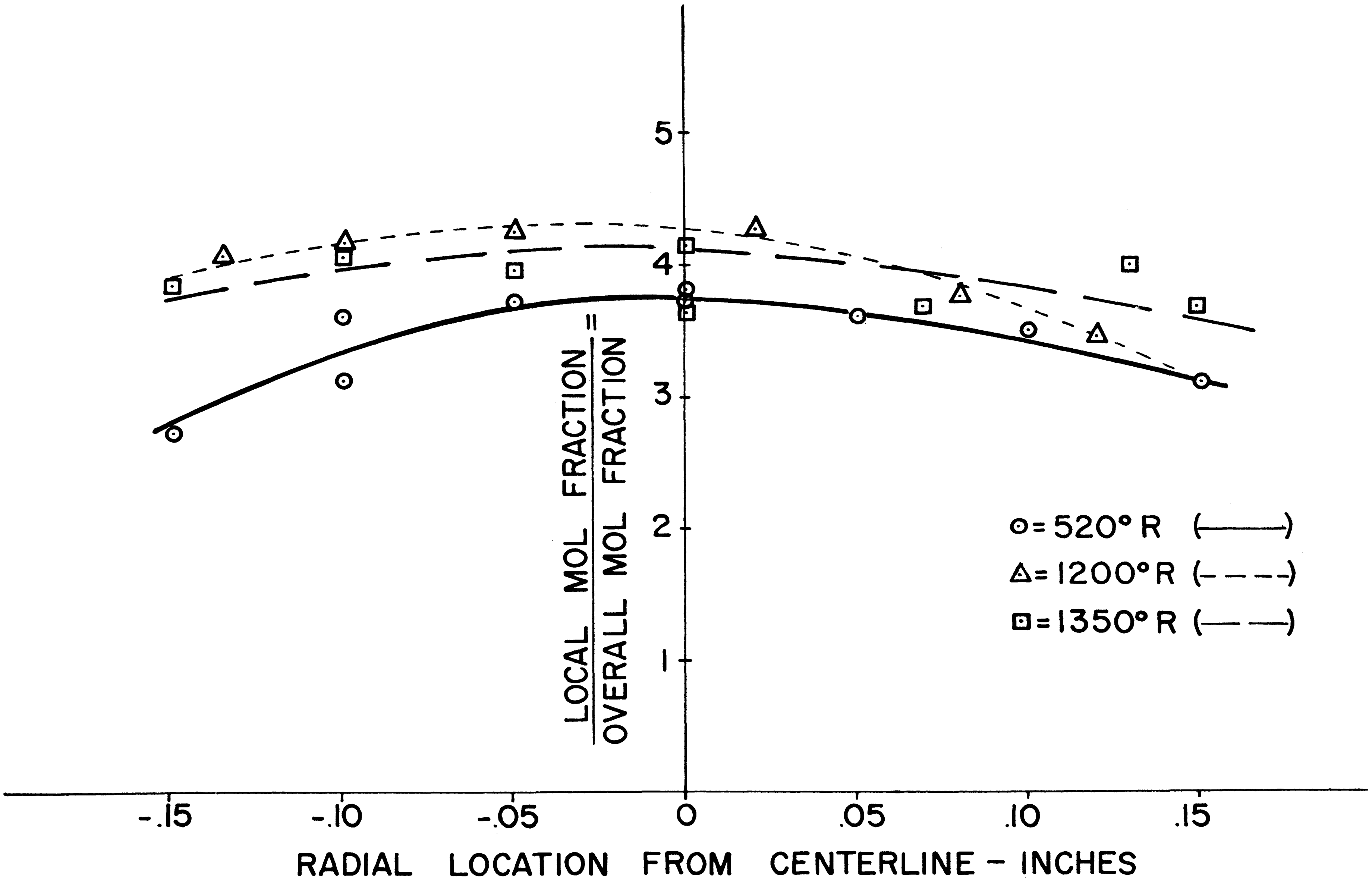


Fig. 4. Hydrogen concentration behind Mach disc.

the desired temperature for different values of air temperature and hydrogen-air ratio.

On the basis of the foregoing, along with other supplementary experiments, the open-jet test was found to have the following characteristics pertinent here. At high pressure ratios (nozzle stagnation to ambient) a high Mach number, essentially normal shock wave exists in the center portion of the jet. A small percentage (about 10%) of the total mass flow passes through this disc so that only a small amount of hydrogen (relative to the total air flow) is required. Furthermore, the flow and mixture ratio are reasonably uniform over most of this disc area. The shock wave (whether combustion occurs or not) is found to be located at that position such that the downstream stagnation pressure is a constant (independent of pressure ratio across the nozzle and hence of Mach number into the shock). In view of the high Mach numbers of interest here, this implies that the downstream Mach number will be very close to 0.4, the downstream static pressure will always be a constant (about 1.3 times ambient pressure), and the downstream static temperature will be very close to the stagnation temperature into the shock. These characteristics result in great simplification of the interpretation of the data. As a further consequence, it is possible to vary appreciably the Mach number into the shock (by changing air pressure and hydrogen pressure) with practically no change in downstream temperature and pressure.

IGNITION TIME DELAY

As indicated above, the experiments on standing detonation waves have consistently revealed an ignition time delay zone between the shock wave and flame front. Experimental evidence for the existence of this delay is shown in Fig. 5, composed of three different photographs of the jet at three different temperatures for approximately the same hydrogen-air ratio. The photographs are simultaneous schlieren and direct, with the flame made visible by the addition of sodium meta-silicate. The delays shown correspond to times of 10 μsec to 25 μsec. The actual physical distance is about 0.28 in. for the longest delay shown. These delays are observed, of course, under steady-state conditions. A direct photograph of the flame is shown in Fig. 6. Much effort, theoretical as well as experimental, has been devoted to the study of the ignition delay. The details of the theoretical analysis are available elsewhere[5] and will not be repeated here. However, it is desirable to mention the major conclusions of this study and to use them in interpreting the experimental results.

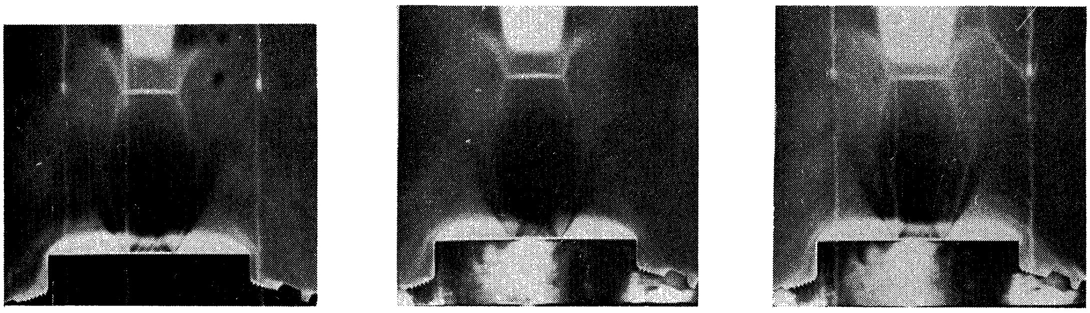
The details of the induction zone of the hydrogen-oxygen reaction at high temperatures have recently been clarified by Duff,[6] Schott and Kinsey,[7] and Nicholls.[5] As a consequence of these studies a qualitative description of the pressure, temperature, and species mole fractions variations between the shock and flame front is as shown in Fig. 7. This is based on the assumption of one-dimensional flow in a constant-area stream tube with no chemical reaction across the shock. It is to be noted that the hydrodynamic and thermodynamic variables are not affected until near the end of the delay period. This ignition delay time is essentially the time required for the well-established chain-branching mechanism to produce sufficient radical concentrations to affect these macroscopic variables.

Nicholls[5] considered the nine reactions given by Duff[6] to arrive at an analytical expression for the ignition time delay as follows:

$$\tau = \frac{1}{2n_{O_2}[C]\,k_2} \ln \left(\frac{n_{O_2}\,k_2}{n_{H_2}\,k_1}\right) \qquad (1)$$

where
τ = ignition time delay,
n_{O_2}, n_{H_2} = initial mole fraction of O_2 and H_2, respectively,
k_1, k_2 = rate constants of the reactions shown below, and
$[C]$ = total concentration

$$H_2 + O_2 \xrightarrow{k_1} OH \qquad (I)$$



(a) τ = 25.5 μsec (b) τ = 20.3 μsec (c) τ = 10.1 μsec

Fig. 5. Photographs showing different ignitition delay length (scale: nozzle O.D. = 1.75").

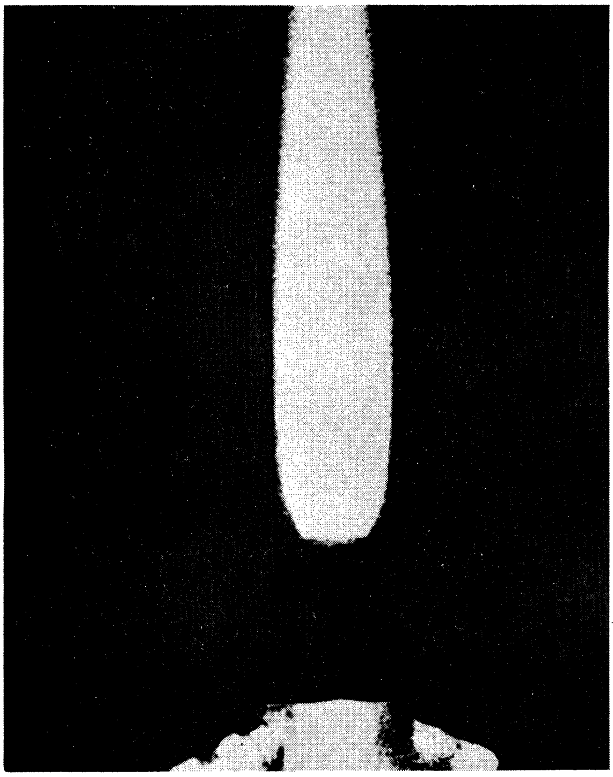


Fig. 6. The visible flame.

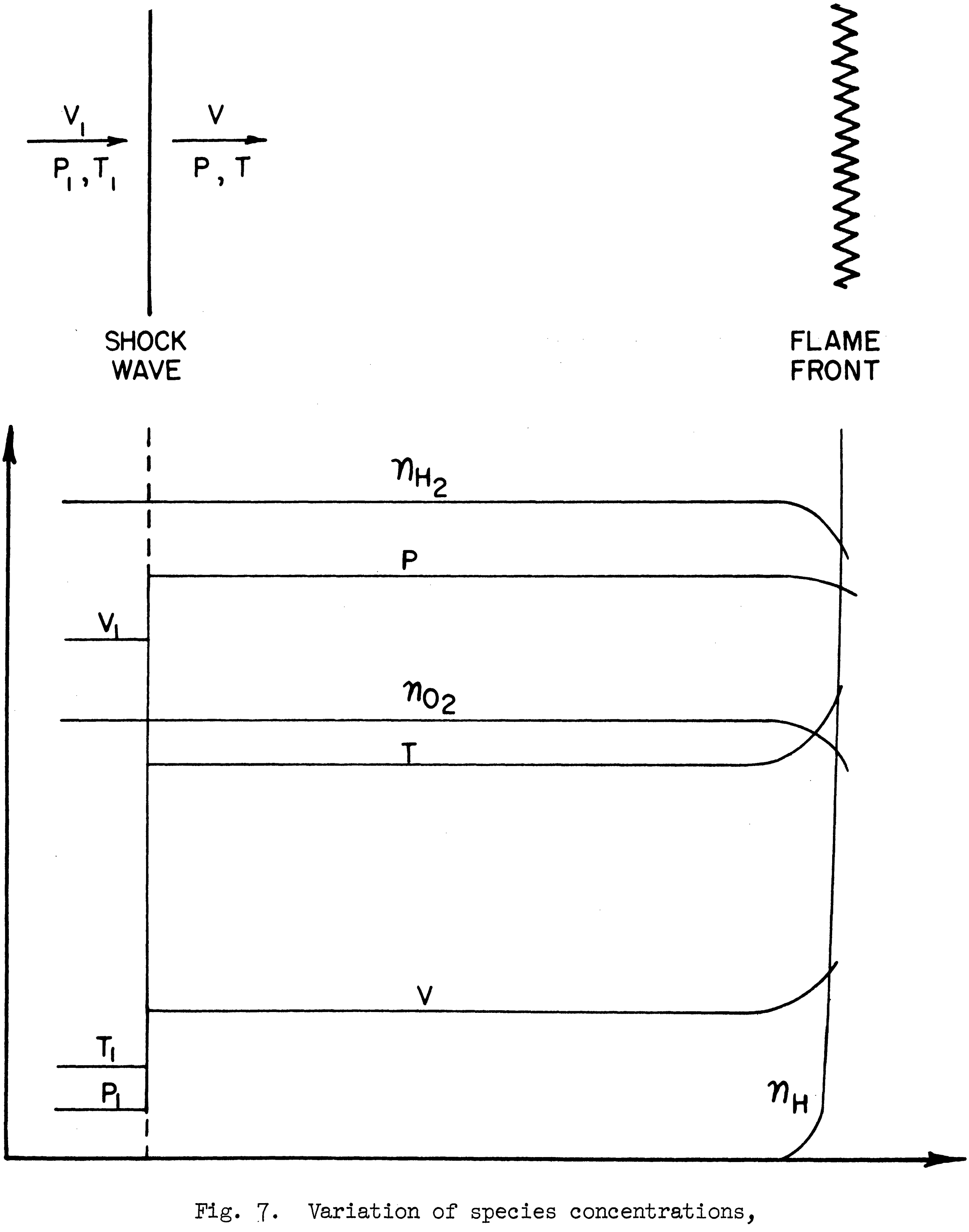


Fig. 7. Variation of species concentrations, thermodynamic properties and velocity in the induction zone.

$$O_2 + H \xrightarrow{k_2} OH + O \text{ (rate controlling)} \qquad \text{(II)}$$

Since $k_2 = A_2 \, e^{-E_2/RT}$ (where A_2 = frequency factor and E_2 = activation energy), consideration of Eq. (1) should be advantageous to deducing the correct activation energy from experimental results.

The predictions of τ from Eq. (1) were shown[5] to be in good agreement with the experimental results of Schott and Kinsey[7] and Steinberg and Kaskan.[8] A comparison of the theory with experimental results obtained in the standing-detonation-wave facility is shown in Fig. 8. It is apparent that the agreement is quite good for the higher temperatures where the flame is relatively close to the shock. At lower temperatures there is considerable scatter. This latter difficulty is attributed to the fact that the flame is located far downstream so that the two-dimensional fluid dynamic effects alter the pressure and temperature field. It is also possible that transport processes become influential in this region. At the higher temperatures the disparity between experiment and theory is well within the range of uncertainty in the appropriate value of k_2. On the basis of these results, it is concluded that the utility of the standing-detonation-wave experimental technique for the steady-state study of chemical kinetics has been proven. Conceivably, the temperature range that could be adequately covered could be extended and the accuracy of the results improved by enlarging the scale of the experiment. This could be accomplished by increasing the pressure ratio across the nozzle and/or increasing the size of the nozzle.

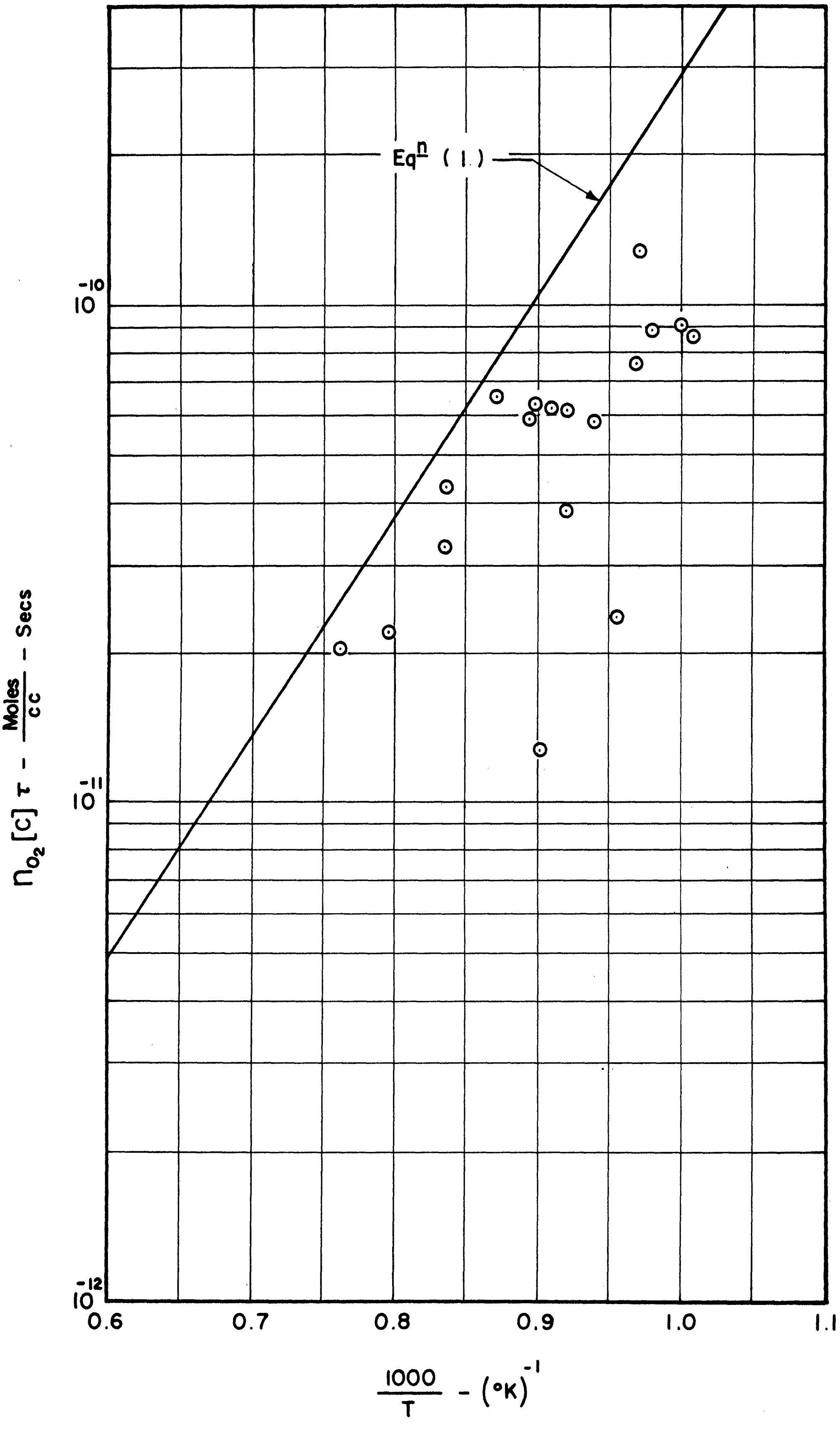


Fig. 8. Comparison of experimental time delays with theory.

CRITERIA FOR ESTABLISHMENT OF STANDING DETONATION WAVES

It has already been pointed out that at lower temperatures there is a finite separation between the shock wave and flame front. Further, experiments have indicated that no interaction occurs between the shock and combustion at lower temperatures, but at higher temperatures the onset of combustion drives the shock upstream to a stable position corresponding to a lower Mach number. It is enlightening to examine the conditions that could be responsible for this different behavior. On the basis of these conclusions an attempt will be made to answer the question: "When is the phenomenon to be considered detonation and when is it merely a case of shock ignition?" The question, as posed, may be somewhat academic. However, there are other implications involved important to the design and interpretation of experiments in a facility of this type. This doubt about proper identification arises from the fact that in a standing wave facility the shock wave and high stagnation enthalpy flow exist independent of the combustion process. In a flame tube or shock tube the shock wave is present only as a result of the energy released via combustion. For this reason the concept of detonation limits has no significance in the stationary case. As discussed by Belles,[9] detonation limits are experienced when the chemical energy release is just sufficient to drive a shock wave at a Mach number such that the static temperature behind the shock is high enough to "explode" the mixture. In the case of the standing wave the energy is already in the stream, so it is merely a matter of instantaneously putting the system out of equilibrium via the standing shock wave. The mixture will then "explode" and detonation will be established if the static temperature behind the shock is high enough. This explosion limit will be discussed shortly.

HYDRODYNAMIC CONSIDERATIONS

If the standing shock-combustion wave is to be legitimately considered as a detonation wave, it must satisfy the conservation equations and an equation of state. Considering, for the moment, only Chapman-Jouguet type waves, a simplified hydrodynamic theory predicts,

$$M_{C-J}^2 = \frac{C}{T_1}, \tag{2}$$

where M_{C-J} is the C-J Mach number of detonation, C is a constant dependent on the particular mixture, and T_1 is the static temperature upstream of the wave. While such an approach is overly simplified for accurate calculation of M_{C-J}, Eq. (2) is quite good[10,11] for predicting M_{C-J} at different T_1 for hydrogen mixtures if C is known from experiment or from detailed calculations based on thermodynamic equilibrium at the C-J plane. Hence, if T_{0_1} is the stagnation temperature upstream of the wave, it follows that:

$$\frac{T_{0_1}}{T_1} = 1 + \frac{\gamma-1}{2} M^2_{C-J} \tag{3}$$

Combining (1) and (2) yields

$$T_{0_1} = C\left(\frac{\gamma-1}{2} + \frac{1}{M^2_{C-J}}\right) \tag{4}$$

This equation is plotted in Fig. 9 for a mixture of 0.295 mole of hydrogen per mole of air (ϕ = equivalence ratio = 0.70) where C was evaluated from the numerical results of Eisen et al.[12] It is to be noted that in a standing detonation wave facility the T_{0_1} requirement can be reduced by operating at higher Mach numbers. In the open-jet system the higher Mach numbers necessitate higher nozzle driving pressures. A similar curve could be drawn for a strong detonation for this same mixture. This curve would lie above the C-J curve so that a strong detonation wave with the same stagnation temperature will propagate at a higher Mach number. A wave which satisfies Eq. (4), or an equivalent expression for a strong wave, automatically satisfies the conservation of mass, momentum, and energy, and thus meets one requirement of a detonation wave. So far no restrictions have been imposed concerning the separation of shock and combustion since such restrictions can be neglected in the hypothetical case where the one-dimensional, constant-area stream tube analysis is valid and dissipative processes transverse to the wave are negligible. This hypothetical case is approached as the total reaction length, shock plus combustion, becomes small. These considerations are discussed in the following section.

CHEMICAL KINETIC CONSIDERATIONS

We infer, then, that if a standing C-J detonation wave is generated it must satisfy Eq. (4). At this point it is not obvious that the static temperature immediately behind the shock (for the given M_{C-J} and T_{0_1}) will be high enough to "explode" the mixture. Certainly some static temperature must be exceeded so that the chemical reactions proceed rapidly. To ascertain this "explosion limit," let us impose the branched chain explosion limit condition as given by Lewis and von Elbe[13] and Belles.[9] Briefly, this condition arises from a gas-phase chain breaking reaction which restrains the chain-branching mechanism. This chain-breaking reaction is:

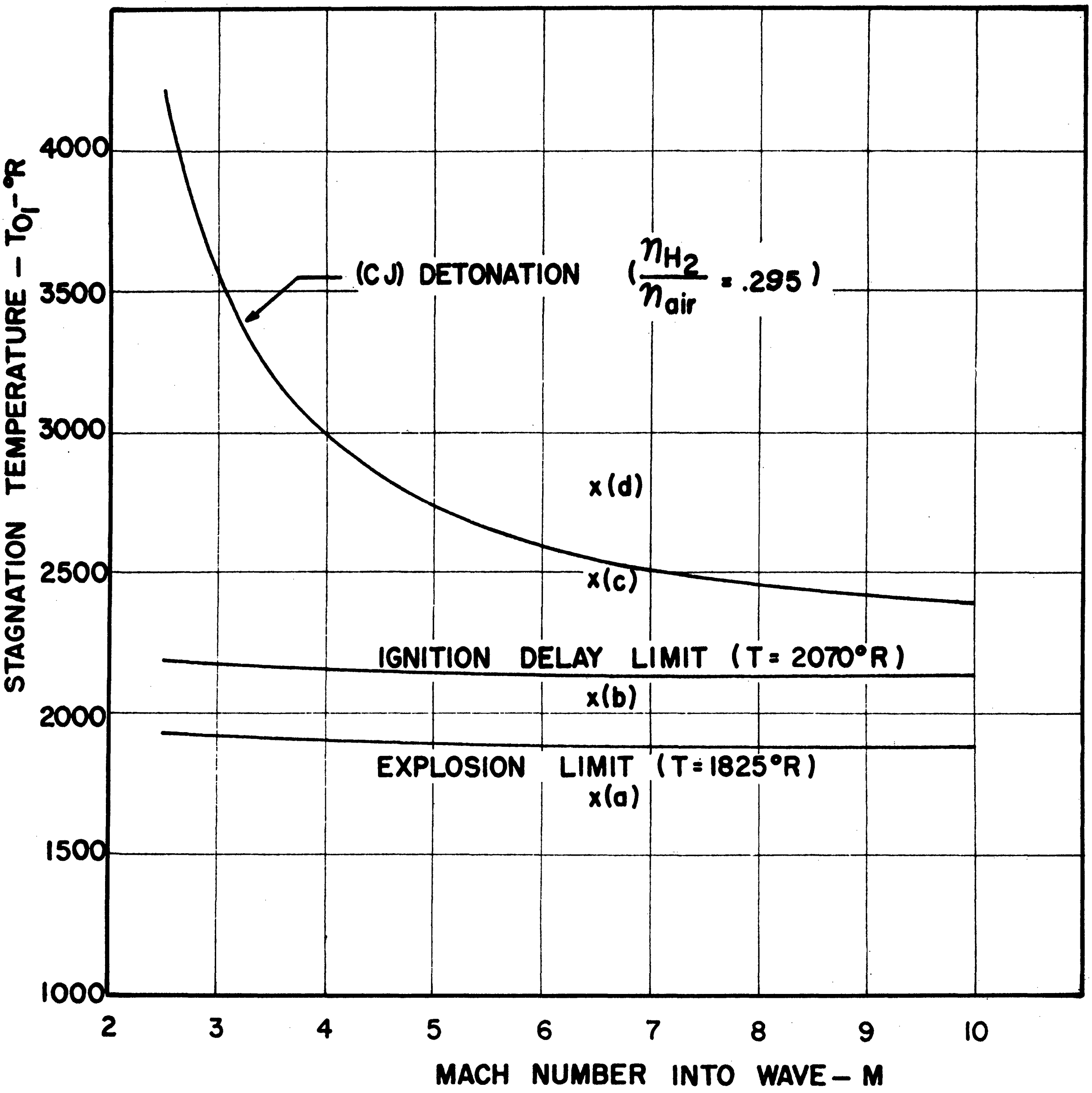


Fig. 9. Stagnation temperature - Mach number conditions pertinent to the establishment of standing detonation waves.

$$H + O_2 + M \xrightarrow{k_3} HO_2 + M \tag{III}$$

The explosion limit condition is satisfied when

$$2k_2 / [M] \ k_3 = 1 \tag{5}$$

Utilizing this condition with the numerical values of Lewis and von Elbe and for the mixture ratio used above, we arrive at a certain constant static temperature for this limit (1825°R). The static pressure is taken as 1.31 atmospheres, which is that pressure behind the shock for all M. For each M in Fig. 9 along with this limiting static temperature (which is the static temperature behind the shock), we can deduce a T_{0_1} explosion limit. These results are included in Fig. 9. Thus, for any Mach number, explosion will be realized if the stagnation temperature is greater than that corresponding to this limit curve. It is to be noted that for the particular mixture assumed the explosion condition will be satisfied for all Mach numbers if the stagnation temperature corresponds to that of the C-J curve or higher. As a consequence we infer that this mixture is capable of detonating.

Another limitation which must be considered in connection with the generation of standing detonation waves arises from the finite reaction times required. That is, for any of the energy released via combustion to affect the shock wave, the exothermic reaction must be initiated within a certain distance. Otherwise the energy addition would, in effect, be aerodynamically insulated from the shock by virtue of the complicated downstream flow pattern. The question arises what this appropriate length might be under certain experimental conditions. While this question cannot be answered unambiguously, it is well to observe in Fig. 1 that at the point where the reflected shock intersects the jet boundary there is a reflected expansion fan. This fan serves to accelerate the flow in the center of the jet. The first position where the fan could possibly affect the center flow would be near the plane where the reflected shock intersects the boundary. Apparently, then, the characteristic length of interest here is the distance from the shock to the plane of the reflected-shock—jet-boundary interaction. This distance increases with an increase in the ratio of nozzle exit pressure to ambient pressure. However, under the usual operating conditions employed this distance is about 0.4 in. Therefore we wish to determine that temperature such that ignition occurs within 0.4 in. The velocity behind the shock is normally close to 1000 ft/sec so that the above distance corresponds to a time of about 33 μsec. From Eq. (1) it can be determined that for the mixture considered here the static temperature behind the shock must be 2070°R or higher for the flame front to be located within this distance. This temperature, converted to stagnation temperature, is plotted in Fig. 9 versus Mach number and, as seen, is appreciably higher than that required to cause explosion.

Still another critical temperature arises when we require the combustion reaction to go to completion within this same distance. Admittedly, this temperature cannot be determined precisely, but the concept helps clarify the situation in regard to experimentally observed results. Reference to the work of Kistiakowsky and Kydd,[14] Duff,[6] and Fay[15] indicates that the reaction zone thickness of hydrogen detonation is of the order of a few tenths of an inch. Accordingly, the ignition delay zone must be appreciably less than the 0.4 in. if the entire heat of combustion is to influence the shock position. Consequently, a temperature of at least a few hundred degrees higher than 2070°R would be required.

INTERPRETATION OF RESULTS

To clarify the above discussion, a few hypothetical cases will be considered. For simplicity we will assume that the hydrogen is heated to the same stagnation temperature as the air so that no change in stagnation temperature is realized as a result of mixing the two gases. Referring to Fig. 9 we first consider a case [point (a)] where the stagnation temperature is below that given by the explosion limit. Under these conditions no rapid reaction can occur, so that either no combustion occurs at all or it occurs too far downstream to be of interest. Point (b), on the other hand, is in a range wherein explosive reaction can occur but the flame front would be too far downstream to influence the shock wave. Changes in the downstream flow (necessitated because of the added stagnation pressure loss of the combustion process) apparently occur with no influence on the shock. In the case of an enclosed section of a supersonic wind tunnel or an engine, it is very possible that the shock position would be changed by boundary-layer action.

Under conditions shown by point (c), the ignition delay zone will be relatively short, and at least a portion of the energy released in the flame should affect the shock position. The wave will not move downstream as this yields higher Mach numbers into the shock and hence higher stagnation pressure losses. Hence with the stagnation temperature being the same (independent of position and hence Mach number), the C-J condition cannot be attained. As a consequence, the wave will tend to move upstream, the extent of this movement being determined by the effective heat release. In those cases where point (c) is close to the "ignition delay limit" curve, only a small portion of the potential chemical energy will influence the shock, so its position will change little. When point (c) lies near the C-J curve, it is likely that about all the available energy will be realized within the critical distance and the shock will move further upstream. If the system were truly one-dimensional and of constant area, the wave would travel all the way upstream, as no stable position would be possible. Apparently, however, the anchoring effect of the Mach reflection zone leading to two-dimensional flow patterns behind the wave is sufficient to cause stabilization at some lower Mach number.

Finally, if the initial condition corresponds to a point above the C-J curve such as point (d), the onset of combustion will drive the wave towards lower Mach number with T_{0_1} a constant. There is some experimental evidence to indicate that the wave does not, in general, go to the C-J Mach number position but rather that it will stabilize at some higher Mach number. Thus it can very likely stabilize as a strong detonation wave and at such a position as to match the complicated boundary conditions. That is, the new position is determined by the stagnation pressure loss across the combustion zone. In the case of high Mach numbers the stagnation pressure loss across the shock will far exceed that across the combustion zone so that the shock will be perturbed little by the heat release.

Because of limited temperatures available, most of the experiments have been run in ranges (b) and (c) with but relatively few in (d). Consistent ignition delay data have been obtained in all these ranges with the exception of those runs where the stagnation temperature was below about 2000°R (see Fig. 8). The results of some representative experiments over a range of fuel-air ratio are shown in Fig. 10. The constant Mach number lines represent the static temperature required for a particular mixture to detonate at that C-J Mach number. These curves were calculated from Eisen's data[12] for an initial temperature of 537°R and then corrected to other temperatures by the inverse square root relation. The explosion limit curve plotted is based on the static temperature behind the shock. The ignition delay limit curve is also shown. It is evident that both limits are insensitive to mixture ratio.

On the basis of many experiments, ignition was found to occur only when the temperature was in the neighborhood of the explosion limit or higher. For runs corresponding to points between the two limits shown in Fig. 10, the shock position was not affected by the onset of combustion. In run 31, combustion drove the shock upstream to a position of lower wave Mach number. It is believed that this run corresponds to case (c) discussed earlier, and is hence a detonation but at an effective mixture ratio leaner than shown. Runs 69, 70, and 92, although close to or above their corresponding C-J curve, showed no change in shock-wave position. This lack of interaction is attributed to the lean mixture ratios and hence small stagnation pressure losses. Run 92 corresponds to a strong detonation because combustion occurs within the delay limit. On the other hand, 69 and 70, as well as all other points between the limit curves, cannot be considered detonations as they fall under the category of case (b).

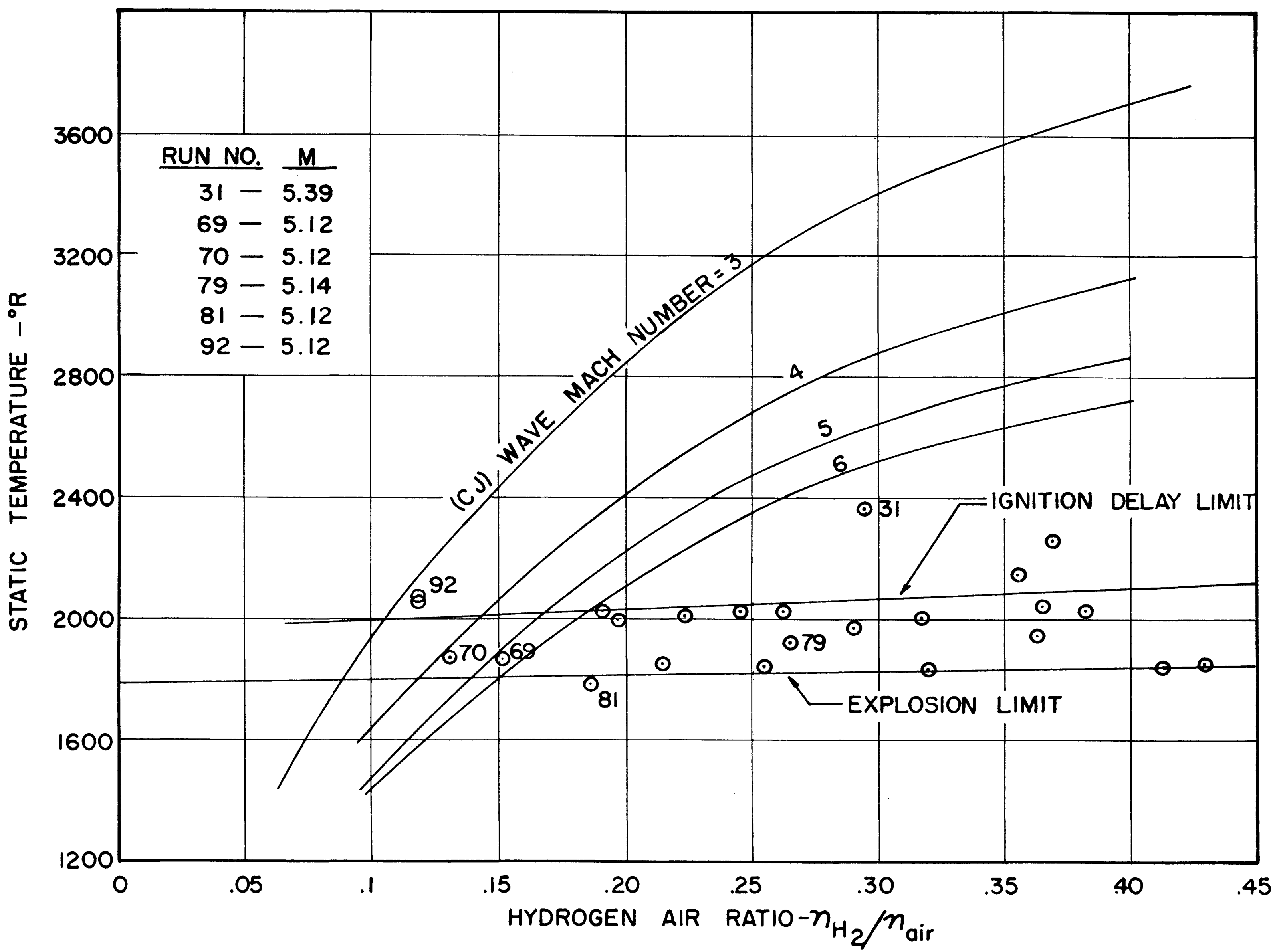


Fig. 10. Interpretation of experimental results.

EFFECT OF TRANSPORT PROPERTIES

It was indicated in the introduction that our results differ from those of Gross[3] where (a) no ignition delay was observed and (b) a hysteresis effect was noted. This phenomenon can be described as follows: once combustion is initiated, it can be maintained even though the stagnation temperature into the wave is reduced appreciably below the "ignition temperature."

One possible explanation that has been advanced regarding the hysteresis phenomenon and the absence of the delay zone reported in Reference 3 is that transport properties in accordance with References 16-18 play an important role in the wave mechanism. von Kármán[19] has shown that, if the reaction is slow, the transport properties have no effect on the shock wave and a detonation wave can be adequately described as a shock followed by combustion. A slow reaction is that wherein the number of collisions resulting in a chemical reaction is much less than the number of collisions due to thermal motion of the molecules and is therefore characterized by a parameter α, equivalent to the ratio of the numbers of the two types of collisions.

For a conservative value of this parameter, the number of collisions due to thermal motion was calculated at conditions upstream of the wave and the number of collisions resulting in a chemical reaction was calculated at conditions downstream of the wave where the temperature is higher. It was found that $\alpha \cong 10^{-4}$. This value of α, coupled with the fact that $M^2 > 1$, shows that the transport terms, both in the momentum and energy equation, are several orders of magnitude lower than other terms. It is concluded that the effect of the transport properties can only be secondary and that the concept of an induction zone corresponds to reality.

An experimental check on the hysteresis effect was conducted in the Michigan facility. It was found that the effect of lowering the temperature once combustion was started was to increase the distance between the shock and flame front. When the temperature was lowered to about 1400°F, the flame disappeared completely. Figure 11 shows this effect. The temperature of the air was controlled by preheating it with small varying amounts of hydrogen ahead of the nozzle. The photographs were taken while the temperature was decreased by decreasing the preheating hydrogen. Experiments of this type were run for lean as well as rich mixtures. Thus no hysteresis phenomenon was observed. In view of these results, along with the theoretically substantiated ignition delay results, we find no justification for the differing results reported by Gross.[3] It appears that the explanation would arise from a major difference in the two experimental techniques, namely, that the hydrogen was heated to the

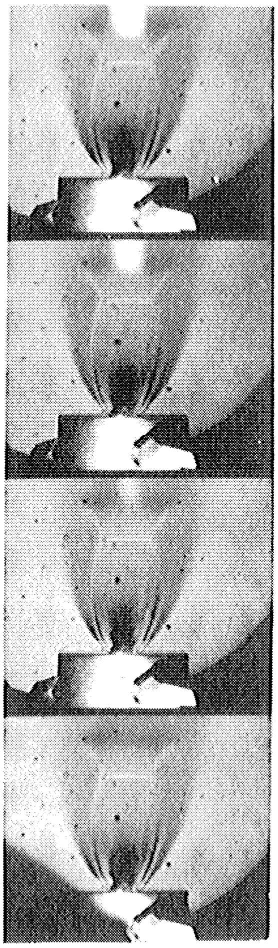


Fig. 11. Photographic sequence showing the disappearance of flame with decreasing temperature. (Temperature dropped from 1870 to 1835°R.)

air stagnation temperature in Gross' study, whereas the hydrogen is unheated in our facility. As a consequence, it is suspected that some combustion occurred immediately downstream of the hydrogen injector in Gross' work. This would explain both difficulties.

CONCLUSIONS

The results of many experiments on standing detonation waves in The University of Michigan facility have been presented. These results have been interpreted in light of a theory for the ignition delay time and the explosion limit criterion. As a consequence, it is possible to delineate those conditions under which the phenomenon can rightfully be considered a detonation wave.

No anomalous results have been encountered and the measured ignition delay times are in good agreement with the theoretical predictions. It is concluded that strong as well as C-J detonations can be stabilized in an open-jet facility, provided the proper levels of stagnation pressure and temperature are maintained commensurate with the mixture ratio employed. Transport phenomenon have proved to be insignificant in the detonations realized.

The standing-wave facility offers attractive possibilities to the experimental study of chemical kinetics.

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