

Theory of Burning Velocity. I. Temperature and Free Radical Concentrations Near the Flame Front, Relative Importance of Heat Conduction and Diffusion

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of mixtures, varying from rich mixtures with only one-half the stoichiometric amount of oxygen to lean mixtures with three times the stoichiometric oxygen content. Moreover, the ratio of oxygen to nitrogen varies from 1:4 to 65:1, and mixtures with and without added hydrogen are included. The last column of Table I contains Jahn's experimental burning velocities, and in Fig. 1 these have been plotted against values of the partial pressures of hydroxyl radicals and of hydrogen and oxygen atoms. It is apparent that no correlation exists between burning velocity and oxygen atom concentration, and a slight one at best between burning velocity and hydroxyl radical concentration. On the other hand, a striking correlation is seen to exist between burning velocity and hydrogen atom concentration.

That such a correlation should exist for hydrogen atom concentration, but not for oxygen atom or hydroxyl radical concentration, is not unexpected. For, if the extent to which free radicals in the flame can be utilized in the combustion process depends upon diffusion—and it is logical to make such a supposition—the effect of hydrogen atoms, because of their very high rates of diffusion, will overshadow that of any of the other radicals. It would further appear that if such a correlation exists in carbon monoxide flames, it should also hold true for pure hydrogen flames. Preliminary calculations show that this is indeed true, and further work on such flames is planned.

Another paper will be presented in the very near future which will suggest a theoretical basis for the results outlined above.

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Theory of Burning Velocity. I. Temperature and Free Radical Concentrations Near the Flame Front, Relative Importance of Heat Conduction and Diffusion¹

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A previous paper having suggested that hydrogen atoms play an important part in combustion, an investigation is made of the relative importance of heat conduction and diffusion in establishing concentrations of hydrogen atoms near the flame front. To do this, differential equations are set up for heat transfer and for material transport. These equations are solved for two typical mixtures, one containing moist carbon monoxide, the other containing hydrogen. It is shown that the temperature falls rapidly as the distance from the flame front increases, and that the local thermal equilibrium concentration of hydrogen atoms, being a negative exponential of that temperature, falls more rapidly still. On the other hand, the local non-equilibrium concentration of hydrogen atoms, which is caused by diffusion from the flame front into unburnt gas, falls only slowly with distance. It is thus concluded that diffusion plays a more important role than heat transfer.

INTRODUCTION

IT has already been suggested by Lewis and von Elbe³ that the diffusion of atoms and free radicals is more important than heat conduction in initiating combustion. This idea received sup-

port in a communication from this laboratory⁴ in which calculations were made of equilibrium atom and free radical concentrations in moist carbon monoxide flames for points at which combustion has proceeded adiabatically to equilibrium. It was shown that there exists a very close correlation between such calculated hydrogen atom concentrations and experimentally

¹ Abstracted in part from a thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Princeton University.

² National Research Council Predoctoral Fellow in Chemistry, 1946-47.

³ B. Lewis and G. von Elbe, *J. Chem. Phys.* 2, 537 (1934).

⁴ C. Tanford and R. N. Pease, *J. Chem. Phys.* 15, 431 (1947).

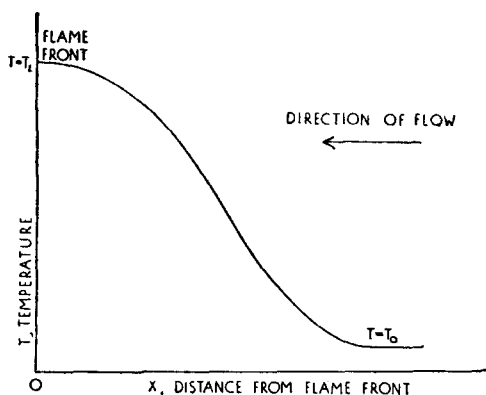


FIG. 1. Flame front and combustion zone.

determined burning velocities. Less correlation was found for hydroxyl radicals, and none at all for oxygen atoms. This observation is a reasonable one if we suppose that the extent to which free radicals in the flame can be utilized for flame propagation depends upon diffusion, for then the effect of hydrogen atoms, because of their very high rate of diffusion, will overshadow that of any other free radicals.

On the other hand, this correlation is not readily explained by theories of burning velocity based upon heat conduction,⁵ for, according to such theories, the burning velocity depends upon the rate at which unburnt gas can be ignited by heat conducted from the flame front (which in this paper is defined as the surface of the flame where combustion has gone to equilibrium). From our present knowledge of combustion processes we would interpret the ignition of gas mixtures by heat conduction as caused by the formation by thermal dissociation of a local concentration of atoms or free radicals high enough to initiate and maintain a chain process leading to combustion.

Thus two alternative pictures of combustion processes present themselves: (1) that the unburnt gas is ignited by free radicals produced locally by thermal dissociation following heat conduction, and (2) that it is ignited by free radicals supplied to the unburnt gas by diffusion from the flame front. It is clearly of advantage to investigate these possibilities more thoroughly.

Accordingly, we have in this paper set up an

equation for heat transfer by means of which the static temperature at any point in the combustion zone can be obtained. From a knowledge of this temperature the thermal equilibrium concentration of any free radical at any point can be calculated. Similarly, we have set up an equation for material transport, from which, if we know the equilibrium concentration of any free radical at the flame front, we can calculate the stationary diffusion concentration of such a radical at any other point in the combustion zone.

It will be shown that in two typical and common cases such stationary non-equilibrium concentrations of hydrogen atoms are much higher than thermal concentrations. Hence in these cases heat conduction cannot play a major role in the determination of burning velocities, which are more probably determined entirely by diffusion of hydrogen atoms from the flame front.

THE TEMPERATURE DISTRIBUTION

In order to obtain the temperature distribution in the vicinity of the flame front we consider the simple model illustrated in Fig. 1. Let the reaction zone be stationary with respect to the coordinate system $x-T$. Then the unburnt gas, initially at the temperature T_0 , moves in the direction of the arrow towards the flame front, which is taken as the point where $x=0$ and where the temperature is the equilibrium flame temperature, T_1 . The flow is taken normal to the flame front, so that in the cold unburnt gas ($T=T_0$) the flow velocity must be the burning velocity as defined in the usual manner.⁶ It is here designated by the symbol u_0 .

We now set up the differential equation for heat transfer, considering at each point (1) the motion of the gas stream, which tends to replace gas of temperature $T(x)$ by cooler gas, and the opposing processes (2) of heat conduction from left to right along the negative temperature gradient, and (3) of heat release by chemical reaction. To obtain the equation for the steady temperature we must find expressions for the rate of change of temperature at any point by each of these three processes, and equate the sum of these changes to zero.

⁵ E. Mallard and H. L. Le Chatelier, *Ann. Mines* **4**, 274 (1883), and subsequent modifications.

⁶ W. Jost, *Explosions- und Verbrennungsvorgänge in Gasen* (Verlagsbuchhandlung Julius Springer, Berlin, 1939), p. 63.

Taking first the rate of change of temperature due to gas motion, we consider a volume element $dS \cdot dx$, parallel to an element dS of the flame front. The gas streaming towards the flame front will replace gas in this element, of temperature T , by that in an adjoining element, of temperature $T + (\partial T / \partial x) dx$, in a time $dt = dx/u$. Hence, per second,

$$\left(\frac{\partial T}{\partial t} \right)_1 = \frac{\partial T}{\partial x} \frac{dx}{u} = u \frac{\partial T}{\partial x}. \quad (1)$$

The rate of change of temperature due to heat conduction is given by Fourier's equation. Where c , the specific heat, and k , the thermal conductivity, are regarded as constant over the whole combustion zone, we obtain, where ρ is the density at any point,

$$(\partial T / \partial t)_2 = (k/c\rho)(\partial^2 T / \partial x^2). \quad (2)$$

Finally, the rate of change of temperature due to the release of chemical energy can be expressed in terms of a variable λ , which defines the progress of the chemical reaction (as measured by the heat release) as a function of x . The variable λ is equal to zero at all points outside the combustion zone (i.e., where x is sufficiently large) and is equal to unity where $x=0$. If Q is defined as the total amount of heat released in the combustion of one gram of unburnt gas, then, if we consider again a volume element $dS \cdot dx$, the amount of heat released per second in this element must be the mass of gas passing through the element per second ($\rho u dS$), multiplied by the factor $-Q(\partial \lambda / \partial x) dx$. This amount of heat released per second must be equal to the rate of change of temperature in the element multiplied by the mass of gas in the element ($\rho dS dx$) multiplied by the specific heat, i.e.,

$$(\partial T / \partial t)_3 \rho dS dx = -Q(\partial \lambda / \partial x) \rho u dS dx,$$

or

$$(\partial T / \partial t)_3 = -(Qu/c)(\partial \lambda / \partial x). \quad (3)$$

Adding Eqs. 1, 2, and 3, equating to zero, and replacing partial by total derivatives, we obtain

$$\frac{k}{c\rho} \frac{d^2 T}{dx^2} + u \frac{dT}{dx} - \frac{Qu}{c} \frac{d\lambda}{dx} = 0.$$

Multiplying by $c\rho/k$, and introducing the condi-

tion of conservation of mass, $\rho u = \text{constant} = \rho_0 u_0$, this reduces to

$$\frac{d^2 T}{dx^2} + \frac{c\rho_0 u_0}{k} \frac{dT}{dx} - \frac{Q\rho_0 u_0}{k} \frac{d\lambda}{dx} = 0. \quad (4)$$

To solve this equation it becomes necessary to make an assumption regarding $d\lambda/dx$. Two simple ones suggest themselves: (a) all heat is released at the flame front ($x=0$) and none elsewhere, so that $d\lambda/dx$ vanishes except at $x=0$; (b) the chemical reaction proceeds evenly over the whole of the combustion zone, which shall be taken to be of thickness δ , so that $d\lambda/dx$ becomes equal to a constant, $-1/\delta$. The true state of affairs is certainly intermediate between these two assumptions. Assumption (a) can therefore be expected to yield too steep a temperature gradient, while assumption (b) probably results in too gradual a drop. In practice it will be found that the results obtained by use of these two assumptions do not differ very greatly, so that a fairly close estimate of the true temperature at any point can be obtained.

Under these two assumptions, Eq. 4 reduces, respectively, to

$$(d^2 T / dx^2) + A(dT/dx) = 0, \quad (5a)$$

or to

$$(d^2 T / dx^2) + A(dT/dx) + AB = 0, \quad (5b)$$

where A and B are used to designate the products $c\rho_0 u_0/k$ and $Q/c\delta$, respectively. It should be noted that Eq. (5b) applies only between the limits $0 \leq x \leq \delta$; where $x > \delta$ no heat is released, and Eq. (5a) must be applied also to the case of assumption (b).

To solve these equations we must introduce the boundary conditions, $T = T_1$ where $x=0$, and $dT/dx=0$ where $T=T_0$. In the case of assumption (b) we must in addition specify that T and dT/dx are continuous at the point $x=\delta$. The two solutions then become: for assumption (a)

$$(T - T_0) = (T_1 - T_0)e^{-Ax}, \quad (6a)$$

and for assumption (b)

$$(T - T_0) = \{T_1 - T_0 - B(1/A + \delta)\}e^{-Ax} - Bx + B(1/A + \delta), \quad (6b)$$

where Eq. (6b) applies for $0 \leq x \leq \delta$. The solution

TABLE I. Data for combustible mixtures.

	Mixture No. 1	Mixture No. 2
Composition	60% CO, ^a 39.4% O ₂ , 0.6% N ₂	40% H ₂ , 24% O ₂ , 36% N ₂
T ₁ , °K ^b	2930	2750
T ₀ , °K	298	298
ρ ₀ , g/cc ^c	1.22 × 10 ⁻³	7.6 × 10 ⁻⁴
u ₀ , cm/sec. ^d	68	362
c, cal./g °C ^e	0.29	0.43
k, cal./sec. cm °C	1.95 × 10 ⁻⁴	4.0 × 10 ⁻⁴
Q, cal./g ^b	795	1015
δ, cm	0.01	0.005
A = cρ ₀ u ₀ /k	123	296
B = Q/cδ	2.74 × 10 ⁵	4.72 × 10 ⁵
p _H , atmos. ^b	2.4 × 10 ⁻³	1.35 × 10 ⁻²
D _H , cm ² /sec. ^g	1.95	2.75
B' (see Eq. (16))	1.35	1.13

^a CO contains 1.35 percent H₂O.^b Calculated as shown in reference 4.^c Density at 1 atmos. and 298°K.^d Jahn, *Der Zündvorgang in Gasgemischen* (Oldenbourg, Berlin, 1934).^e Estimate from values given by Wagman, Kilpatrick, Taylor, Pitzer, and Rossini, J. Research Nat. Bur. Stand. **34**, 143 (1945).^f Extrapolation and estimate for mixtures from values given by McAdams, *Heat Transmission* (McGraw-Hill Book Company, Inc., New York, 1942).^g Calculated from Stefan-Maxwell equation, using molecular radii from Chapman and Cowling, *The Mathematical Theory of Non-Uniform Gases* (Cambridge University Press, England, 1939), p. 248; and the value 0.53A (the Bohr radius) for the hydrogen atom. Values for mixtures obtained by suitable interpolation.for $x > \delta$ is

$$(T - T_0) = \{T_1 - T_0 - B(1/A + \delta) + (B/A)e^{A\delta}\}e^{-Ax}. \quad (6c)$$

Equations (6a), (6b), and (6c) have been used to evaluate the temperature distributions of two typical mixtures, one containing moist carbon monoxide, the other containing hydrogen, for both of which experimental values of the burning velocity are available. Estimates of 0.01 and 0.005 cm, respectively, have been made for the thickness of the flame front, these being the distances beyond which the lower limit of the

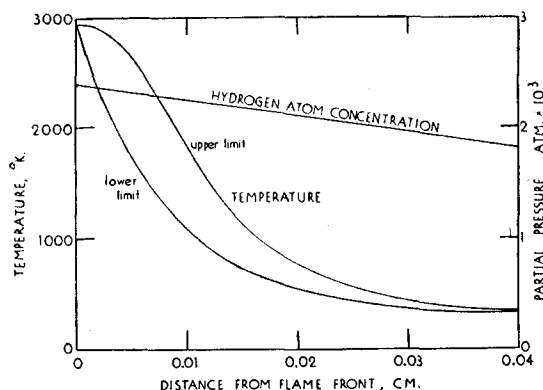


FIG. 2. Temperature and hydrogen atom concentration near flame front in carbon monoxide mixture (mixture No. 1).

temperature falls below 1000°K.⁷ Other data used in the evaluation (as well as those used in the diffusion calculation below) are listed in Table I, together with references to the sources from which they have been obtained.

The resulting temperature distributions are plotted in Figs. 2 and 3. The lower limit of the temperature distribution is probably closer to the truth than the upper limit, for the velocities of any rate-determining chemical reactions must increase exponentially with temperature, with the result that the heat release is probably concentrated much closer to the flame front than has been supposed in assumption (b).

RADICAL CONCENTRATION DUE TO DIFFUSION

In order to obtain the concentration of any free radical at any point in the combustion zone and due to diffusion from the flame front, it is necessary first to calculate the equilibrium partial pressure, p , of the radical at the flame front, using the method described in our previous paper.⁴ A differential equation for material transport can then be set up, similar to that for heat transfer given above. Unfortunately, if this equation is set up in rigorous form, with the temperature gradient taken into account, it becomes insoluble by ordinary means. Thus it becomes necessary to simplify the problem by assuming that the flame front and the whole combustion zone are all at

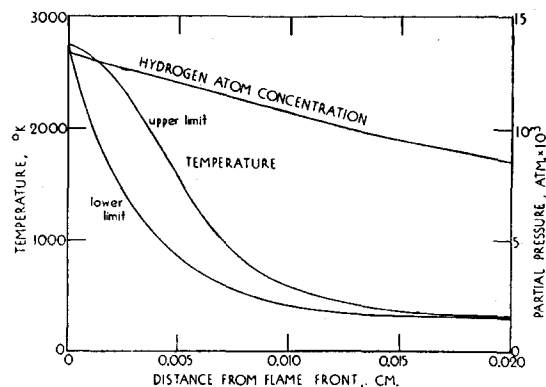


FIG. 3. Temperature and hydrogen atom concentration near flame front in hydrogen mixture (mixture No. 2).

⁷ These are extreme estimates. Most observers give smaller values, e.g. Lewis and von Elbe, reference 3, compute a thickness of 10⁻³ to 10⁻⁴ cm. Use of such a small value would, of course, bring the upper limit of the temperature obtained by us even closer to the lower limit.

one constant mean temperature, T_m , which we shall take, in general, to be some fraction of the flame temperature. The effect of such a simplification is to give to the density and the flow velocity values ρ_m and u_m , which are constant over the entire combustion zone.

As in the case of heat transfer, we now enumerate the changes in radical concentration, c , taking place at any point, and, since we are interested in the steady state, equate the sum of these changes to zero. The changes in radical concentration which we must consider are (1) those due to the motion of the gas stream, which tends to replace gas of radical concentration $c(x)$ by gas with a smaller concentration, (2) those due to chemical processes, and (3) those due to diffusion.

Taking first the rate of change due to gas motion: by reasoning exactly analogous to that used in the case of heat transfer we get

$$(\partial c / \partial t)_1 = u_m (\partial c / \partial x). \quad (7)$$

Next, the chemical processes: these may be of zero, first, or second order with respect to the radical concentration. Since the differential equation which we shall obtain will be non-linear if we include terms in c^2 , it will be necessary to estimate the rates of second-order processes relative to the first order processes and to take them into account in the first-order term. Zero-order terms can be taken care of without difficulty where they occur: they are of no importance in the cases which we shall discuss in this paper, and so are omitted for the sake of simplicity. The net effect of chemical reactions is then described by a term

$$(\partial c / \partial t)_2 = A'c, \quad (8)$$

where A' is negative if there is a net loss of radicals because of chemical reaction.

Finally, Fick's equation gives the rate of increase of radical concentration due to diffusion from left to right. Where D_m is used to designate the diffusion coefficient of a given radical into unburnt gas at the temperature T_m , we have

$$(\partial c / \partial t)_3 = D_m (\partial^2 c / \partial x^2). \quad (9)$$

We now add Eqs. (7)–(9) and equate to zero. Since x is our only independent variable, we can replace partial by total derivatives, and so obtain

$$D_m (d^2 c / dx^2) + u_m (dc / dx) + A'c = 0. \quad (10)$$

At the point $x=0$ the partial pressure of any free radical, and, hence, the corresponding concentration, c_1 , are known. Also, as x becomes large, both c and dc/dt tend to zero. Allowing for these boundary conditions, and giving to A' an average value independent of x , we can solve Eq. (10) and obtain

$$c = c_1$$

$$\times \exp \left(- \left\{ \frac{1}{2} [1 + (1 - 4A'D_m/u_m^2)^{\frac{1}{2}}] \right\} \frac{u_m x}{D_m} \right); \quad (11)$$

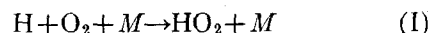
or

$$c = c_1 \exp(-B'u_m x / D_m), \quad (12)$$

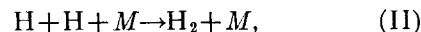
where we have replaced the expression in brackets in Eq. (11) by the symbol B' . We see that where changes in radical concentration due to chemical processes are negligible, i.e., where A' vanishes, B' is equal to unity.

Since hydrogen atoms appear to be the most important free radicals in the combustion of hydrogen and carbon monoxide,⁴ we shall evaluate by means of Eq. (12) the concentrations of hydrogen atoms in the two mixtures already discussed above. To do so we must first find appropriate expressions for B' .

Of the possible reactions involving hydrogen atoms, only two are probably fast enough to have an appreciable effect upon the hydrogen atom concentration. These are



and



where M represents any third body.⁸ From a knowledge of the rates of these reactions it will be possible to evaluate A' (Eq. (11)), and, hence, B' .

The rate of disappearance of hydrogen atoms by reaction (I) is most conveniently expressed by

$$-dc_H/dt = k_1 q_M q_{O_2} c_H, \quad (13)$$

where q_M is the mole fraction (total pressure one atmosphere) of all possible third bodies, which is, of course, equal to unity, while q_{O_2} is a mean value of the oxygen mole fraction over the reac-

⁸ V. Kondratyev, [Bull. acad. sci. U.R.S.S., Classe sci. chim. 501 (1940)] and others have shown that the reactions $OH + CO \rightarrow CO_2 + H$, and $OH + H_2 \rightarrow H_2O + H$ are slow compared with I. G. von Elbe and B. Lewis (reference 9) arrive at a slow rate for HO_2 formation in the absence of a third body.

tion zone. The rate constant k_1 is then in units of sec^{-1} . Now von Elbe and Lewis⁹ give for the three-body reaction $\text{H} + \text{O}_2 + M$ a rate constant of $0.81 \times 10^{13} \text{ cm}^6 \text{ mole}^{-2} \text{ sec}^{-1}$ (298°K) where the third body is hydrogen, and about one-third of that where the third body is oxygen or nitrogen. There is apparently no change in the rate constant with temperature. For mixture No. 1, therefore, which consists largely of O_2 , N_2 , and CO (cf. Table I), the best value of this rate constant is probably about $0.3 \times 10^{13} \text{ cm}^6 \text{ mole}^{-2} \text{ sec}^{-1}$. Converting to the units of k_1 by multiplication by $L^2/N^2\theta_m^2$, where N is Avogadro's number, L is the number of molecules per cc at room temperature, and θ_m is T_m/T_0 , the ratio of the mean temperature to room temperature, we obtain $k_1 = 6000/\theta_m^2$. For mixture No. 2 a similar estimate yields $k_1 = 11,000/\theta_m^2$. Hence, by comparison of Eq. (13) with Eq. (8), the contribution of reaction (I) to A' must be, for mixture No. 1,

$$A_1' = -\frac{6000}{\theta_m^2} q_{\text{O}_2} \quad (14)$$

while A' for mixture No. 2 is 11/6 of this expression.

The rate of disappearance of hydrogen atoms by the recombination reaction (II) is

$$-dc_H/dt = 2k_2' q_M c_H^2,$$

the number 2 indicating that two hydrogen atoms are lost per successful collision. Since, as has already been mentioned, we must make this expression first order with respect to the hydrogen atom concentration, c_H , we shall introduce in place of one of the terms c_H an average hydrogen atom concentration. Choosing for this one-half the equilibrium concentration at the flame front, and again expressing in the most convenient units, we obtain

$$-dc_H/dt = k_2 q_M p_H c_H,$$

where q_M is again equal to unity, and p_H is the equilibrium partial pressure of hydrogen atoms at the flame front. Steiner¹⁰ has found the rate constant of reaction (II) to be $1.1 \times 10^{16} \text{ cm}^6 \text{ mole}^{-2} \text{ sec}^{-1}$. Again converting to the proper units we obtain $k_2 = 2.2 \times 10^7/\theta_m^2$, i.e., the con-

tribution of reaction (II) to A' , for both mixtures 1 and 2, is

$$A_2' = -\frac{2.2 \times 10^7}{\theta_m^2} p_H. \quad (15)$$

Adding contributions (14) and (15), we obtain for the correction term B' , for mixture No. 1,

$$B' = \frac{1}{2} \left\{ 1 + \left[1 + \frac{24,000 D_0}{u_0^2 \theta_m^2} (q_{\text{O}_2} + 3700 p_H) \right]^{\frac{1}{2}} \right\}, \quad (16a)$$

and for mixture No. 2,

$$B' = \frac{1}{2} \left\{ 1 + \left[1 + \frac{44,000 D_0}{u_0^2 \theta_m^2} (q_{\text{O}_2} + 2000 p_H) \right]^{\frac{1}{2}} \right\}. \quad (16b)$$

Equation 12, with the proper expressions for B' , has been applied to the two mixtures discussed in the last section. For θ_m we have used the value $0.7T_1/T_0$, for D_m we have used the value $D_0\theta_m^2$, where D_0 is the diffusion coefficient for hydrogen atoms into the unburnt gas at room temperature, and for u_m we have used the value $u_0\theta_m$, where u_0 is the normal flow velocity of the unburnt gas, i.e. the burning velocity. A value for q_{O_2} has been estimated from initial and final compositions; all other necessary numerical data are contained in Table I.

The resulting hydrogen atom concentrations are given in the last column of Table II and are plotted in Figs. 2 and 3. It is seen that the hydrogen atom concentration changes with distance more slowly than does the temperature. This is not unexpected, since the conduction of heat, depending on the mean free path of an average molecule, is less efficient than the diffusion of hydrogen atoms, which depends on the relatively large mean free path of hydrogen atoms.

It should be remembered that these radical concentrations have been obtained on the assumption of a constant temperature, T_m , over the whole combustion zone. The effect of this assumption has been to steepen the concentration curve very near the flame front, and to flatten it at greater distances.

RELATIVE IMPORTANCE OF HEAT CONDUCTION AND DIFFUSION

As was mentioned in the introduction, these calculations have been made not only for their

⁹ G. von Elbe and B. Lewis, *J. Chem. Phys.* **7**, 710 (1939).

¹⁰ W. Steiner, *Trans. Faraday Soc.* **31**, 623 (1935).

own intrinsic interest, but also to decide whether the ignition of unburnt gas approaching the flame front is more likely to be caused by hydrogen atoms or other free radicals produced thermally (heat conduction theory), or by hydrogen atoms supplied by diffusion from the flame front. Hence it is desirable to compare the calculated hydrogen atom concentrations due to diffusion with local equilibrium concentrations to be expected from thermal dissociation.

To estimate the latter, a maximum value of the molecular hydrogen concentration has been assumed for every point. For mixture No. 1, which has no hydrogen present initially, we have taken this concentration to be the equilibrium concentration due to water dissociation at the flame temperature; for mixture No. 2 we have assumed that all of the molecular hydrogen initially present remains unchanged up to a distance of 0.001 cm from the flame front. For both mixtures the equilibrium constants for hydrogen dissociation given by Lewis and von Elbe¹¹ have then been used to calculate the thermal hydrogen atom concentrations. Since the molecular hydrogen concentrations are maximum values, the atomic concentrations will also be maximum ones.

Figures for such a comparison, for the two mixtures already discussed, are given in Table II, in which are listed, for various distances from the flame front, the temperature half-way between the upper and lower limits (Figs. 2 and 3), the equilibrium thermal hydrogen atom concentration at that temperature, and, finally, the hydrogen atom concentration due to diffusion. It is seen that the thermal equilibrium concentration, being a negative exponential of the temperature, drops with extraordinary rapidity. The diffusion concentration, however, drops only very slowly.

It is clear from Table II that heat conduction is not a factor of importance in establishing hydrogen atom concentrations in unburnt gas approaching a combustion zone, but that such atom concentrations are more probably de-

TABLE II. Hydrogen atom concentrations due to thermal dissociation and to diffusion.

Partial pressure H atoms, atmos.			
x, cm	T, °K	Therm. dissoc.	Diffusion
		(Maximum value)	
Mixture No. 1			
0	2930	2.4×10^{-3}	—
0.002	2630	8.5×10^{-4}	2.4×10^{-3}
0.004	2330	2.3×10^{-4}	2.3×10^{-3}
0.006	2030	4.0×10^{-5}	2.3×10^{-3}
0.008	1740	4.4×10^{-6}	2.3×10^{-3}
0.010	1460	2.2×10^{-7}	2.2×10^{-3}
0.012	1200	4×10^{-9}	2.2×10^{-3}
0.014	1000	5×10^{-11}	2.2×10^{-3}
0.016	850	5×10^{-13}	2.2×10^{-3}
0.018	720	2×10^{-16}	2.1×10^{-3}
0.020	630	1×10^{-17}	2.1×10^{-3}
Mixture No. 2			
0	2750	1.35×10^{-2}	—
0.001	2390	9.6×10^{-3}	1.32×10^{-2}
0.002	2060	5.2×10^{-3}	1.29×10^{-2}
0.003	1760	1.8×10^{-4}	1.26×10^{-2}
0.004	1480	9.6×10^{-6}	1.23×10^{-2}
0.005	1200	2×10^{-7}	1.20×10^{-2}
0.006	970	1×10^{-9}	1.17×10^{-2}
0.007	800	2×10^{-12}	1.15×10^{-2}
0.008	680	6×10^{-16}	1.12×10^{-2}
0.009	580	6×10^{-18}	1.09×10^{-2}
0.010	500	6×10^{-21}	1.07×10^{-2}

terminated entirely by diffusion from the flame front. It should be mentioned that no consideration has been given here to the possibility of a maximum in the hydrogen atom concentration at a point other than the flame front, due to chain branching. Such a maximum is unlikely to occur for hydrogen atoms, however, because of the high rates of three-body recombination and reaction to form HO_2 .

A quantitative theory for burning velocity based upon the concept that diffusion from the flame front is the determining factor, and utilizing some of the equations derived in this paper, will be presented in the near future.

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¹¹ B. Lewis and G. von Elbe, *Combustion, Flames and Explosions of Gases* (Cambridge University Press, England, 1938), p. 382.