536.25 : 662.612

Ignition in a Free Convection from Vertical Hot Plate*

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Since the flow velocity in a free convection from a vertical plate is comparatively small, it may be considered that the influence of the divergent flame propagation on the ignition is negligible except in the case of very low burning velocity and then the inflammable conditions are determined only by the hot surface.

In this experiment, changes in the flow and the composition of mixture around the plate in every experiment under the same conditions are small compared to those in a forced flow. Therefore, it is relatively easy to know the qualitative characteristics of ignition.

From the point of view described above, the authors arranged the experimental results making use of the relation between experimental parameters and critical ignition temperature obtained from a numerical analysis of the fundamental equations and showed that the experimental results agreed well with theoretical prediction.

1. INTRODUCTION

Many of the studies on the ignition by heated body have been restricted to those in forced flow of mixture. Those in a free convection flow have apparently not been made.

From the similarity consideration of the solution of boundary layer equations, Admeit⁽¹⁾ made a general discussion about the ignition problem in relation to heat transfer from heated body. However, he treated the case of negligible effect of buoyancy.

Toong et al.⁽²⁾, carried out an experiment in the forced flow by making use of a partially heated circular tube regarded as a horizontal flat plate. In this case, unlike the former investigations, there was no wake effect on the heated surface. They discussed about the ignition conditions⁽³⁾ related to the temperature gradient on the heated surface as was done by Semenov et al. In case of fast flow, however, the flame propagation from the surface to a free stream becomes divergent⁽⁴⁾. Therefore, this effect should be taken into consideration.

On the other hand, since the flow velocity in a free convection from a vertical plate is comparatively small, it is considered that the influence of the divergent flame propagation on the ignition may be negligible except in the case of very low burning velocity, and then the inflammable conditions are determined only by the hot surface.

In a free convection boundary layer, the flow velocity and the mixture concentration

may be less disturbed compared to those in a forced flow. Therefore, the investigation of ignition in a free convection flow is very useful to know the qualitative nature of the ignition on the hot surface.

From these view points, the authors investigated the ignition condition in a free convection boundary layer. The results were arranged by making use of the relation between the critical ignition temperature and the other experimental parameters which was obtained from the numerical analysis of the fundamental equations, and it was shown that the experimental results agreed well with the theoretical prediction.

2. EXPERIMENTAL APPARATUS

An electrically heated vertical plate is installed at the center position of a cylindrical combustion chamber set horizontal by a support penetrating the combustion chamber through a cylindrical wall. This test vessel has three observation windows through which various measurements can be made. A mixing apparatus is installed on the bottom wall of the combustion chamber in order to make a homogeneous mixture. The diameter and the length of the cylindrical vessel are taken as 200mm, respectively, so as to reduce the effect of flow recirculation as much as possible. A general view of the combustion chamber and its cross-section are shown in Fig.1 and Fig.2 respectively. The heating plate is thermally and electrically insulated from the support at both ends, and the heat capacity of the support is taken as large as possible to avoid flow disturbance by hot support. A deformation of hot surface owing to the thermal expansion can be corrected by pre-tensioning of the plate. 18-8 Chromium-Nickel steel plate of 0.3mm in thickness and 40mm in width was used as heating plate. A vertical length of the plate was varied from 5 to 30mm at intervals of 5mm. The effective heating width was about 20 to 30mm depending on the vertical length. Fig.3 shows details of the support.

* Received 14th June, 1974

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Fig.1 Combustion chamber

Fig.2 Cross-sectional view of combustion chamber

Fig.3 Details of the support of the heating plate

3. EXPERIMENTAL PROCEDURE

The heating plate was previously heated in the air for a proper period so that the progress of surface oxidation became considerably slow. A scattering of the experimental data could be reduced by this treatment because of little change in emissivity of the surface.

The surface temperature of the plate was measured by a radiation pyrometer which was previously corrected using a thermocouple.

The temperature distribution in a central region on the surface was almost flat in the horizontal direction, and this part of the plate acted as an effective heating surface.

The temperature in the vertical direction along the center line of the plate decreased at both ends by a few percent. The representative hot surface temperature was determined by measuring the mean temperature in the central area of the plate within a diameter of 1mm, and a constant temperature distribution was assumed. The measured profiles of

Fig.4 Profiles of temperature distribution

temperature distribution for various heating lengths are shown in Fig.4.

Experiment was performed with the following procedure to determine the critical temperature of hot surface above which the ignition of mixture took place within the limit of heating length (hereafter, this temperature is defined as the ignition temperature).

After full stirring of the mixture of a fixed composition and pressure, the plate was rapidly heated close to the ignition temperature and the subsequent heating was gradually made until a flame propagation occurred from the hot surface. The temperature of the plate just before ignition was defined as the ignition temperature.

Since there was no scattering of the data owing to the difference in heating period, it was assumed in the subsequent analyses that the prescribed composition of mixture had hardly changed during this period.

For the purpose of more plain explanation of experimental results in comparison with the theoretical analyses, the flow measurement in the boundary layer by particle tracing and the observation of ignition by high speed schlieren photography were carried out. The general arrangements of the measuring devices are shown in Fig.5 and Fig.6.

Fig.5 Flow measurement by particle tracing

Fig.6 Observation of ignition by schlieren method

4. CONSIDERATION OF IGNITION CONDITION BY MEANS OF THE BOUNDARY LAYER APPROXIMATION

4-1 Symbols used in the analysis

x	vertical distance along the plate
y	horizontal distance from the plate
u	x -component of flow velocity
v	y -component of flow velocity
T	absolute temperature
c	mass fraction of fuel
H	vertical length of the plate
P_0	pressure of mixture
ξ	x/H
ζ	$\sqrt{\xi}$
η	$(Grx/4)^{1/4} x^{-1} \int_0^y (\rho/\rho_\infty) dy$
U	$\partial F/\partial \eta$
V	$3F+2\zeta(\partial F/\partial \eta)$
θ	$(T-T_\infty)/(T_w-T_\infty)$
C	c/c_∞
β	thermal expansion coefficient, $1/T_\infty$
ρ	density of mixture
g	acceleration of gravity
C_p	specific heat at constant pressure
λ	heat conductivity
D	diffusion coefficient
R	gas constant
E	activation energy
μ	viscosity coefficient
ν	kinematic viscosity coefficient
Q	heat of combustion
a	reaction rate
K	rate constant
n	order of reaction
ψ	$4\nu_\infty(Grx/4)^{1/4} F(\xi, \eta)$
t	time
Pr	Prandtle number
Sc	Schmidt number
Grx, Gr_H	Grashoff number (subscript)
w	values on the hot surface
∞	values outside the boundary layer

4-2 Fundamental equations

According to the measurement of flow velocity, the boundary layer over the hot surface is so thin, unless the pressure in the combustion chamber is too low, that the boundary layer approximation can be reasonably applied to the present analysis. And the change in the composition of mixture outside the boundary layer may be neglected, because it takes relatively short time from the start of heating until the ignition takes place. Under these considerations the following assumptions are made for numerical analysis of the fundamental equations;

- (1) isothermal hot surface
- (2) uniform pressure in the vessel
- (3) two-dimensional thin boundary layer
- (4) ideal gas mixture with constant molecular weight, specific heat, Prandtle number and Schmidt number
- (5) proportionality of viscosity to temperature⁽⁵⁾
- (6) incompressible fluid
- (7) Arrhenius type reaction rate, and reaction kinetics independent of pressure and temperature.

In addition to these assumptions, variations of density of mixture and concentration of combustible species in the boundary layer are taken into account. The fundamental equations are written as follows.

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \quad (1)$$

$$\rho(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}) = \frac{\partial}{\partial y}(\mu \frac{\partial u}{\partial y}) + g \beta(T - T_\infty) \quad (2)$$

$$c_p \rho(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}) = \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) + aQ \quad (3)$$

$$\rho(u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y}) = \frac{\partial}{\partial y}(D \rho \frac{\partial c}{\partial y}) - a \quad (4)$$

Boundary conditions :

For $0 \leq x \leq H, y=0, u=v=0, T=T_w, \partial c/\partial y=0$

For $0 \leq x \leq H, y=\infty, u=0, T=T_\infty, c=c_\infty$

For $x=0, y>0, u=v=0, T=T_\infty, c=c_\infty$

From the observation that the ignition point located at the trailing part of the heated plate, Semenov's condition for ignition was applied to this point, i.e. $(\partial T/\partial y)_{x=H, y=0} = 0$.

4-3 Dimensional analysis of fundamental equations

The solution of equation (1) can be written as usual in terms of stream function ψ ,

$$u = \frac{\rho_\infty}{\rho} \frac{\partial \psi}{\partial y}, \quad v = -\frac{\rho_\infty}{\rho} \frac{\partial \psi}{\partial x}.$$

The reaction rate is assumed to follow the n th order of Arrhenius rate law², $a = K(\rho c)^n \exp(-E/RT)$.

Since Eq.(1) is automatically satisfied by introducing a stream function ψ , the fundamental equations are transformed to non-dimensional forms by changing the coordinate system from (x, y) to (ξ, η) system with substitutions of nondimensional temperature and concentration.

$$\frac{\partial^3 F}{\partial \eta^3} + 3F \frac{\partial^2 F}{\partial \eta^2} - 2 \left(\frac{\partial F}{\partial \eta} \right)^2 + 4\xi \left(\frac{\partial F}{\partial \xi} \frac{\partial^2 F}{\partial \eta^2} - \frac{\partial^2 F}{\partial \xi \partial \eta} \frac{\partial F}{\partial \eta} \right) + \theta = 0 \quad (5)$$

$$\frac{1}{Pr} \frac{\partial^2 \theta}{\partial \eta^2} + 3F \frac{\partial \theta}{\partial \eta} + 4\xi \left(\frac{\partial F}{\partial \xi} \frac{\partial \theta}{\partial \eta} - \frac{\partial F}{\partial \eta} \frac{\partial \theta}{\partial \xi} \right) + 2\xi^{1/2} A' \tau' \frac{1}{T_w/T_\infty - 1} = 0 \quad (6)$$

$$\frac{1}{Sc} \frac{\partial^2 C}{\partial \eta^2} - 3F \frac{\partial C}{\partial \eta} + 4\xi \left(\frac{\partial F}{\partial \xi} \frac{\partial C}{\partial \eta} - \frac{\partial F}{\partial \eta} \frac{\partial C}{\partial \xi} \right) - 2\xi^{1/2} \frac{A'}{B} \tau' = 0 \quad (7)$$

where

$$A' = (K/\sqrt{g}) B c_\infty^{n-1} \rho_\infty^{-1} \sqrt{H}, \quad B = c_\infty Q / c_p T_\infty,$$

$$\tau' = [C^n / (T_w/T_\infty - 1)^{1/2} \{ (T_w/T_\infty - 1)\theta + 1 \}] \times \exp[-E/RT_\infty \{ (T_w/T_\infty - 1)\theta + 1 \}^{n-1}]$$

In numerical analysis, to reduce the influence of error fluctuation in a region of small ξ , a new independent variable is defined as $\zeta = \xi^{1/2}$, and also to reduce the order of equation (5) the following nondimensional velocities are introduced, $U = \partial F / \partial \eta$, $V = 3F + 2\zeta \partial F / \partial \eta$.

By making use of these variables, the fundamental equations are rearranged as follows.

$$\frac{\partial V}{\partial \eta} = 3U + 2\zeta \frac{\partial U}{\partial \zeta} \quad (8)$$

$$\frac{\partial^2 U}{\partial \eta^2} + V \frac{\partial U}{\partial \eta} - 2U^2 - 2\zeta U \frac{\partial U}{\partial \zeta} + \theta = 0 \quad (9)$$

$$\frac{1}{Pr} \frac{\partial^2 \theta}{\partial \eta^2} + V \frac{\partial \theta}{\partial \eta} - 2\zeta U \frac{\partial \theta}{\partial \zeta} + \tau = 0 \quad (10)$$

$$\frac{1}{Sc} \frac{\partial^2 C}{\partial \eta^2} + V \frac{\partial C}{\partial \eta} - 2\zeta U \frac{\partial C}{\partial \zeta} - \gamma = 0 \quad (11)$$

where

$$\tau = \zeta A' \tau' / (T_w/T_\infty - 1), \quad \gamma = \zeta A' \tau' / B, \quad A = 2A'$$

Boundary conditions:

For $0 \leq \zeta \leq 1, \eta = 0, U = V = 0, \theta = 1, \partial C / \partial \eta = 0$.
For $0 \leq \zeta \leq 1, \eta = \infty, U = 0, \partial V / \partial \eta = 0, \theta = 0, C = 1$.

4-4 Numerical evaluation of a parameter A

Since the distributions of θ and C depend on P_r, S_c and constant quantities in reaction terms, the surface temperature, T_w satisfying the ignition condition, $(\partial T / \partial y)_{x=H, y=0} = 0$ is uniquely determined corresponding to a set of these fixed values. Namely, if P_r, S_c, B, T_∞ and n are constant for a specified mixture, A is numerically determined as the function of T_w / T_∞ and E / RT_∞ . Comparing the values of $C_{\infty} h$ for each stoichiometric mixture of four different fuels used in the experiment, they practically take one constant value. For the present analysis, the following values are given to each experimental parameter, $P_r = 0.7, S_c = 0.65, n = 1.7$ and $2.0, C_{\infty} h / cp T_\infty = 9.4 (T_\infty = 293^\circ K)$ and $7.4 (T_\infty = 373^\circ K)$.

Figure 7 shows the relation between A and T_w for different activation energies, E .

Replotting of A versus $1/T_w$ shows an almost linear relation on semi-logarithmic graph paper as Fig. 8. Therefore it is expected for the same relation to be obtained in the experiment. According to the numerical analysis, values of P_r and S_c do not substantially affect this relation but change the ignition temperature. A combination of the larger P_r and the smaller S_c reduces the ignition temperature.

5. EXPERIMENTAL RESULTS

Fig. 7 Relation, between A and T_w

Fig. 8 Relation between A and $1/T_w$

5-1 Location of ignition point

The observation of ignition was carried out with high speed schlieren photography.

To synchronize the camera with the ignition phenomenon, the instantaneous additional heating of the plate was made by a passage of electric current through the plate which had been kept just below the ignition temperature. A sequence of pictures indicating the location of ignition point are shown in Fig. 9. According to a number of observations, the ignition took place in a region just upstream from the trailing edge of the plate, irrespective of the length of the plate. This can be clearly seen in the 2nd frame of the pictures in Fig. 9. Hence, it is assumed in the analysis that the heating of the mixture while it flows in free convection along the plate from the leading to the trailing edge, results in the critical ignition at the trailing part on the plate.

5-2 Flow pattern over the hot plate

The observation of free convective motion of fluid over the plate was carried out with particle traces of magnesium oxide ($5\mu\phi$) and stroboscopic light source (20,000 cpm).

Observed examples are shown in Fig. 10.

At the higher pressure, owing to the thin boundary layer and the small u at the leading edge, the flow pattern seems to approach the profile of the usual boundary layer approximation. The lowering of the pressure results in the deviation from the ideal boundary layer flow whose tendency becomes remarkable as

$H = 20mm$
 $P_0 = 400mmHg$

Fig. 9 Position of ignition

H=20mm $P_0=750$ mmHg H=20mm $P_0=100$ mmHg

Fig.10 Flow over the hot plate

Fig.11 Influence of P_0 upon U_{max}

Influence of δ_1 upon T_w

the plate is shortened.

According to the analysis by Sparrow et al⁽⁷⁾, the following relation holds for air,

$$U_{max,H}/\sqrt{g(T_w-T_\infty)H/T_\infty} \approx 0.556.$$

The value of the left side was calculated for various experimental conditions shown on Fig.11. Referring to this figure, the similarity of flow in a boundary layer seems to be approximately satisfied when the pressure is not too low. Although the measurement in the air may differ from that in a combustible mixture accompanied with the chemical reaction, the boundary layer approximation is assumed to be applicable in the present analysis.

5-3 Measurement of ignition temperature

The critical ignition temperatures were measured by the previously mentioned procedure for the stoichiometric mixtures of C_3H_8 -air, CH_4 -air, C_2H_5OH -air and $(C_2H_5)_2O$ -air with changing of the pressure from 50mmHg to 760mmHg at the constant temperature of 293°K.

The results of measurement are summarized in the section 6-1.

5-4 Influence of the concentration on the ignition temperature

The change of the ignition temperature with the concentration was examined for the propane-air mixture in a lean region where the measurement was comparatively easy because the explosive combustion did not take place. Results of measurement for various P_0 and H are shown in Fig.12. Although the

limit of flame propagation seems to depend on H , the scattering of the limit concentration was within an experimental error. Near the concentration of 2.25%, the flame speed was so reduced that the visual inspection of the flame propagation became possible. Further decreasing the concentration, the flame could not propagate any longer while it attached to the hot surface, and the glowing part caused by reaction became gradually small and came to be limited to the trailing part of the plate. The glow on the surface disappeared at the concentration below 1%. The ignition temperature decreased with the concentration within the limits of experiment. This tendency has been observed for a natural gas-air mixture by Coward and Guest⁽⁸⁾, and for hydrogen-air mixture by Mullen⁽⁹⁾.

6. CONSIDERATION

6-1 Relation between H and P_0 at the critical ignition condition

If the ignition temperature is specified for a certain mixture with the constant quantities of P_r , S_c , cp , E , Q , T_∞ and c_∞ , a constant value of the parameter A gives the same profiles of the dependent variables in fundamental equations irrespective of the quantity of the other experimental parameters except the one just described above. This condition is expressed as follows.

$$A = (2K/\sqrt{g})(c_\infty Q/cp T_\infty) c_\infty^{n-1} \rho_\infty^{n-1} \sqrt{H} = \text{const.} \quad (12)$$

Assuming all the terms except ρ_∞ and H to be constant, as $\rho_\infty \propto P_0$ because of constant T_∞ , the above expression is simplified as follows,

$$\sqrt{HP_0}^{n-1} = \text{const.} \quad (13)$$

This means that if H and P_0 change according to this relation, the ignition temperature is uniquely determined.

Taking the logarithms of both sides of Eq.(13), the following relation is obtained for the same ignition temperature.

$$\ln P_0 = -(\ln H)/2(n-1) + \text{const.} \quad (14)$$

The over-all order of reaction, n can be determined by Eq.(14) from the experimentally observed relation between P_0 and H for various T_w . In the present analysis the mean value of n for each constant T_w is defined as the order of reaction. n takes the following value for each fuel-air mixture used in the experiment, $n \approx 2$, (C_3H_8) and $n \approx 1.7$, (CH_4 , C_2H_5OH , $(C_2H_5)_2O$). Using these values of n , the experimental result can be arranged according to Eq.(13) as shown in Fig.(13). In this figure, H and P_0 are made dimensionless by dividing by the standard value of each.

They are set in this arrangement as follows for convenience; $H = H/1000(\text{mm})$, $P_0 = P_0/760(\text{mmHg})$. From this figure, it may be concluded that Eq.(13) expresses considerably well the similarity relation between H and P_0 . This relation seems to be applicable to the case of relatively low pressure (corresponding to the larger T_w in the figure) where the boundary layer approximation may not be quite proper.

6-2 Relation between $\sqrt{HP_0}^{n-1}$ and T_w

From the numerical analysis of the fun-

damental equations described in section 4-4 A and T_w are expected to be related as follows, $\ln A = \text{const.}/T_w + \text{const.}$. This relation can be now rearranged with consideration of the foregoing section as follows, $\ln \sqrt{HP_0}^{n-1} = \text{const.}/T_w + \text{const.}$. This can be also derived from the following consideration.

The critical ignition condition may be satisfied at the trailing part of the plate by consumption of a certain amount of reactant while the mixture flows in a boundary layer from the leading edge through the trailing part. Putting the reacted mass before ignition as a , and the mean reaction rate as $W(T, c)$, the time elapsed from the instant of inflow till ignition is expressed as $t_p \propto a/W(T, c)$. a can be related to the concentration of mixture by $a \propto (\rho_\infty c_\infty - \rho c) = \rho_\infty c_\infty (1 - C_* T_\infty/T)$ where C_* denotes the concentration ratio at the trailing part of the boundary layer. The reaction rate is assumed to obey the Arrhenius law.

If the reaction takes place in a relatively thin layer near the hot surface, the change of temperature in this zone is small, and consequently, $(T_w - T)/T_w \ll 1$. Applying the Frank-Kamenetskii approximation⁽¹⁰⁾ to the exponential term of the reaction rate using ΔT for $(T_w - T)$, the reaction rate can be expressed by the following equation.

$$W(T, c) = K(\rho_\infty c_\infty)^n \left(\frac{T_\infty}{T_w}\right)^n \exp\left(-\frac{E}{RT_w}\right) \exp\left(-\frac{E\Delta T}{RT_w^2}\right) \quad (15)$$

Now, the relation $t_p \propto a/W(T, c)$ is rearranged with the substitution of Eq.(15).

If only the pressure-dependence term, ρ_∞ and the exponential terms are taken into consideration regarding the other temperature-dependence terms as constant, for a fixed concentration of mixture the time required for the mixture to pass through the boundary layer along the surface is expressed as follows,

$$\ln t_p = (1-n) \ln P_0 + \frac{E}{RT_w} + \frac{E\Delta T}{RT_w^2} + \text{const.} \quad (16)$$

Assuming the termination of the main reaction at the temperature decreased from T_w by $RT_w^2/E^{(1)}$, the 3rd term of the above equation can be included in the 4th constant term. Thus, t_p in Eq.(16) expresses the time required to consume a certain amount of reactant at the initial reaction rate at the leading edge³.

Taking u_{max} as the representative velocity in the boundary layer, from $u_{max} = 4\nu_\infty b^2 (H\xi)^{1/2} (\partial F/\partial \eta)_{max}$ it follows that $u_{max} \propto \sqrt{(T_w - T_\infty)H/T_\infty}$. Assuming that $t_p \propto H/u_{max}$ and neglecting the change of u_{max} with T_w compared to the change of E/RT_w , Eq.(16) is rearranged as follows,

$$\ln \sqrt{HP_0}^{n-1} = \frac{E}{RT_w} + \text{const.} \quad (17)$$

This relation can be also derived from the ignition model of Khitrin⁽¹²⁾ which is written for the n th order of reaction as follows,

$$\left(\frac{NuH}{H}\right)^2 (T_w - T_\infty)^2 = \frac{2Q}{\lambda} K(\rho_\infty c_\infty)^n \left(\frac{T_\infty}{T_w}\right)^n \frac{RT_w^2}{E}.$$

Fig.13 Arrangement of the experimental result by Eq.(13).

$$\exp\left(-\frac{E}{RT_w}\right) \cdot \Pi\left(\frac{T_k - T_w}{T_k - T_\infty}\right) \quad (18)$$

$$\Pi(z) = z^n + a_1 z^{n-1} + \dots,$$

Π is nondimensional function of concentration, and T_k adiabatic combustion temperature. As $Nu_H \propto G_p^{1/4} (d_p)^{1/4}$, the left side of Eq.(18) is proportional to the term, $\rho_\infty \sqrt{H(T_w - T_\infty)^{5/2}}$. Substituting this relation into Eq.(18) and considering the effect of the change in T_w only for the exponential term, Eq.(18) is rewritten as follows,

$$\ln \rho_\infty \sqrt{H} = \ln \rho_\infty^n - \frac{E}{RT_w} + \text{const.} \quad (19)$$

Rearrangement of Eq.(20) with expression of ρ_∞ in terms of p_0 yields again Eq.(17).

From the numerical analysis, the relation, $\ln \sqrt{HP_0}^{n-1} = A_1/T_w + A_2$ was previously assumed.

The value of A_1 expressed in terms of E became $(E - k)/R$ in the numerical analysis (k , constant quantity independent of E).

Therefore, the value of E obtained from the experiment using the relation of Eq.(17) differs by k from that of numerical calculation. Considering that each relation is independently derived from different approximations, this discrepancy may be inevitable, and it is not assured either that the coefficient of $1/T_w$ becomes E/R . From the above considerations, it may be concluded that H , P_0 and T_w are generally related by the following equation,

$$\ln \sqrt{HP_0}^{n-1} = \frac{C_1}{T_w} + C_2 \quad (20)$$

where C_1 and C_2 are experimental constants.

The experimental results shown in Fig.13 can be rearranged as Fig.14 by making use of the above relation. The scale of the ordinate is same as Fig.13. The experimental points almost satisfy the relation of Eq.(21) in a range of relatively large values of $\sqrt{HP_0}^{n-1}$. However, with a decrease of $\sqrt{HP_0}^{n-1}$, they deviate from the theoretical prediction. Since the small value of $\sqrt{HP_0}^{n-1}$ corresponds to the small H and/or the low P_0 , either effect of H or P_0 , or both effects on the boundary layer may cause this deviation. The lower pressure results in a thicker boundary layer and consequently, the flow pattern is so changed that the flow

velocity in the vertical direction at the leading edge takes a certain value as seen in Fig.10. The reduction of the received heat by mixture due to the shortening of the passing time through the boundary layer may be one of the fundamental causes of this deviation. This tendency is the more remarkable, the shorter H is used.

6-3 Influence of inhomogeneity in surface temperature on the ignition

The temperature of the plate is lowered at both ends due to heat loss as mentioned before. However, as the hot surfaces have a similar distribution of temperature, the effective heating length can be defined as αH , where α is a constant less than unity and independent of H . Therefore, the influence of inhomogeneity in surface temperature on the equation (20) may only result in the uniform transfer of the left side value parallel to the ordinate of logarithmic scale. Hence the fundamental difference in the ignition characteristics between isothermal and nonisothermal surface may not be so large that the physical length of the heating plate can be used to arrange the experimental results.

6-4 Influence of the initial temperature of the mixture

The raising of the mixture temperature

Fig.14 Relation between $\sqrt{HP_0}^{n-1}$ and $1/T_w$

for a fixed surface temperature reduces the convection velocity. Hence the passing of the mixture through boundary layer takes longer time. According to the experiment on the effect of the convection velocity by Guest⁽¹⁴⁾, the reduction of it by the opposed flow made the ignition temperature lower.

And the heat supply for the mixture required to ignite it should be reduced by the higher initial temperature.

To clarify these, an experiment was carried out using a well stirred mixture so as to make its temperature equilibrium with the surrounding wall of the combustion chamber in which an electric heater was installed.

The experimental results for the mixture temperature of about 60°C are plotted on Fig.15 comparing with those at 20°C and the theoretical calculation. The pre-heating of the mixture results in a lowered ignition temperature. From the experimental results for $T_{\infty} = 293^{\circ}\text{K}$, the theoretical values of the ordinate were estimated for $T_{\infty} = 333^{\circ}\text{K}$ and 373°K . The experimental values considerably well coincide with the theoretical estimation, even though a deviation in a region of higher ignition temperature can still be seen.

Fig.15 Influence of T_{∞} upon T_w

7. CONCLUSIONS

Since the free convective flow along the vertical hot plate was relatively stable in this experiment, the ignition temperature regularly changed with the experimental parameters. In consequence, a narrow scattering of the data led to a better comprehension of the qualitative characteristics of the ignition phenomena.

From the experiments and the analyses of the boundary layer equations, the following conclusions are derived.

(1) The initiation of ignition at the trailing part of the hot surface is recog-

nized by a high speed schlieren photography.

- (2) When the pressure of mixture is not too low, the boundary layer approximation may be reasonably applied.
- (3) With assumptions in the analysis, the over-all order of reaction can be determined by the following relation for a fixed ignition temperature.

$$\ln P_0 = -\frac{1}{2(n-1)} \ln H + \text{const.}$$

- (4) The values of n derived from the above relation are as follows, $n \approx 2$ for propane, and $n \approx 1.7$ for methane, ethyl-alcohol and diethylether.
- (5) The ignition temperature, the initial pressure of mixture and the length of the plate are related to each other through the following equation,

$$\ln P_0^{n-1} \sqrt{H} = \frac{\text{const.}}{T_w} + \text{const.}$$

- (6) From a certain fixed experimental condition, the ignition condition for various combinations of experimental parameters in a moderate range can be reasonably estimated by numerical analysis.
- (7) By examining the effect of the concentration on the ignition temperature for propane-air mixture, it becomes evident that the ignition temperature decreases with concentration, and the lower inflammable limit of concentration is 2.25%.
- (8) The ignition temperature decreases with an increase of the initial temperature of the mixture.

REFERENCES

- (1) Admeit, G., Proc. 1963 Heat Trans. & Fluid Mech. Inst., (1963), 160.
- (2) Toong, T.Y., 6th Int. Symp. Comb., (1957), 532.
- (3) Semenov, N.N., NACA TM, No.1024 (1942).
- (4) Karlovitz, B., et al, 4th Int. Symp. Comb., (1953), 613.
- (5) Williams, F.A., Combustion Theory, (1965), 424. Addison-Wesley.
- (6) von Rosenberg, D.U., Method for Numerical Solution of Partial Differential Equations, (1969), American Elsevier Pub.
- (7) Sparrow, E.M. and Gregg, J.L., Trans. ASME, (1958-5), 875.
- (8) Coward, H.F. and Guest, P.G., J. Amer. Chem. Soc., 49(1927), 2479.
- (9) Mullen, J.W., et al, 3rd Int. Symp. Comb., (1949), 317.
- (10) Frank-Kamenskii, D.A., Diffusion and Heat Transfer in Chemical Kinetics, (1969), Plenum Press.
- (11) references (3), (10) and Sokolik, A.S., Self-Ignition, Flame and Detonation of Gases., (1963), 153, IPST. Cat. No.818.
- (12) Khitrin, L.N. and Goldenberg, S.A., 6th Int. Symp. Comb., (1957), 545.
- (13) Ostrach, S., NACA TR, No.1111 (1953).
- (14) Guest, P.G., U.S. Bur. Mines Tech. Paper, (1930), 475.