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A STUDY ON OPPOSED GASEOUS JET FLAMES STABILIZED IN A UNIFORM AIRSTREAM (4TH REPORT : EXTINCTION MECHANISM OF OPPOSED GASEOUS JET FLAMES)*

BY SHIGEKI YAMAGUCHI**, NORIO OHIWA***
AND RYOTARO IZUMI****

As a final stage of this study the extinction mechanism is treated qualitatively on the basis of preceeding results. It is found that the partial extinction in the frontal flame zone can be explained with the relation between the first Damköhler number and the maximum temperature on the axis, and that this mechanism is similar to that of laminar opposed diffusion flames. To deal with the overall extinction at the stability limit the excess-reaction variable is found analytically, which has a physical meaning of an overall and average reaction ability of the flame. With this variable and the first Damköhler number three stability curves with different nozzle pressure can be collapsed into a single curve, and the mechanism of extinction at each stability limit can be elucidated independently of the nozzle pressure. It is found that the kind of flame in the stable region depends only on the excess-reaction variable.

1. INTRODUCTION

The objective of this study is to elucidate the mechanism of combustion and stabilization of turbulent jet flames produced by issuing a counterflowing gaseous fuel jet into a uniform airstream. In the preceeding reports(1)~(3), by considering hydrodynamical features and temperature characteristics within the flames analytically and experimentally, it was shown that the excess-momentum radius, the excess-mass-flux ratio at the nozzle exit and the maximum temperature on the axis may be useful characteristics for elucidating the extinction mechanism of the opposed gaseous jet flames. One of the authors, on the other hand, has already referred to the combustion mechanism of the flames under consideration by the visual observations and the temperature and concentration measurements(4). In the present paper the extinction mechanism of the opposed gaseous jet flames is treated qualitatively on the basis of such a foundation.

In the first place the partial extinction in combustion at the forward stagnation point of the flames, which causes the transition of the flame shape from the standard flame to the trumpet and is similar to the

extinction in a laminar opposed diffusion flame, is analyzed with Fendell's relation (5) between the first Damköhler number and the maximum combustion temperature. It is found that the mechanism of the partial extinction is similar to that of a laminar opposed diffusion flame. In the second place, in order to elucidate the extinction mechanism at the stability limit of the flames, the excess-reaction variable is defined analytically with the mass conservation equations for fuel and oxygen, which has a physical meaning of an overall and average reaction ability of the flames. With this variable and the first Damköhler number, it is found that the extinction at the stability limit of arbitrary nozzle pressure can be elucidated collectively, and that the kind of flame in the stable region depends only on the excess-reaction variable.

2. NOMENCLATURE

- a : distance from source to stagnation point
- B : frequency factor
- b_0, b_∞ : nozzle radius and outer edge radius of jet, respectively
- c : stoichiometric coefficient in Eq. (7)
- D_1 : first Damköhler number
- d : stoichiometric coefficient in Eq. (7)
- F : amount of fuel in Eq. (8)
- m : $m = cm_f + dm_{O_2}$
- m_f, m_{O_2} : molecular weight of fuel and of oxygen, respectively
- O, P : amounts of oxygen and combustion product, respectively
- p : stoichiometric coefficient in Eq. (7)

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** Associate Professor, Faculty of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464.

*** Assistant.

**** Professor.

- r : stoichiometric ratio in Eq.(13)
 s : distance measured from stagnation point along dividing stream line
 T_{xm} : Maximum temperature on axis
 u, v : axial and radial velocities, respectively
 u', v' : axial and radial fluctuation velocities, respectively
 U : velocity of uniform airstream ($U < 0$)
 x, y : axial and radial distances, respectively
 Y : mass concentration
 α : mass fraction of oxygen contained in air
 ϵ_D : eddy diffusivity for mass
 σ_0 : excess-mass-flux ratio at nozzle exit
 θ : excess-momentum radius
 ρ : density
 τ_f, τ_r : characteristic times of flow and reaction, respectively
 X : excess-reaction variable
 X, X' : reaction variable and its fluctuation component, respectively
 λ_j : air-fuel ratio
 ω_f, ω_{O_2} : mass consumption rate of fuel and of oxygen, respectively

SUBSCRIPT

- 0 : nozzle exit
 s : stagnation point
 th : theoretical
 max : maximum
 ∞ : outer edge of mixing region
 a : uniform airstream
 cr : critical at transition
 ext : critical at extinction

3. EXPERIMENTAL APPARATUS AND METHOD

The outline of the experimental apparatus is shown in Fig.1. The fuel jet with nozzle pressure P_n is issued from the nozzle of 2mm in inner and 10mm in outer diameters against a uniform airstream supplied from the Pyrex glass tube of 80mm in inner diameter, and a flame is established as shown in the figure. The fuel used is propane. The nozzle and the Pyrex glass tube are set 100mm apart. The inner and outer flames and the position of the stagnation point are also shown on the basis of the experimental considerations(3).

Flames with a constant nozzle pressure are stabilized within a single curve, which

Fig.1 Schematic diagram of experimental apparatus

consists of the upper and lower limits of the velocity of a uniform airstream. Figure 2 shows the stability curves with nozzle pressure as a parameter.

When the air-fuel ratio is held at a constant, the flames are classified into the following three kinds independent upon the nozzle pressure; the trumpet flame(a) in the region close to the upper limit of the velocity of a uniform airstream, the standard flame(b) in the middle and the lifted flame(c) in the region close to the lower(3). The schematic diagram of these flames are shown in Fig.3 (a), (b) and (c) respectively, in which the primary and the secondary combustion zones indicate the first stage of reaction and the reaction of intermediate products, respectively. It may be considered that the transition from the standard flame to the trumpet is due to the partial extinction in combustion in the frontal stagnation region of the standard flame.

In this paper experimental data are restricted to those with the nozzle pressure $P_n=60\text{mmHg}$ gauge for the elucidation of the partial extinction mechanism, and to those with $P_n=30, 60$ and 120mmHg gauge for that of the extinction mechanism at the stability limit.

Fig.2 Stability curves

Fig.3 Transition of flame shape at $\lambda_j = \text{const.}$

4. CONSIDERATIONS ON

THE EXTINCTION MECHANISM

4 - 1 Partial extinction mechanism

As it may be considered that the process of partial extinction in the frontal stagnation point of the standard flame is similar to that of a well-known laminar opposed diffusion flame, Fendell's relation (5) between the first Damköhler number D_1 and the maximum combustion temperature $T_{\max}$ is adopted in this case. By the way, the first Damköhler number is defined by the ratio of the characteristic time of flow τ_f to that of reaction τ_r , and is given by the following equation (6)

$$D_1 = \frac{\text{characteristic time of flow}}{\text{characteristic time of reaction}} = \frac{\tau_f}{\tau_r} \quad (1)$$

In the first place, the characteristic time of flow can be obtained by replacing the flow around the frontal stagnation point of the flame with the potential one around a axisymmetric semi-infinite body set in a uniform stream with the velocity U . As shown in Fig.4, such a flow is given by a set of a source and a uniform stream (7), where the uniform stream flows in the negative direction of x . Then, as can be seen from the figure, the coordinates of the intersection of x -axis and y -axis with the dividing stream line become a_0 and $\sqrt{2}a_0$, respectively, and there exists a relation given by $\xi = \tan^{-1}\sqrt{2} = 54.7^\circ$. With this relation the experimental values of a_0 can be obtained from experimental data of the dividing stream lines.

Now, indicating the distance measured from the stagnation point along the dividing stream line by s , the velocity on the

Fig.4 Flow model near stagnation point

O_2	flame shape	θ_{th}^* mm	θ_0^* mm	a_0 mm	a_0/θ_{th}^*	a_0/θ_0^*
-0.223	trumpet	2.80	6.11	6.42	2.30	1.05
-0.187	standard	3.41	7.18	7.37	2.16	1.03
-0.162	lifted	3.99	8.06	8.30	2.08	1.03

($P_0 = 60 \text{ mmHg g.}$)

Table 1 Experimental values of a_0

dividing stream line near the stagnation point u is represented approximately, after simple calculations, by

$$u = - (U/a_0) s \quad (2)$$

In Eq.(2), $-(U/a_0)$ has a dimension of $[1/s]$. Thus, its reciprocal, having a dimension of $[s]$, may be regarded as a characteristic time of flow, namely

$$\tau_f = - (a_0/U) \quad (3)$$

Table 1 shows the experimental values of a_0 , the dimensionless values a_0/θ_0^* and a_0/θ_{th}^* referred to the experimental and theoretical values of the excess-momentum radius θ_0^* and θ_{th}^* , respectively. According to Table 1, a_0 can be represented approximately by the following equation

$$a_0 = 2.2 \theta_{th}^* = \theta_0 \quad (4)$$

where

$$\theta_{th}^{*2} = \frac{b_0^2(1+\sigma_0)}{2\sigma_0^2}, \quad \sigma_0 = \frac{\rho_a U}{\rho_0 u_0 - \rho_a U} \quad (5)$$

Equation (5) shows that θ_{th}^* can be calculated easily with the parameters, which depend only on the setting conditions of the flame. Therefore, for the simplification of the treatment, $a_0 = 2.2\theta_{th}^*$ is used instead of θ_0^* . Accordingly, Eq.(3) is finally represented by

$$\tau_f = 2.2 \theta_{th}^* / (-U) \quad (6)$$

According to Fendell (5), on the other hand, the characteristic time of reaction τ_r is given by

$$\tau_r = m / \rho c d B \quad (7)$$

where the chemical reaction is simplified to the following overall stoichiometric reaction

in which F , O and P indicate the amount of fuel, oxygen and combustion product, respectively, c , d and p the stoichiometric coefficients, ρ and B the density and frequency factor, respectively, and $m = cm_f + dm_{O_2}$, where m_f and m_{O_2} are the molecular weights of fuel and of oxygen, respectively. In Eq.(7), if B is assumed to be independent upon both temperature and pressure, then, τ_r has a unique value depending only on the kind of fuel. For the propane the following numerical values are adopted.

$$\left. \begin{aligned} c &= 1, d = 5, m = 0.204 \text{ kg/mole} \\ \rho &= 6.164 \text{ kg/m}^3, B = 1 \times 10^6 \text{ m}^3/\text{mole} \end{aligned} \right\} \quad (9)$$

With Eqs.(6) and (7) the first Damköhler number D_1 is represented by

$$D_1 = \tau_f / \tau_r = 2.2 \theta_{th}^* \rho c d B / (-U) m \quad (10)$$

By analyzing the extinction of laminar opposed diffusion flames, Fendell obtained a relation between the first Damköhler number D_1 and the maximum combustion temperature $T_{\max}$, which is well-known as Fendell's curve. He found that the extinction occurs when $T_{\max}$ comes below a critical value, and that the corresponding value

of D_1 to the critical value of $T_{\max}$ may be the criterion for the extinction. In order to apply Fendell's idea to the partial extinction under consideration, the relation between D_1 from Eq.(10) and the experimentally obtained maximum temperature on the axis T_{xm} are shown in Fig.5 with respect to the flames with $P_n = 60$ mmHg gauge.

Although the present turbulent diffusion flame has neither clear flame zone nor sharp temperature rise as a laminar flame and the relation between the position of T_{xm} and that of the frontal flame zone is not distinct, T_{xm} is useful as a characteristic temperature not only for the whole flame but also for the frontal local flame zone, according to the experimental consideration⁽³⁾. From such a view-point, T_{xm} is adopted here in place of the maximum combustion temperature $T_{\max}$.

In the figure T_{xm} is plotted against D_1 with the velocity of a uniform airstream $(-U)$ and the air-fuel ratio λ_j as parameters, denoted by a chain dotted line and a dashed line, respectively. The curve of stability limit is also shown by a solid line.

In Fig.5, if $(-U)$ or λ_j is held constant, the changing rate in D_1 with T_{xm} breaks at a boundary $T_{xm} = T_{cr}$ indicated by a dotted line. Then, it may be considered that the partial extinction occurs and the flame shape changes from the standard flame to the trumpet. The mechanism may be explained qualitatively as follows. If the velocity of a uniform airstream $(-U)$ increases from the lower limit of the stability curve to the upper with a constant air-fuel ratio, the residence time of reactant in the combustion zone in the vicinity of the stagnation point t_f , therefore, D_1 decreases. Accordingly, the combustion intensity is weakened and the combustion temperature T_{xm} decreases. When T_{xm} reaches the boundary T_{cr} , the combustion intensity in the vicinity of the stagnation point is so weak that a flame can not exist there. Then, the partial extinction in combustion

Fig.5 Transition of flame shape

occurs at the stagnation point, and the flame shape changes from the standard to the trumpet. It is found, therefore, that the mechanism of the partial extinction at the stagnation point of the opposed gaseous jet flame is similar to the extinction of a laminar opposed diffusion flame.

In Fendell's analysis, because of a constant initial condition of flame, the extinction is explained by a pair of $T_{\max}$ and D_1 . On the other hand, in the present case, as the initial condition varies for each flame, the critical values of D_1 at the partial extinction vary for each flame as well. In Fig.6 the variations of $D_{1,cr}$ with λ_j and $(-U)$ are shown, where $D_{1,cr}$ indicates the critical value of D_1 corresponding to T_{cr} .

4 - 2 Extinction mechanism

at the stability limit

The extinction at the stability limit can not be explained with the local relation at the stagnation point between D_1 and T_{xm} shown in Fig.5. For the upper limit, although the extinction mechanism may at glance be explained by a decrease in T_{xm} , the frontal combustion wave does already not exist in the trumpet flame. For the lower limit, on the other hand, the explanation with D_1 and T_{xm} causes a incompatible result that the extinction occurs despite of increases in both D_1 and T_{xm} . Therefore, in order to elucidate the extinction mechanism at the stability limit, it is necessary to find out not local but overall and average characteristics of the flame. However, since θ_{th}^* in Eq.(6) or (10) is a characteristic length proportional to the dimension of whole flame⁽³⁾, the first Damköhler number D_1 can also be adopted as an overall characteristic variable. Then, as another variable the excess-reaction variable X_{th} is found out analytically in place of the combustion temperature T_{xm} as follows.

Now, it is assumed that the eddy diffusivities for mass of fuel and of oxygen

Fig.6 Relation between $D_{1,cr}$ and $(-U), \lambda_j$

are equal, and denoted by ϵ_D , then, the conservation equations of fuel and of oxygen are given, respectively, by

$$\rho u \frac{\partial Y_f}{\partial x} + \rho v \frac{\partial Y_f}{\partial y} + \frac{\partial(\rho u' Y_f')}{\partial x} = \frac{1}{y} \frac{\partial}{\partial y} (\rho \epsilon_D y \frac{\partial Y_f}{\partial y}) - \dot{\omega}_f \quad \text{--- (11)}$$

$$\rho u \frac{\partial Y_{O_2}}{\partial x} + \rho v \frac{\partial Y_{O_2}}{\partial y} + \frac{\partial(\rho u' Y_{O_2}')}{\partial x} = \frac{1}{y} \frac{\partial}{\partial y} (\rho \epsilon_D y \frac{\partial Y_{O_2}}{\partial y}) - \dot{\omega}_{O_2} \quad \text{--- (12)}$$

where the axial mass transport due to turbulence is taken into consideration.

By assuming that the reaction obeys the simple overall equation

without the formation of any intermediate compounds, the following relation between $\dot{\omega}_f$ and $\dot{\omega}_{O_2}$ is obtained

$$\dot{\omega}_f = \dot{\omega}_{O_2} / r \quad \text{--- (14)}$$

Then, the substitution of the reaction variable defined by

$$\chi \equiv Y_f - Y_{O_2} / r \quad \text{--- (15)}$$

into Eqs.(11) and (12) makes an important simplification possible, and gives

$$\rho u \frac{\partial \chi}{\partial x} + \rho v \frac{\partial \chi}{\partial y} + \frac{\partial(\rho u' \chi')}{\partial x} = \frac{1}{y} \frac{\partial}{\partial y} (\rho \epsilon_D y \frac{\partial \chi}{\partial y}) \quad \text{--- (16)}$$

Equation (16) shows the fact that, if fuel and oxygen have equal eddy diffusivities, the reaction variable χ is also a conserved property.

Integration of Eq.(16) over the cross-sectional area with the following continuity equation and boundary conditions

continuity equation ;

$$\frac{\partial(\rho u)}{\partial x} + \frac{1}{y} \frac{\partial(\rho v y)}{\partial y} = 0 \quad \text{--- (17)}$$

boundary conditions ;

$$\left. \begin{aligned} y=0 & ; \partial \chi / \partial y = 0, v=0 \\ y=b_\infty & ; \partial \chi / \partial y = 0, v=v_\infty, u=U \\ \chi & = \chi_\infty, u' \chi' = 0 \end{aligned} \right\} \quad \text{--- (18)}$$

gives

$$\int_0^{b_\infty} \rho u (\chi - \chi_\infty) y dy + \int_0^{b_\infty} \rho u' \chi' y dy = \text{const.} \quad \text{--- (19)}$$

The left hand side of Eq.(19) represents the total flux of χ across the cross section, which is also conserved. Equation (19) holds constant so far as the assumptions used in the derivation of the funda-

mental equations (11) and (12), namely, the boundary layer approximation and the neglect of molecular diffusion compared with eddy diffusion are satisfied. The range of constancy may be considered to be similar to the case of the excess momentum (2). The experimental verification of Eq. (19), however, will be an important future problem.

Now, using θ_0^* , U and ρ_a as representative values of length, velocity and density, respectively, the excess-reaction variable X is defined from Eq.(19) as

$$-\rho_a U \theta_0^{*2} X \equiv \int_0^{b_\infty} \rho u (\chi - \chi_\infty) y dy + \int_0^{b_\infty} \rho u' \chi' y dy \quad \text{--- (20)}$$

Although the value of X for a given flame can be obtained experimentally by the measurements of χ and ρu across the section of nozzle exit with Eq.(20), it is not only difficult but also troublesome to measure χ accurately. Therefore, for simplicity the theoretical value X_{th} is used here, which is obtained analytically as follows:

By assuming the rectangular profiles of the mass flux and of the reaction variable at the section of nozzle exit as

$$\left. \begin{aligned} y \leq b_0 & ; \rho u = \rho_0 u_0, \chi = \chi_0 \\ y > b_0 & ; \rho u = \rho_a U, \chi = \chi_\infty \end{aligned} \right\} \quad \text{--- (21)}$$

and by neglecting the integrated term of turbulence in Eq.(20), the following equation for X_{th} is obtained.

$$-\rho_a U \theta_0^{*2} X_{th} = \rho_0 u_0 (\chi - \chi_\infty) b_0^2 / 2 \quad \text{--- (22)}$$

in which the experimental value of the excess-momentum radius θ_0^* is replaced by the theoretical one, θ_{th}^* from Eq.(5). Furthermore, χ_0 and χ_∞ are given by

$$\chi_0 = \frac{r - \alpha \lambda_j}{r(1 + \lambda_j)}, \quad \chi_\infty = -\frac{\alpha}{r} \quad \text{--- (23)}$$

Finally, the substitution of Eqs.(5) and (23) into Eq.(22) yields

$$X_{th} = -\frac{\sigma_0 (r + \alpha)}{r(1 + \lambda_j)} \quad \text{--- (24)}$$

where α indicates the mass-fraction of oxygen contained in air and is equal to 0.233, and for propane the stoichiometric ratio r in Eq.(13) has a value of 3.631. From Eq.(24) it is found that the excess-reaction variable X_{th} can easily be obtained with only the setting conditions of each flame.

Figure 7 shows the dimensionless curve of stability limit in the D_1 versus X_{th} diagram. According to the figure three stability curves in the $(-U)$ versus λ_j diagram shown in Fig.2 are fairly well reduced to a single curve, which is given averagely by $D_1 = D_{1,ext}$. Flames are stable within the range of $D_1 > D_{1,ext}$. The transition points of a flame shape from the

standard to the trumpet are also plotted in the figure with respect to the flame with $P_n = 60\text{mmHg}$. It shows that the transition occurs at $X_{th} = 0.0384$ independent upon D_1 , at which D_1 becomes minimum. The branches of stability reaction curve with $X_{th} > 0.0384$ and with $X_{th} < 0.0384$ correspond to the upper limit and the lower, respectively.

It is concluded from Fig.7 that the overall and average structure of opposed gaseous jet flames may be determined by the first Damköhler number D_1 and the excess-reaction variable X_{th} , and the kind of the flame depends only on X_{th} .

By the way, the physical meaning of D_1 and X_{th} are as follows. D_1 used in Fig.7 may be considered to have not a local character at the stagnation point but an overall and average one given, for example, by a ratio of the residence time of fuel particle in the whole reaction zone to the reaction time. On the other hand, X_{th} has an average reaction ability of the whole flame caused by the turbulent mixing. Namely, flames with $X_{th} = 0.0384$ have the maximum reaction ability, which causes the minimum of $D_{1,ext}$, and for flames with $X_{th} > 0.0384$ and with $X_{th} < 0.0384$, which correspond to the conditions of rich and lean in fuel respectively, the weaker the reaction ability, the longer the residence time required, therefore, the larger the first Damköhler number for extinction $D_{1,ext}$.

Fig.7 Dimensionless stability curve

5. CONCLUSIONS

The results obtained in this paper are summarized as follows;

(1). The partial extinction at the stagnation point, which causes the transition of the flame shape from the standard to the trumpet, can be explained with the first Damköhler number D_1 and the maximum temperature on the axis T_{xm} .

(2). It is found that the mechanism of the partial extinction is similar to that of the laminar opposed diffusion flames.

(3). In order to explain the extinction at the overall stability limit, the first Damköhler number D_1 is also an important variable, while T_{xm} is meaningless. Therefore, the excess-reaction variable X_{th} is found analytically in place of T_{xm} , which represents an average reaction ability of the flame.

(4). The curves of stability limit with different nozzle pressure can be collapsed into a single dimensionless curve $D_1 = D_{1,ext}$ in the D_1 versus X_{th} diagram. With this the overall extinction at the stability limit is elucidated regardless of the nozzle pressure.

(5). It is found that the average structure of the flame is determined by D_1 and X_{th} , and that the kind of the flame depends only on X_{th} . The flames with $X_{th} = 0.0384$ have the maximum reaction ability, which causes the minimum of $D_{1,ext}$.

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