A STUDY ON OPPOSED GASEOUS JET FLAMES STABILIZED IN A UNIFORM AIRSTREAM
(3RD REPORT: SOME EXPERIMENTAL CONSIDERATIONS ON RELATIONS BETWEEN
A FLAME SHAPE AND A FLOW PATTERN, AND TEMPERATURE DISTRIBUTIONS)*

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To elucidate the extinction mechanism of the flame, further detailed considerations are necessary about the mutual relations among the flame shapes, the hydrodynamic features such as velocity distributions and the temperature characteristics within the flames close to both the upper and lower stability limits, in addition to the results indicated in the preceding reports.

From such a viewpoint, the velocity distributions and the axial and radial temperature profiles are minutely measured for three typical flames and two series of flames respectively. According to the comparison of the experimental results obtained with each visual flame shape, some special features are found, which seems to be relative to both extinctions at the stability limit and the transition of flame shape. From these results the validity of the excess-momentum radius as a characteristic length of the flame is confirmed, and a step to solve the extinction mechanism is obtained.

1. INTRODUCTION

In the preceding paper(1) it was shown that the excess-momentum radius of an opposed gaseous jet flame $\theta^*$ would be possible to be a characteristic length of the flame as in the case of an isothermal opposed jet(2). On the other hand, the appearance of the flame and the temperature and concentration distributions within flames were reported in the early investigation(3). However, the knowledge is not yet enough to elucidate the extinction mechanism of the flames. In order to solve it, a further observation is required particularly with respect to the velocity distributions within flames. Thus, by considering the mutual relations between various results obtained up to this time, a key for the solution of the problem would be offered.

From such a view point, in the first place, the velocity distributions within flames are measured and compared with the visible flame shapes. In the second place, the temperature distributions in the axial and radial directions are plotted against the dimensionless distance referred to the excess-momentum radius to verify whether this radius is valid as a characteristic length of the flame. These results give evidence of the validity and some thermal features, which seems to be useful to examine the extinction mechanism of the flames.

2. NOMENCLATURE

- $U$: velocity of uniform airstream ($U<0$)
- $u$: axial velocity component
- $u'$: fluctuation velocity
- $\sigma$: excess-mass-flux ratio, defined by Eq. (5)
- $\lambda_j$: air-fuel ratio of jet
- $p_n$: nozzle pressure
- $x, y$: coordinates in axial and radial directions, respectively
- $x_s$: penetrating distance of jet
- $\theta^*$: excess-momentum radius
- $a, b$: nozzle radius and jet radius, respectively
- $a^*$: shifting distance of axial temperature
- $T_x, T_y$: axial and radial temperatures, respectively
- $T_n$: temperature at nozzle exit
- $\xi$: dimensionless maximum temperature on jet axis [$=(T_{x_m}-T_0)/(T_n-T_0)$]
- $\eta_x$: heat flux in axial direction
- $\rho$: density
- $C_p$: specific heat at constant pressure
- $\gamma$: rate of heat release
- $\chi$: eddy diffusivity for heat
- $k_t$: apparent turbulent heat conductivity
- $N_u$: turbulent Nusselt number

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Subscripts
0 : nozzle exit
a : uniform airstream
m : outer edge of mixing zone
n : radial position at which $u = 0$
m : on jet axis
s : stagnation point
th : theoretical
c : inflection point of temperature profile

3. Experimental apparatus and method

The experimental apparatus used is shown schematically in Fig. 1, which consists of a Pyrex glass tube of the inner diameter of 80 mm and a nozzle of the inner and outer diameters of 2 mm and 10 mm respectively. The nozzle and the Pyrex glass tube are set 100 mm apart.

After fully mixed with a primary air, a fuel mixture with the air-fuel ratio $\lambda_j$ is ejected from the nozzle against the uniform airstream supplied from the blower through the Pyrex glass tube. The fuel used is propane. In Fig. 1 an outline of the flame established is also shown schematically, which consists of the visible inner and outer flames.

The temperature distribution within flames is measured with a Pt / Pt-Rh(13%) thermocouple of the wire diameter of 0.3 mm in diameter. In all measurements the jet supply pressure, called the nozzle pressure and denoted by $P_n$, is held constant at 30, 60, 120 mmHg gauge. In this paper, because of similar results, the experimental data are restricted to those at $P_n = 60$.

4. The flame stability curve and the condition of flames measured

The region of stable burning is bounded by such a single curve as is shown in Fig. 2, which consists of the upper and lower limits of the velocity of a uniform airstream. The ordinate and abscissa are $-U$ and $\lambda_j$ respectively. According to visual observations flames within the stable region are classified into the following three kinds: the trumpet flame which is close to the upper limit, the standard flame in the middle and the lifted flame close to the lower limit. As will be mentioned later, the primary combustion zone increases with increasing in the velocity of a uniform airstream from the upper limit to the lower, and accordingly the temperature field shows a characteristic change. Therefore, in order to elucidate the extinction mechanism of the flames, it is necessary to consider not only the relations between a flame shape and a flow pattern but also the temperature characteristics for the flames close to both the upper and lower limits.

From the point of view mentioned above, three kinds of flame and two serieses of flames are examined experimentally, the measuring conditions of which are located at the points 1, 2, 3 and on the curves I, II within the stability curve as shown in Fig. 2.

5. Relations between a flame shape and a flow pattern

Figures 3 ~ 5 show the flow patterns for the three kinds of flame: the trumpet flame with $\lambda_j = 1.8$, the standard flame $\lambda_j = 3.8$ and the lifted flame $\lambda_j = 6.4$ respectively. Each of them is established in a constant uniform airstream of $-U = 16.8$ m/s.

In these figures the stream lines are drawn by means of the graphical integration. The chain lines indicate the locus of the position where $u = 0$ and the arrows give the velocity vectors. The broken line, furthermore, represents the flame shape obtained by visual observations.

In each figure it is observed that, according to the arrows and the closed...
stream lines along the jet axis, the jet is put back by the uniform airstream, and that a recirculation zone exists. These general hydrodynamic features are quite similar to those of the case without combustion except for an acceleration of fluid resulted from the heat generation in the outer flame region. It may be considered, as already mentioned in the second report(1), such a similarity corresponds to the experimental results that the flow with combustion can be represented by the superposition of a virtual heated field on a hypothetical incompressible flow, and that there exist some similar characters in such a hypothetical flow to the case without combustion.

The eye of the recirculation zone, which is affected by the transition of a flame shape, shifts closer to the jet axis and the nozzle exit with burning condition nearing the lower limit of the stability curve. In addition, the change of a flame shape being greatly affected by the temperature field, it is considered that the flow and temperature fields are closely connected each other.

General features of these flames, on the other hand, are the existence of a conical inner diffusion flame, the appearance of which depends on the burning conditions. The flames under consideration are generally regarded as a turbulent diffusion flame.

5.1 Properties of the trumpet flame

\( \lambda_j = 1.8, -U = 16.8 \text{ m/s} \)

Properties of the trumpet flame shown in Fig.3 are found in the existence of the unburnt region on all over the flame axis, of the elongated trail of the outer flame part and of the front of the outer flame with a character of premixed flame. It is considered that those properties attribute mainly to such a rich burning condition as \( \lambda_j = 1.8 \). By the way the inflammability limit of propane is given by \( 5.2 \leq \lambda_j \leq 24.7 \) (4).

It is seen in the figure that the flame length and the penetrating distance of jet are 60 and 67 mm respectively, and that the cross section of the eye of the recirculation zone is near the flame front. It is supposed, however, that owing to turbulent mixing fuel attains further upstream beyond the stagnation point.

5.2 Properties of the standard flame

\( \lambda_j = 3.8, -U = 16.8 \text{ m/s} \)

As shown in Fig.4 the standard flame, the burning condition of which is in the middle of the stable burning region, is dominated all over the burning zone by turbulent diffusion flame. The unburnt jet with the relatively rich burning condition of \( \lambda_j = 3.8 \) streams against the uniform airstream along the axis, as heat and oxygen being provided from the surroundings. Finally, near the stagnation point, it burns to a hemispherical diffusion flame.

The flame length and the penetrating distance are 72 and 66 mm respectively.

5.3 Properties of the lifted flame

\( \lambda_j = 6.4, -U = 16.8 \text{ m/s} \)

The lifted flame with \( \lambda_j = 6.4 \) and \(-U = 16.8 \text{ m/s} \), as shown in Fig.5, is established apart from the nozzle exit.

Because of the burning condition of \( \lambda_j = 6.4 \) within the inflammability limit at the nozzle exit, the jet needs not so much oxygen as the previously mentioned two flames but enough heat to ignite. There-
fore, there exists a primary combustion zone in considerable region of the flame axis, where the jet is provided sufficient heat from the surroundings in addition to oxygen. This results, on the other hand, in shortening of the trail of the outer flame, which consists mainly of a secondary combustion zone, and in reduction of heat transferred to the jet near the nozzle exit. Thus, the inner flame cannot be formed until the jet comes to some distance apart from the nozzle exit. The part of the inner flame near the nozzle exit is considered to have a character of premixed flame.

The eye of the recirculation zone positions nearly in the middle cross section of the flame, and the flame length and the penetrating distance are 65 and 56 mm, respectively.

6. Temperature Characteristics

In the preceding chapter several features about the relations between a flame shape and a flow pattern were investigated for three typical flames. However, the mechanism of change in flame shape from the lifted flame to the trumpet can not be explained simply by the previously mentioned variation of the air-fuel ratio. Because, when the uniform airstream velocity is increased from the lower limit to the upper at any constant air-fuel ratio, flames show the same change in shapes. It is supposed, therefore, that this mechanism depends on both the decrease in the flame length and the change of temperature characteristics with increasing in the uniform airstream velocity.

In this chapter, from such a viewpoint, in order to find a step for elucidation of the extinction mechanism the temperature characteristics of flames in the vicinity of the stability limit are considered experimentally by plotting the axial and radial temperature profiles against the dimensionless distance referred to the excess-momentum radius of an opposed gaseous jet flame.

6.1 Excess-momentum radius of an opposed gaseous jet flame

In the case of an isothermal opposed jet without combustion, the excess-momentum radius \( \Theta \) is defined from the following consideration. The equation of momentum balance is obtained by integrating Reynolds' first equation for an incompressible axisymmetric steady flow, which is given

\[
\int_0^{b_0} \rho \left( u(u-U) \right) dy + \int_0^{b_0} \left( u^2 - \bar{u}^2 \right) dy \\
+ \int_0^{b_0} (p - p_a) dy = \text{const.}
\]

Equation (1) is transformed to such a simple expression as consists only of the terms of excess momentum by adding the empirical relations shown in the first report (2). Finally, that leads, after the manner of the boundary layer theory to the definition of the excess-momentum radius \( \Theta \),

\[
(U0)^2 = \int_0^{b_0} u(u-U) y \, dy - \int_0^{b_0} u(u-U) y \, dy
\]

\[
\frac{\rho}{\rho_a} u = \text{const.}
\]

(2)

where \( \rho_a \) represents the radial position at which \( u = 0 \).

In the case of an opposed gaseous jet flame, on the other hand, the local variation of density makes analytical treatment of the flow field within the flame difficult. However, the introduction of the concept of an equivalent velocity gives a proper method of approach to it. Namely, the flow field with combustion is assumed to be represented by the superposition of a hypothetical incompressible flow and a heat generation. Then, it is found from a similar relation to Eq. (2), which is given in the form

\[
\int_0^{b_0} u^* (u^* - U) y \, dy - \int_0^{b_0} u^* (u^* - U) y \, dy
\]

\[
\frac{\rho}{\rho_a} u = \text{const.}
\]

(3)

where \( u^* \) is the excess-momentum radius of the opposed gaseous jet flame and \( u^* \) the equivalent velocity defined by

\[
u^* = \left( \frac{\rho}{\rho_a} \right) u
\]

(4)

If we assume an ideal rectangular profile for \( u^* \) at the section of the nozzle exit and refer this case to the theoretical, the theoretical excess-momentum radius \( \Theta_{th} \) can be obtained from Eq. (3) in the form

\[
\frac{\Theta_{th}}{b_0} = \frac{1 + \Theta_0}{2 \Theta_0}
\]

(5)

Equation (5) shows the same dependence of \( \Theta_{th} \) only upon the excess-mass-flux ratio \( \Theta_0 \) as the case without combustion.

From now on, for simplicity of experimental treatment we use \( \Theta_{th} \) from Eq. (5) instead of \( \Theta^* \) obtained by measurement.

6.2 Dimensionless axial temperature profiles

The dimensionless axial temperature profiles for the trumpet and lifted flames which belong to the groups of I and II in Fig.2 are shown in Fig.6 (a) and (b), in which \((Xm - X_0)/(Ym - Y_0)\) are plotted against \((X - X_0)/(Ym - Y_0)\). \(Xm\) denotes the maximum axial temperature and \(\Theta^*\) the shifting distance of temperature profile. Since, for profiles in the region of uniform airstream velocity of \(-0.6 \leq 20 \, \text{m/s}, \) the positions at which the axial temperature is
maximum \( \frac{(T_X - T_0)}{(T_{Xm} - T_0)} = 1 \) are given by constant values of \( x/\theta^* = 17 \) and 14 for the trumpet and lifted flames respectively, the axial temperature profiles are not shifted, therefore, \( a^* = 0 \). For profiles in the region of \(-U > 20 \, \text{m/s}\), they are so shifted that the maximum axial temperature position coincides with those above-mentioned values. The burning conditions and the experimental values of \( T_{Xm} \) and \( a^* \) are also shown in the figures.

From the figures a good similarity is seen among the axial temperature profiles for the same kind of flames with exceptions of the frontal region for the trumpet flames (a) and the vicinity of the nozzle exit for the lifted flames (b) respectively. It is supposed that the distinctive flame shapes in the regions close to the upper and lower limits previously mentioned in Chap.5 result in such exceptive axial temperature profiles. Therefore, it may be expected that the extinction at each stability limit depends upon the process of reaction and heat transfer in each unburnt region.

Further characteristic features are seen in the flame length, which is assumed to be a distance from the origin \( x/a^* \) or \( \theta^* = 0 \) to the end of the axial temperature boundary layer, and the maximum temperature position, which are given by the following universal values independent on the burning conditions.

for the trumpet flames
the flame length \( (x - a^*)/\theta^* = 22 \sim 24 \)
the maximum temperature position \( (x - a^*)/\theta^* = 17 \)
for the lifted flames
the flame length \( (x - a^*)/\theta^* = 19 \)
the maximum temperature position \( (x - a^*)/\theta^* = 14 \)
\[ \text{(6)} \]

According to the universal values given in Eq. (6) the excess-momentum radius \( \theta^* \) from Eq.(5) can be regarded as a characteristic length of the flames.

6.3 Variation in the maximum axial temperature

The maximum axial temperature \( T_{Xm} \) depends upon the nozzle temperature \( T_n \) as well as upon the velocity of uniform airstream \(-U\) and the air-fuel ratio \( \lambda_j \). In Fig.7 are shown some examples of such a dependence when \(-U\) is held constant at 14.2, 20.4 and 24.9 m/s. In order to manifest the correspondence between the flames measured and the stable burning region, the variation in \( T_{Xm} \) drawn in the dimensionless form of \( \xi = (T_{Xm} - T_0)/(T_n - T_0) \) vs. \( \lambda_j \) is superposed on the flame stability curve.

From the figure the variation of \( \xi \) against \( \lambda_j \) for each constant velocity can be divided into the following two regions. In the first region both \( T_{Xm} \) and \( T_n \) increases with increasing in \( \lambda_j \), and consequently \( \xi \) is held constant. In the second, on the other hand, a further increase in \( \lambda_j \) causes the decrease in \( T_n \) because of the reduction of the outer flame part in the vicinity of the nozzle exit in contrast with the increase in \( T_{Xm} \), and as a matter of course \( \xi \) increases. This change in \( \xi \) seen in the figure, which is supposed to be discontinuous, is considered to be corresponding to the transition from the trumpet
flame without flame front to the standard flame with one.

6.4 Dimensionless radial temperature profiles

In Fig. 8 are shown two representative profiles of the radial temperature in nondimensional form of \( \left( T_	ext{r} - T_	ext{m} \right) / \left( T_	ext{rm} - T_	ext{m} \right) \) vs. \( y/\theta^* \). (a) is the profile of the trumpet flame with \( \lambda_1 = 1.98 \) and \( -U = 19.3 \) m/s, and (b) the lifted flame with \( \lambda_1 = 6.10 \) and \( -U = 19.0 \) m/s.

A notable feature in Fig. 8(a) is seen in the large difference between the axial and radial temperatures. Thus, it is considered that the change in temperature on the flame axis depends mostly on the heat transferred from the circumferences. In addition, the peak of heat release at the inner flame region near the nozzle exit can hardly be seen in the figure (a) because of the remarkable heat generation in the elongated outer flame region. Fig. 8(b), on the other hand, shows the heat generation due to combustion on the flame axis is remarkable, according to the small difference between the axial and radial temperatures. A further point of interest is the sharp peak in the radial temperature profile near the nozzle exit. This is because of the reduction in circumferential temperature around the inner flame.

In general, it is seen from the figures that the maximum temperature appears close to the flame axis with the burning condition nearing the lower limit, and that the pronounced heat and mass transfer within flames produces such a smooth profile of the radial temperature.

The flame radius which is defined here by the outer edge of the radial temperature boundary layer is given in the dimensionless and universal values for both the upper and lower limit as follows:

\[
\begin{align*}
\text{for the upper limit} & \quad y/\theta^* = 7 \\
\text{for the lower limit} & \quad y/\theta^* = 5.5
\end{align*}
\]

6.5 Relations between axial temperature and stagnation point

Fig. 9 shows the variation of \( x_s \), which is the distance between the nozzle exit and stagnation point, against the excess-mass-flux ratio \( \phi_0 \) for three typical flames. The dimensionless values \( x_s/\theta^* \) in the figure are constant for the same kind of flames, and those values are 17.5, 20 and 21 for the lifted, standard and trumpet flames respectively. In Fig. 9 is also shown the upper critical value of \( x_s/\theta^* \) obtained from the inspection of Eq. (6) by hatching.

From these values it is supposed for the extinction at the upper limit of stable burning region to occur when \( x_s/\theta^* \) attains to the critical value. Furthermore, comparison Fig. 9 with Eq. (6) and Fig. 6 shows that the axial distance of mixing region upstream of the stagnation point is relatively small, and that the stagnation point nearly coincides with the inflection point of the axial temperature profile of the frontal region of the flame.

6.6 Overall process of axial heat transfer in the frontal region of flames

The equation of energy on the axis in a turbulent mixing region is given in the following simplified form:

\[
\frac{d}{dx} \left( -k_t \frac{dT}{dx} \right) = \rho c_p u \frac{dT}{dx}
\]

Fig. 9 Variation of penetrating distance of jet
where $\gamma$ is the heat release rate and $k_t$ the apparent turbulent heat conductivity. By introducing the eddy diffusivity $\varepsilon_H$, $k_t$ is expressed in the form

$$k_t = \rho c_p \varepsilon_H$$

Now, on the basis of the experimental results already mentioned, we assume that the inflection point of the axial temperature profile coincides with the stagnation point, and that there is no heat generation due to reaction in the upstream region of the stagnation point, which are expressed as follows.

$$X_S = X_C, \quad X < X_S; \quad \gamma \geq 0, \quad X > X_S; \quad \gamma = 0$$

With these assumptions Eq. (8) holds qualitatively in each region corresponding to the shape of the axial temperature profile. Thus, the axial heat flux $q_x$, which is transported from the downstream region of the stagnation point to the upstream, depends only on the tangential slope at the inflection point of the axial temperature profile, and is given, by substituting the conditions $u = 0$ and $\gamma = 0$ at $X = X_C$ into Eq. (8)

$$q_x = -k_t \left( \frac{dT_x}{dx} \right)_{X = X_C} = \text{const.}$$

Eq. (11) shows that $q_x$ can be represented by the overall convective heat flux based on the temperature difference $(T_{X_M} - T_\infty)$, that is,

$$q_x = h^* (T_{X_M} - T_\infty)$$

where $h^*$ is the average turbulent heat transfer coefficient.

From Eqs. (11) and (12) we obtain

$$-k_t \left( \frac{dT_x}{dx} \right)_{X = X_C} = h^* (T_{X_M} - T_\infty)$$

By introducing the excess-momentum radius $\theta^*$ as a reference length, Eq. (13) is transformed to

$$h^* \theta^* = -\left[ \frac{d((T_x-T_\infty)/(T_{X_M}-T_\infty))}{d((x-a^*)/\theta^*)} \right]_{X = X_C}$$

The left-hand side of the last equation can be regarded as the Nusselt number referred to the excess-momentum radius $\theta^*$ and an apparent turbulent heat conductivity $k_t$, therefore it is termed the turbulent Nusselt number and denoted by $Nu^*$. Then, from Eqs. (14) and (9)

$$Nu^* = \frac{h^* \theta^*}{\rho c_p \varepsilon_H}$$

$$= \left[ \frac{d((T_x-T_\infty)/(T_{X_M}-T_\infty))}{d((x-a^*)/\theta^*)} \right]_{X = X_C}$$

is obtained.

Figure 10 represents the experimental values of $Nu^*$ calculated from the axial temperature profiles shown in Fig. 6. From this figure we obtain a constant value of $Nu^*$ independent upon the kinds of flame within the stable burning region and the burning condition.

$$Nu^* = 0.45 = \text{const.}$$

Therefore, it can be concluded that the axial heat transfer process in the frontal region of flames has a similar mechanism.

![Fig.10 Numerical values of turbulent Nusselt number](image)

7. CONCLUSIONS

The results obtained in this report are summarized as follows:

1. General features of the flow patterns and the relations between a flame shape and a flow pattern are shown with respect to three typical flames, and some special characters are also represented for the flames close to both the upper and lower limits.

2. A good similarity is found in the dimensionless axial temperature profiles for the same kind of flames, and some temperature characteristics which affect on the extinction mechanism at both the upper and lower limits are considered.

3. According to the variations in the maximum axial temperature, it can be expected that the transition occurs discontinuously from the trumpet flame to the standard.

4. General features of the trumpet and lifted flames are shown for the dimensionless radial temperature profiles.

5. The point of the maximum axial temperature, the flame length and the flame radius are given by universal constants as shown in Eqs. (6) and (7).

6. It is found that the penetrating distance of jet has a constant value for the same kind of flames by dividing it by the excess-momentum radius, and that the stagnation point nearly coincides with the inflection point of the axial temperature profile.

7. The turbulent Nusselt number defined by Eq. (15) is held constant regardless the kinds of flame, and therefore the process of average axial heat transfer in the frontal region of flames has a similar mechanism.

8. From the above-mentioned results it is concluded that the excess-momentum
radius $\theta^*$ from Eq.(5) is valid for the characteristic length of the flame, and that the maximum axial and nozzle temperatures are also of importance as characteristic temperatures.

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