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Stabilization of a Round Jet Flame with a Recirculation Zone in Parallel Air Flow*

(Part I. General Properties of the Flame and the Mixing
Process in the Recirculation Zone)

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The stability limits were measured for a double concentric propane-air premixed jet flame. The burner tubes have an 8 mm inner diameter with rims of 0-7 mm thicknesses. The flame was stabilized in a higher velocity region where the rim is of sufficient thickness because of a recirculation zone forming behind a thick rim. For the recirculation zone, the aerodynamic structures such as the length and flow directions were investigated as well as the thermodynamic structures, that is, the distribution of temperatures, gas components concentration and local mixing ratio. The results showed that the real mixing ratio of the recirculation zone changed with the flow conditions. The real mixing ratio was measured by CO₂ trace method with cold flow, and was predicted successfully with a simple assumption for the ratio of the mass exchanges.

1. Introduction

It is well known that the air flow around a burner tube has strong influence on the stability limits of a Bunsen-type flame^{1),2)}. One typical example of Bunsen flame with the surrounding air flow is a double concentric jet formation, the center round jet being fuel or mixture and the coaxial annular jet a parallel air flow. Generally, the parallel air flow disturbs the flame. The blow off limits of these flames were analyzed by Nomaguchi³⁾ using the boundary velocity gradient theory, which was supplemented by Sakai⁴⁾ with the mixing theory based on the momentum effects.

On the other hand, if the burner rim is of sufficient thickness, a recirculation zone is formed on the rim by the parallel air flow. The flames are stabilized in a higher velocity region within this recirculation zone. Such phenomena have been reported by Saima⁵⁾. In such flames, the thermodynamic characteristics are determined after more complex processes, that is, the exchange between the recirculation zone and the outer flows, and the change of the real mixing ratio in the zone.

In this paper, the stability limits were measured for a double concentric premixed jets flame, and the aerodynamic

structures of the recirculation zone were investigated experimentally. The measurements of the mean real mixing ratios of the zone were made, and the results were compared with the theoretical predictions.

2. Experimental apparatus

A schematic diagram of the experimental apparatus is shown in Fig.1. Fuel used here is L.P.G (C₃H₈, purity 97%), and is premixed with the primary air in the mixing chamber. The mixture is carried to a round brass burner set coaxially in a glass combustion tube which has a diameter of 55 mm and a length of 1700 mm. Then, the parallel air flow surrounds the burner tube. The velocities of the mixture U_{mix} and of the parallel air U_2 can be controlled up to

1. Burner tube	6. Secondary air
2. Combustion tube	7. Primary air
3. Mixing chamber	8. Fuel
4. Orifice	9. Mixture
5. Pitot tube	10. Exhaust duct
B; Blower S; Variable voltage trans.	

Fig. 1 Schematic diagram of experimental apparatus

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70 m/s and 30 m/s, respectively. The thicknesses of the rim at each burner tip t are 0, 1.5, 3, 5 and 7 mm, and the inner diameter of all burners is 8 mm.

3. Flame stability limits and flame geometries

3.1 Flame geometries

A flame stability limit is shown in Fig.2 on the axes of the mixture velocity U_{mix} and the mixing ratio ϕ (air/fuel) / (air/fuel)_{st.}. The larger ϕ is, the leaner the fuel ratio becomes. Blow out is defined as the extinguishment of the flame, and the flash back limit is not examined. The flames are formed between the upper limit line and the lower limit line in the figure. The forms of the flames are mainly distinguished into two types, the inner flame (A region) and the outer flame (B region), by the position of the flame front in the recirculation zone formed behind the burner rim. Flame fronts in the flame base are located near the inner edge of the rim for the inner flame and the outer edge for the outer flame, respectively.

On the boundary of the inner flame and the outer flame, the flame has a transitional form of the two. In this flame, referred to as transitional flame, the flame

fronts are formed near both the inner and the outer circumferences of the rim, or a repetition of each form is seen. But the flame front is never formed on the inside of the recirculation zone.

In C region, the flame stays only in the recirculation zone, and the remainder, the main flame, blows off. This is referred to as crown flame and was also reported by Saima⁵⁾ and Matsumoto et al.⁶⁾. Almost the whole mixture is unburned because of extinguishment of the main flame. The crown flame is also divided into the inner and the outer flames.

In D region, the parallel air enters the center jet inversely, because U_2 exceeds U_{mix} by far. Luminous flame can be seen in the inside of the flame. This is called reverse flame. Fig.3 shows these flame geometries.

3.2 Effects of rim thickness t and of parallel air flow velocity U_2 on stability limits

The stability limits vary with t and U_2 . The changes in the limits with t are shown in Fig.4. The inflammable region spreads and the maximum blow out mixture velocity shifts to larger values as t increases. The shift of the maximum point is seen in the same manner with an increasing value of U_2 .

Fig. 2 Inflammable region

Fig. 4 Effects of t on stability limits

Fig. 3 Photographs of flame forms

3.3 Roles of the flame base

In the crown flame, combustion occurs only at the flame base and the main flame blows off. Although the transition to the crown flame from the normal flame (with the main flame) is abrupt, the boundary between the regions of each form is also shown clearly in Fig.2. The upper and lower limit lines, however, are continuous near the boundary. It shows that blowout is defined by the extinguishing of the flame at the

Fig. 5 Change of l_{RZ} vs. U_{mix}

Fig. 6 Critical ignition delay time

Fig. 8 Schematic flow patterns

flame base irrespective of flame form. Therefore, it is suggested that the structures of the flame base have a strong effect on the flame stability.

The flame base mainly consists of the recirculation zone, and acts as a heat source for the unburned mixture, as well as the recirculation zone formed behind a bluff body set in the uniform mixture flow. In the double concentric jets flame, however, the chemical composition in the recirculation zone must be changed by the exchange of the parallel air. Knowledge of aerodynamic and thermodynamic structures is required for discussion of the stability mechanism.

4. Aerodynamic characteristics of the recirculation zone

4.1 Length of the recirculation zone

For the flames held by a bluff body, or a recessed wall located in the uniform mixture flow, the stability mechanism based on the ignition delay concept^{7),8)} has been well known. According to this theory, the length of the recirculation zone l_{RZ} is one of the most important factors. In this paper, l_{RZ} is measured by means of the flame reaction of sodium. The length measured by this method includes not only the recirculation zone, but also the reverse flow zone out of the recirculation zone. When $t \leq 1.5$ mm, the reverse flow zone could not be observed by this method. Fig.5 shows the relation of l_{RZ} to U_{mix} when $t \geq 3$ mm. l_{RZ} decreases as U_{mix} increases, and increases as t and U_2 increase. And it is found that l_{RZ}

Fig. 7 Tip geometry of rotary total pressure probe

does not depend on ϕ , but only depends upon the aerodynamic processes.

The critical ignition delay time τ_{BO} obtained by the ignition delay concept is shown in Fig.6 as a relation of ϕ . The very ϕ which brings the minimum τ_{BO} is smaller than unity, and the minimum τ_{BO} is two or three times larger in comparison with the results which E.E.Zukoski⁷⁾ obtained for a bluff body. It is suggested that the differences arise from the exchange between the parallel air and the recirculation zone. Therefore the theory cannot be applied to this model.

4.2 Schematic flow pattern near the recirculation zone

It is necessary for the flow directions of the recirculation zone to be measured to understand the aerodynamic structure of the recirculation zone. In this experiment, however, turbulence in the recirculation zone is so intensive, and the zone is so small that it is difficult to visualize the flow pattern or to measure it accurately. Fig.7 shows a rotary total pressure probe which has a total pressure hole on the rotary axis. The probe for cold flow is made of stainless tubing (diameter of 1 mm) and has a hole of 0.3 mm diameter, and for combustion flow the probe is made of a quartz glass tube (diameter of 1 mm) and has 0.2 mm hole made by using ultrasonic machining. These probes are inserted perpendicularly in to the measuring face. The

Fig. 9 Change of flow pattern against U_{mix}/U_2 . $t = 5$ mm

$U_{mix} = 27.0$ m/s, $U_2 = 18.0$ m/s
 $t/d = 7/8$, with cold flow

Fig. 10 Static pressure distribution

direction of the hole which gives the maximum total pressure must be reverse to the flow.

Extreme transformations of the schematic flow pattern can be observed as U_{mix} and U_2 change, as shown in Fig.8. In (a), the reverse flow of the parallel air is formed on the burner axis at $U_{mix} \ll U_2$. This is called reverse vortex. In (b), there is one vortex rotating from inside to outside on the burner rim, which is called inner vortex. In (c), there are two opposing vortices, which are referred to as double vortex. In (d), there is one vortex from the outside to the inside, referred to as the outer vortex. These transformations of the flow pattern are formed in the order of (a) $\rightarrow$ (d) as U_{mix} increases. The order is same at different U_2 and t . Since it is considered that the transformations of the flow pattern are concerned with the exchanges between the zone and both the primary and the parallel fluids, the forms of the vortices are ordered by the velocity ratio U_{mix}/U_2 as shown in Fig.9. The figure shows that the form of the vortex is roughly determined by U_{mix}/U_2 . In combustion flow, the length of the reverse flow zone is 1.5 ~ 2 times in comparison with that with a cold flow.

4.3 Static pressure distribution near the recirculation zone

Static pressure distribution is also one of the most important factors to indicate the flow field. In this experiment, the static pressure probe which has a hole (diameter of 0.3 mm) opened perpendicularly to a thin rectangular plate (3x3 mm, thickness of 0.2 mm) is used only for cold flow. Although there is but a little swirl, and much difficulty is encountered in setting up the probe, the tendencies of distribution, for instance, the static pressure gradient showed a sufficiently reliable reproducibility. A typical static pressure distribution is shown in Fig.10. The form of the vortex cannot be directly discriminated by static pressure distribution. Generally, the pressure gradient, especially through the axis, becomes sharper and the minimum pressure on the rim decreases as U_{mix} increases. The minimum pressure region on the rim includes the vortex center. Although it is not shown in Fig.10, a maximum pressure region is formed downstream of the minimum pressure region. This maximum region is located on the burner axis when U_{mix} is sufficient. The phenomenon was also reported by Chigier et al.⁹⁾

5. Thermodynamic characteristics of the recirculation zone

5.1 Distribution of temperatures and gas components

Temperature of the flame is measured by Pt-PtR 13 % thermocouple inserted into the flame. The errors arising from radiation from the tip of the thermocouple were not compensated for. Gas components in the recirculation zone are sampled with a quartz

Fig. 12 Temperature and concentration distribution of stable inner flame

Fig. 13 Temperature and concentration distribution of inner flame near the upper limit

glass tube (diameter of 0.3mm) and each component is measured by gas-chromatography.

The temperature distribution of the outer flame is as shown in Fig. 11, and the temperature and the concentration distribution of the stable inner flame are as shown in Fig. 12. and those of the inner flame near the upper limit is as shown in Fig. 13. Generally, the maximum temperature region (over 1400°C) and the minimum concentration region of O_2 and the maximum concentration region of CO_2 roughly overlap. The maximum temperature region in the outer flame is located just inside of the flame front, or it overlaps with the flame front. On the other hand, the region in the inner flame is located outside of the flame front, and moves to the flame front as the flame approaches the upper blow out limit. CO is distributed over the entire recirculation zone in the stable inner flame, but only near the flame front in the inner flame near limit. And O_2 concentration increases as the flame approaches the upper limit. Thus it is suggested that the exchange of the parallel air with the recirculation zone increases as U_{mix} increases.

5.2 Local mixing ratio and location of flame front

The gas components and the local mixing ratio ϕ_{RZ} distribution in the section of 3 mm downstream from the burner nozzle are shown in Fig. 14. Practically, only CO and H_2 are burned at the flame front in the outer flame. In the inner flame, rapid reaction of C_3H_8 is carried out. Many intermediate products (much CH_4 , C_2H_2 , a little C_2H_4 , C_2H_6) are distributed above the burner rim in the outer flame, but hardly any is found in the inner flame. Local mixing ratio ϕ_{local} is distributed almost uniformly in the recirculation zone, and when viewed in detail, the position of the flame front is found to be located at the same position of $\phi_{\text{local}} = 1.0$ for every flame (outer flame (i), transitional flame (ii) and inner flame (iii)). It can be concluded that the flame front is formed at the position of $\phi_{\text{local}} = 1.0$. This phenomenon agrees with the results of the diffusion flame held by a disk as reported by Minx et al.¹⁰⁾ The form of flame is consequently de-

terminated by the real mixing ratio which is different from that of the primary mixture, in the recirculation zone.

6. Mixing processes in the recirculation zone

6.1 Constant ϕ_{RZ} diagram

As stated above, an important part of the behaviours of the flame has a strong dependence on the mixing processes of the mixture and the parallel air in the recirculation zone. Using CO_2 as a tracer instead of fuel, the resulting distribution by diffusion of mixture can be readily investigated with a cold flow. The CO_2 concentration distribution is as shown in Fig. 15. The concentration in the recirculation zone is almost uniform except for the region in which U_{mix} is much smaller than U_2 . Then the mean mixing ratio in the recirculation zone ϕ_{RZ} can be represented by the value at one point inside the zone and therefore the fluctuation of ϕ_{RZ} with U_{mix} and ϕ can be easily examined for the fixed

Fig. 15 Concentration distribution of mixture

Fig. 16 Constant ϕ_{RZ} diagram

Fig. 17 Confluence model of axisymmetric parallel flows with recirculation zone

t and U_2 . The constant ϕ_{RZ} diagram drawn on $U_{\text{mix}} - \phi$ plane shows a characteristic of mixing process in the double concentric jets. The representative measurement positions of ϕ_{RZ} (r, z) are (2, 3) and (1.5, 2) (mm, mm) at $t=5$ and $t=3$ mm, respectively, where r is a radial distance from the inner circumference and z is an axial distance from the burner rim. Fig. 16 shows the constant ϕ_{RZ} diagram overlapping with the inflammable region (the shadowed region). Both limit lines and the constant ϕ_{RZ} curves have the same tendency, that is, they have similar gradients. And $\phi_{RZ}=1.0$ line is regarded as the axis in the spread of the inflammable region. It is found, therefore, that behaviours of the flame have great dependence on the mixing processes. The figure also shows that ϕ_{RZ} increases as U_{mix} increases for the fixed t , U_2 and ϕ . Namely, the exchange of the parallel air with the recirculation zone increases with an increasing U_{mix} .

6.2 Mixing theory

A confluence model of axisymmetric parallel flows with a recirculation zone is shown in Fig. 17. The recirculation zone can be regarded as a confined mixing region in this model. The exchange areas of mixture side and of parallel air side can be defined as S_{mix} , S_2 , respectively. When it is assumed that the section form of the recirculation zone is an isoscale triangle whose vertical angle is 2θ , each exchange with the zone per unit time q_{mix} , q_2 can be expressed as

$$q_{\text{mix}} = V_{\text{mix}} \cdot \cos \theta \cdot S_{\text{mix}} \\ q_2 = V_2 \cdot \cos \theta \cdot S_2$$

where V_{mix} , V_2 are perpendicular exchange velocities. Then the assumption of Kármán⁽¹⁾ on confluence of parallel flows is applied to this model,

$$U_{\text{mix}}/U_2 = -V_2/V_{\text{mix}} \\ = (q_2/S_2)/(q_{\text{mix}}/S_{\text{mix}}) \\ = (S_{\text{mix}}/S_2)(q_2/q_{\text{mix}}).$$

(S_{mix}/S_2) is determined by dimension of the recirculation zone. When it is expressed as

$$S_2/S_{\text{mix}} = k, \\ q_2/q_{\text{mix}} = k(U_{\text{mix}}/U_2) \quad (1)$$

is obtained. Then equation (1) can be rewritten by substitutions on conditions of mixing ratio and so on, as

$$\phi_{RZ} = (\phi + 1/23.8) k (U_{\text{mix}}/U_2) + \phi \\ \text{for } \text{C}_3\text{H}_8 \quad (2).$$

When the section of the recirculation zone can be simulated with an isoscale triangle, each exchange area S_{mix} , S_2 is represented by circumferential areas of part of cones, and the ratio k is written as

$$k = S_2/S_{\text{mix}} = (2d + 3t)/(2d + t) \quad (3).$$

According to equation (3), k is expressed by only inner diameter of burner tube d and thickness of rim t , independent of l_{RZ} .

Fig.18 shows the theoretical value of k (k_{theo} ; real line) in comparison with experimental values (k_{ex}). k_{ex} is not varied with the change of U_2 , U_{mix} and ϕ , and coincides well with k_{theo} , which is 1.48 at $t=5$ mm, 1.32 at $t=3$ mm. For $t=5$ mm, in smaller U_{mix}/U_2 region, k_{ex} is much larger than k_{theo} because of a lot of reverse entrainment of parallel air into the center jet. Generally, however, k_{ex} is smaller when $U_{\text{mix}}/U_2 < 1.0$ and is larger when $U_{\text{mix}}/U_2 > 1.0$ than k_{theo} . This fact is caused by simulating the section form of the recirculation zone to be an isoscale triangle, while the wave of k_{ex} value to U_{mix}/U_2 shows that, in fact, the recirculation zone is deformed by change of U_{mix}/U_2 .

Theoretical constant ϕ_{RZ} diagram is presented from eqs. (2) and (3) as shown in Fig.19 in comparison with that from experimental results. Good agreement between predicted and experimental values for ϕ_{RZ} confirms the propriety of this theory.

Fig.18 Values of k_{theo} and k_{ex}

Fig.19 Theoretical constant ϕ_{RZ} diagram

7. Conclusions

The following conclusions are drawn from this work.

1) In a double concentric jets flame, when the burner rim is of sufficient thickness, maximum blow out mixture velocity increases with an increase of parallel air velocity. This phenomenon is in contrast to the result for the thin rim. The flame is stabilized by the recirculation zone formed behind the thick rim.

2) The recirculation zone, which has strong influence on flame stability, has a peculiar flow pattern with the velocity changing in the center jet and the parallel surrounding flow. Forms of flame are roughly distinguished into the inner and the outer flames, which have peculiar temperature and gas components concentration distributions.

3) Flame front is formed on the face where local mixing ratio is 1.0. The position of the flame front depends on the real mixing ratio in the recirculation zone.

4) The exchange rate of the parallel air into the recirculation zone increases as the mixture velocity increases. Mixing processes in the recirculation zone are proposed theoretically, assuming that the exchange ratio of each parallel flow is in inverse proportion to the velocity ratio. According to the theory, the mean real mixing ratio in the zone ϕ_{RZ} is determined by the exchange area ratio, the velocity ratio and the mixing ratio. The exchange area ratio can be obtained by dimension of the burner tubes. The theoretical results of ϕ_{RZ} were in good agreement with the experimental.

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