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Effects of the Recirculation Zone on the Stabilization of Double Concentric Burning Jets

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Abstract

The characteristics of the recirculation zone forming behind a burner rim was investigated experimentally in several tube burners with different rim sizes fitted in parallel with air flow. Propane-air mixture was supplied to the burners with 14 and 20 mm inner diameter. Temperature and length of the zone were measured for various mixing ratios, mixture and parallel air velocities.

The results show that temperature of the recirculation zone is affected by the mixing ratio and the flow velocities, but the length of the zone is not affected by the mixing ratio. The representative temperature of the zone depends on the mean mixing ratio within the zone as a result of mass exchange between the zone and the two streams.

Measurements for cold flow indicate that the length shows different behaviors in comparison with combustion flow. Empirical equations for the characterized length of the recirculation zone were obtained for each flow state as a function of blockage ratio and mass velocity ratio. It was found that the characterized length is independent of the inner diameter of burner tube.

1. Introduction

The Blow-off mechanism of a simple premixed burner flame was explained in terms of the boundary velocity gradient theory proposed by Lewis and von Elbe1). A number of experiments confirmed the applicability of the theory. However, this theory can not be applied to the case of double concentric burning jets, because the flame seems to be stabilized by the recirculation zone formed behind the burner rim. This fact suggests that the blow-off mechanism of the double concentric jet flame is different from that of a simple burner flame.

It was revealed in our previous papers2~3) that the recirculation zone in which burnt gases as well as active species are circulating, acts as a low velocity region and a source of heat and active species for fresh mixtures, which coincides with the observation in a wake flame of a bluff body fitted within a mixture stream. Therefore the double concentric jet flame is stabilized by the recirculation zone, in spite of the fact that our previous and present results do not correspond with the results for a bluff body by Zukoski and Marble4).

According to the ignition delay concept4), blow-off limits can be determined by the passage time, namely the time that a mass element of fresh mixture requires

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to sweep past the recirculation zone (the time is obtained by dividing the length of the zone by the mixture flow velocity). A fresh mixture is given sufficient energy to be ignited within this time. Therefore, blow-off is governed by the length and the temperature of the zone.

In the present paper, we clarified the effects of parallel air flow velocity and thickness of burner rim on the flame stability limits, and the behaviors of the temperature and the length of the recirculation zone which are the basic factors for flame stabilization.

2. Experimental apparatus

A schematic diagram of the main part of the experimental apparatus is shown in Fig. 1. Propane used here as fuel is of 97.5% purity and is premixed with primary air. The mixture is carried to a burner tube set coaxially in the cylindrical test section. The parallel air stream, ensuring a fully developed turbulent flow, surrounds the burner tube. The range of mixture and parallel air velocities are 10～100 and 20～70 m/s, respectively. Seven kinds of burners shown in Fig. 2 are used. The rim thicknesses t with burner of 14 mm inner diameter d are 4.9, 10 and 14 mm, and with 20 mm i. d., 7, 13, 18 and 20 mm. The outer wall expanded angle of each burners are designed for less than 14 degree angle to prevent flow separation on the wall. Experiments were also performed in an isothermal flow for the purpose of comparison.

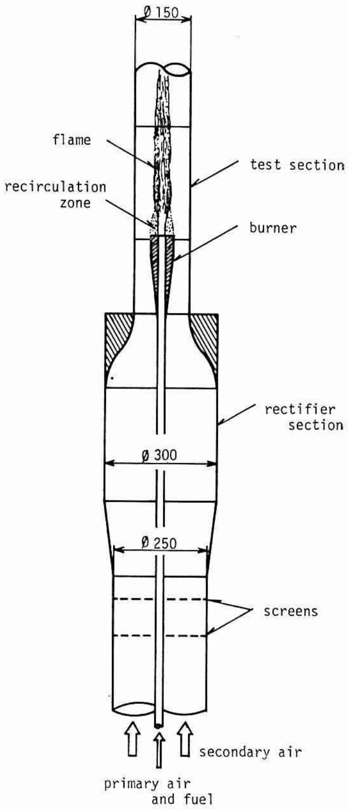


Fig. 1. Schematic diagram of main-part of experimental apparatus.

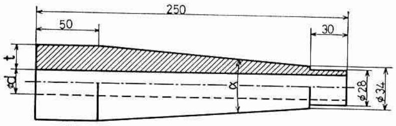


Fig. 2. Geometry of burner tube.

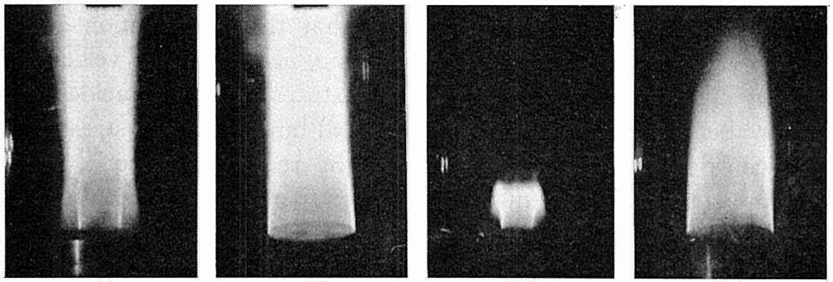

(i) (ii) (iii) (iv)

Fig. 3. Photographs of various flames.

(i) Inner flame (ii) Outer flame
(iii) Crown flame (iv) Counter flow flame

3. Flame geometries

The forms of the flames are classified into the outer flame, the inner flame, the crown flame and the counter flow flame by the situation of the flame front and flame geometries. Photographs of those flames are shown in Fig. 3. The regions appearing in these flames are shown in Fig. 4. In the figure U_2 is parallel air flow velocity and U_{mix} mixture flow velocity and ϕ mixing ratio defined as (air/fuel)/(air/fuel)$_{\mathrm{st}}$. The inner flame has a flame front on the inside edge of burner rim and the outer flame on the outside edge. In the photograph of the inner flame in Fig. 3, the recirculation zone can be clearly recognized outside the flame base. The crown flame is formed only in the recirculation zone, and the main flame behined the zone is blown out. The counter flow flame does not have the zone behind the rim, and swirling luminous particles are observed in the flame. These results are the same as our previous results obtained with small burners of 8 mm i. d.[2~3].

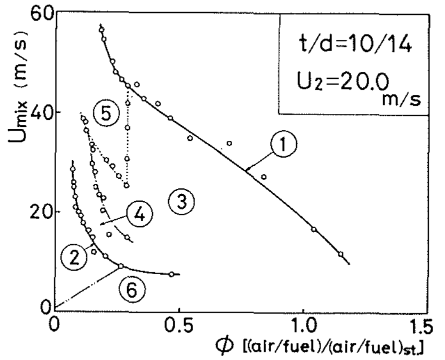


Fig. 4. The existence region of each flame.

① Upper blow-off limit
② Lower blow-off limit
③ Inner flame
④ Outer flame
⑤ Crown flame
⑥ Counter flow flame

4. Effects of parallel air flow velocity and the thickness of the burner rim on flame stability region

The results shown in Figs. 5 and 6 indicate that the flame stability region is varied by the parallel air flow velocity U_2 and thickness of rim t. The same tendency was also reported in our previous papers[2~3].

The effect of increasing U_2 is shown in Fig. 5. The flame stability region shifts in the directions of increasing U_{mix} and ϕ. A case which shows an increasing t is

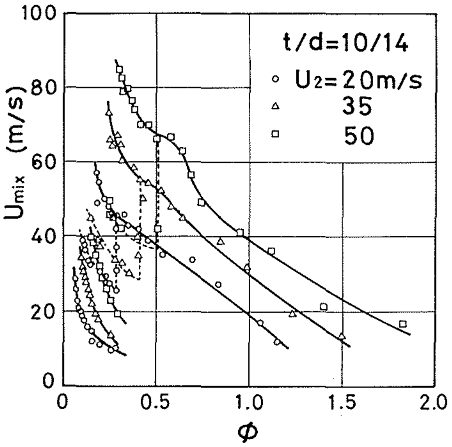


Fig. 5. Effects of parallel air flow velocity U_2 on flame stability region.

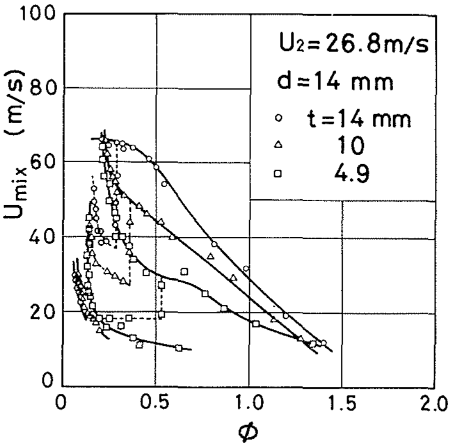


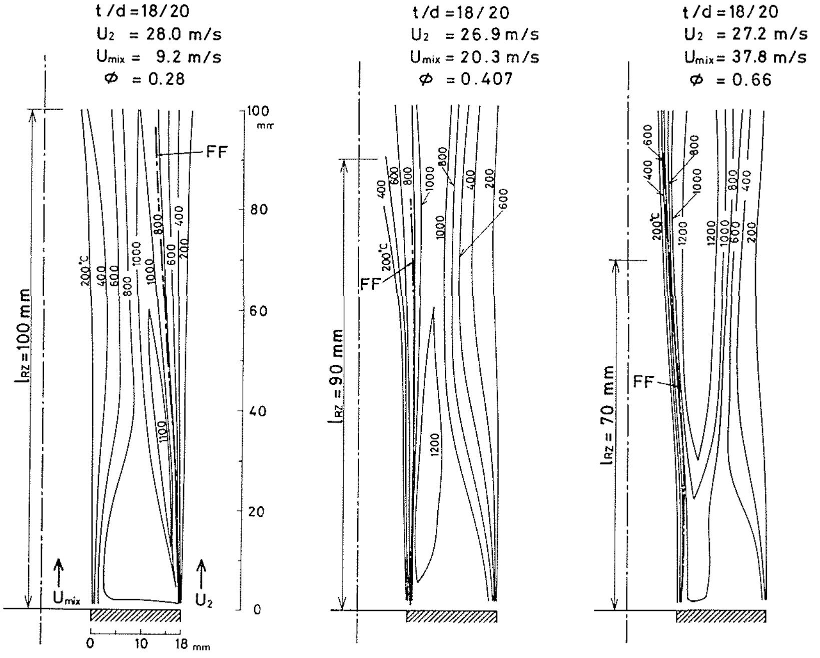
Fig. 6. Effects of rim thickness t on flame stability region.

shown in Fig. 6. The upper limits shifts in the direction of both increasing U_{mix} and ϕ, but the lower limits show an opposite tendency, and the region in which the crown flame appears shifts in the direction of greater U_{mix} and smaller ϕ. Any increase of U_2 and t effect the flame stabilization since the recirculation zone becomes larger, however, these results show that the variation of the flame stability region can not be explained by the size of the zone only.

5. Temperature in the recirculation zone

Temperature measurements were carried out with a silica coated Pt-Pt 13% Rh thermocouple of 0.1 mm diameter, without radiation correction. It has been reported that the gas temperature in the recirculation zone behind a bluff body was uniform[4], however, for double concentric burning jets, as shown in Fig. 7, the recirculation zone had a temperature gradient because of the cold air flow surrounding the burner tube. In Fig. 7, l_{RZ} is the length of the recirculation zone and dot-dash lines (FF) represent the situations of the flame fronts.

The temperature gradient close to the burner rim is so small that the temperature distribution within the zone is regarded as almost uniform. Consequently, the representative temperature of the zone T_{RZ} was decided at a distance of t above the rim on the center plane of the rim. Variation of T_{RZ} with U_{mix}, U_2 and ϕ was measured. The constant T_{RZ} diagram is shown in Fig. 8 together with the flame stability region. Under the conditions of constant U_{mix} or ϕ, in case of the inner



(i) (ii) (iii)

Fig. 7. Temperature distribution.
(i) Outer flame (ii) Inner flame (iii) Inner flame near blow-off

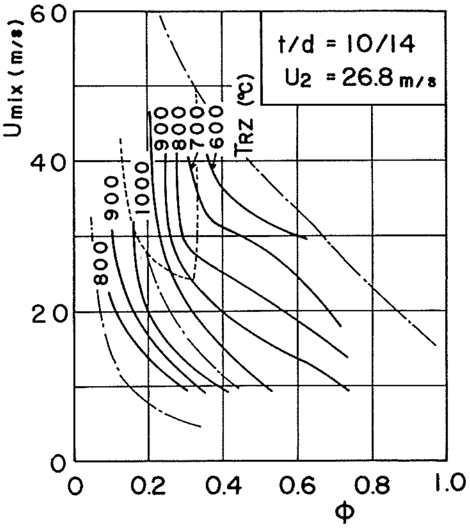


Fig. 8. Isothermal lines of the representative temperature in the recirculation zone T_{RZ}.

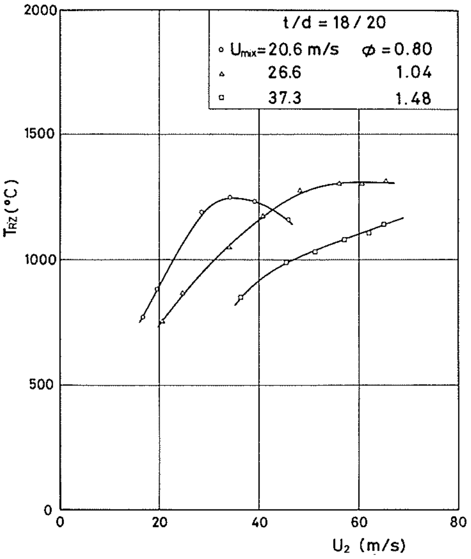


Fig. 9. Effects of U_2 on T_{RZ}.

flame, T_{RZ} decreases according to the increase in ϕ or U_{mix}, and in case of the outer flame, T_{RZ} shows the opposite tendency. The effect of U_2 on T_{RZ} is shown in Fig. 9. Flame geometries of each measuring point were all in the inner flames except for the right end point of the line of 20.6 m/s U_{mix}. In this figure, T_{RZ} increases with an increase in U_2 at the inner flame, and decreases in case of the outer flame. Both figures show that T_{RZ} becomes maximum at the inner flame near the transitional region between the inner and the outer flame, and shows minimum values at the flammability limits.

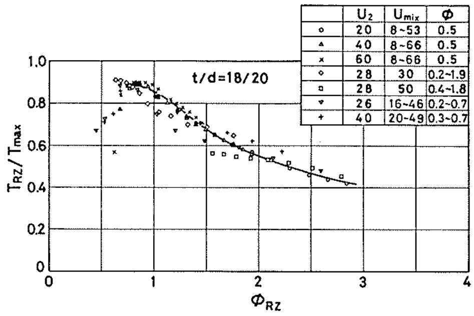


Fig. 10. Variation in $T_{RZ}/T_{\max}$ vs. ϕ_{RZ}.

From these results, it can be assumed that the increase in U_{mix} brings on the increase in quantity of the parallel air flowing into the recirculation zone, and the increase in U_2 brings on the increase in quantity of burnt gases flowing into the zone.

T_{RZ} depends on the mean mixing ratio ϕ_{RZ}, since T_{RZ} is a result of mixing the burnt gas and the parallel air which flows into the recirculation zone. Further the maximum temperature in the zone $T_{\max}$ varied with the conditions of flow velocities and ϕ. Therefore, T_{RZ} will probably vary in conjunction with the variation of $T_{\max}$. The variation of the ratio of T_{RZ} to $T_{\max}$ versus ϕ_{RZ} is shown in Fig. 10. The measured values in which ϕ_{RZ} was below 0.7 were for the outer flame and the other for the inner flame. For the inner flame, keeping ϕ constant ($\phi=0.5$), $T_{RZ}/T_{\max}$ presented a good correlation to ϕ_{RZ}, but the other points did not show such a correlation. It is assumed that this discrepancy is caused by the exothermic reaction in the recirculation zone. Hence, for the estimation of T_{RZ} from ϕ and the flow velocities, it is necessary to carry out more detailed measurements with special consideration to the chemical reactions.

6. The length of the recirculation zone

The length of the recirculation zone l_{RZf} was measured by means of flame reaction to salt solution in combustion flow. The boundary of the recirculation zone was defined as the middle of a space where flame reaction occurred intermittently in the flow. For cold flow, the length l_{RZc} was measured using the smoke scattered light technique in a similar to combustion flow.

Typical results of measurements in combustion are shown in Fig. 11. λ defined as $\rho_2 U_2/\rho_{\mathrm{mix}} U_{\mathrm{mix}}$ is mass velocity ratio, where ρ is density. Since ϕ was different for each measured point, l_{RZf} is independent of ϕ, and increases with the increasing λ exponentially. The same results were obtained for other burners, thus it may be said that l_{RZf}/t is proportional to $\lambda^{0.36}$. Moreover Fig. 12 shows the effect of the blockage ratio t/B where B is the width of the annular jet. It was shown that l_{RZf}/t is proportional to $(t/B)^{0.58}\lambda^{0.36}$ since the slope in Fig. 12 is about 0.58. Finally the following empirical equation may be obtained for the length of the recirculation zone

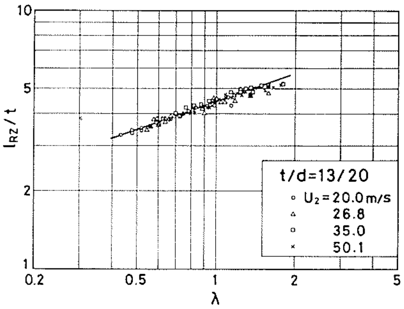


Fig. 11. Length of recirculation zone in combustion flow.

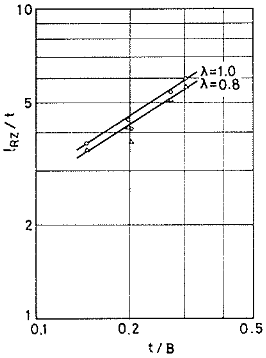


Fig. 12. Effects of blockage ratio on l_{RZf}.

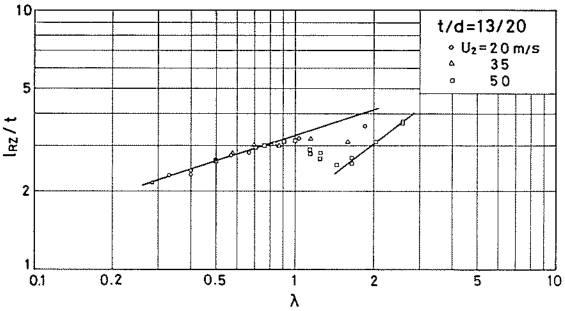


Fig. 13. Length of recirculation zone in cold flow.

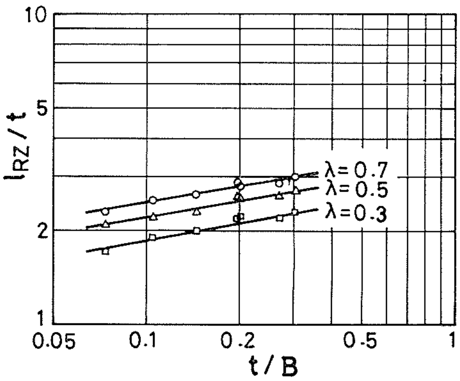


Fig. 14. Effect of blockageratio on l_{RZc} for $\lambda<1$

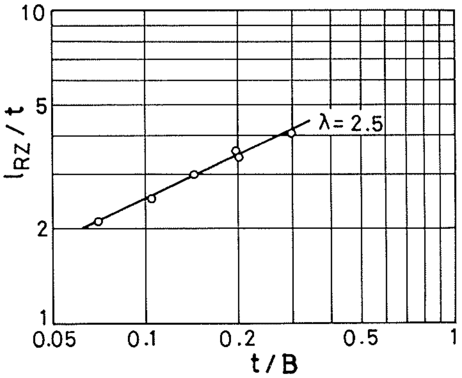


Fig. 15. Effect of blockage ratio on l_{RZc} for $\lambda>1.5$

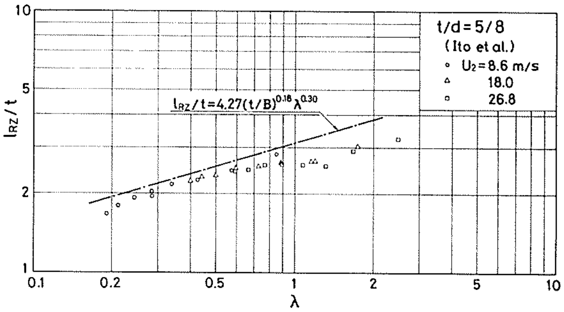


Fig. 16. Comparison between previous results on a small burner and present results.

in combustion,

$$l_{RZf}/t = 11.5\,(t/B)^{0.58}\lambda^{0.36}. \qquad (1)$$

However, the above equation is not applicable in the greater λ.

For cold flow the behavior of l_{RZc} shown in Fig. 13 differed greatly from the tendency seen in combustion. The behavior of l_{RZc} to λ is distinguished into three regions, namely, $\lambda<1$, $1<\lambda<1.5$ and $\lambda>1.5$. In the region of $\lambda<1$, l_{RZc} is proportional to $\lambda^{0.30}$, and in the region of $\lambda>1.5$, it is proportional to $\lambda^{0.66}$. These results also agreed well with the results obtained with the other burners. The effect of blockage ratio is shown in Figs. 14 and 15. Each slope of curves is 0.18 and 0.47, respectively. From the above results we may express the length for cold flow approximately as follows,

$$l_{RZc}/t = 4.27\,(t/B)^{0.18}\lambda^{0.30}, \qquad (\lambda<1), \qquad (2)$$

$$l_{RZc}/t = 4.30\,(t/B)^{0.47}\lambda^{0.66}, \qquad (\lambda>1.5). \qquad (3)$$

The previous result with a small burner for cold flow is compared with the present results in Fig. 16. The agreement between the two is generally good, however, there is a slight disagreement which is thought to be attributable to the difference in the measurement method and the evaluation of the blockage ratio. Therefore it is concluded that the above equations are proper in general and the generalized l_{RZ} is irrespective of the inner diameter of burner tube.

7. Discussion

The remarkable difference between l_{RZf} and l_{RZc} is caused directly by the thermal expansion of the recirculation zone. Disagreement in each corresponding exponent of the empirical equations suggests that the rate of expansion of the zone is different according to the variation of λ and t/B. It is surmised that the expansion depends on T_{RZ}, with emphasis on t.

Although we obtained the result that l_{RZf} is independent of ϕ, T_{RZ} depends on ϕ and the variation in T_{RZ} with ϕ is not small. T_{RZ} varies as ϕ varies, and if the rate of expansion of the zone depends on T_{RZ}, l_{RZf} is expected to vary, however, the experimental results showed no effect of ϕ on l_{RZf}. This is a clearly discrepant phenomenon, however, it could not be explained based on the present measurements.

In accordance with the relation between flame stabilization and the recirculation zone, an increase in either U_2 or t results in the increase in the length of the zone, however, each of the effects on flame stabilization is not similar as shown in Figs. 5 and 6. As described above, the mechanism of the flame stabilization for double concentric burning jets can not be explained only by the length and the temperature of the zone alone. The ignition delay concept cannot be applied to these phenomena. In order to clarify the flame stabilization mechanism, the aerodynamical and chemical structure of the recirculation zone must be studied in more detail.

8. Conclusions

(1) The increase in the parallel air flow velocity and the thickness of burner rim increases the limit of the upper blow-off, as a result of the increase in the length of the recirculation zone.

(2) For the inner flame, the representative temperature of the recirculation zone decreases as the mixture velocity and the mixing ratio increase, and increases as the parallel air flow velocity increases. For the outer flame, the opposite tendency to the inner flame is observed.

(3) Maintaining a constant mixing ratio, the representative temperature in the recirculation zone depends on the mean mixing ratio in the zone.

(4) From the measurment of the recirculation length it was found that the length is independent of the inner diameter of a burner tube, and the length in the combustion flow is independent of the mixing ratio. Empirical equations related to the length of the recirculation zone in both combustion and cold flow were obtained.

(5) The ignition delay concept can not be applied to the blow-off mechanism of double concentric burning jets.

Acknowledgement

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