Stabilization of a Round Jet Flame with a Recirculation

Zone in Parallel Air Flow

(Part III. Prediction of Blow-off Limits*)

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Blow-off limits were predicted for a double concentric propane-air premixed jet flame by using a proposed theoretical model. In the recirculation zone formed behind a thick rim of burner tube, a chemical reaction takes place. The combustion in the zone was regarded as homogeneous or well stirred. The flames reach the blow-off limits when the rate of the chemical reaction in the zone attains a critical speed with an increase of mass exchange rate between the recirculation zone and the outer flows. Prior to the prediction, the mass exchange rates were determined experimentally by measuring the residence time in the recirculation zone in different burners and for various flow velocities. The rate limiting reaction was assumed to be oxidation of CO in the zone. Predicted results show a good agreement with the experimental blow-off.

Key Words: Combustion, Jet Flame, Flame Stabilization, Premixed Flame, Turbulent Flame, Recirculation Zone, Blow-off Limits

1. Introduction

A double concentric jet flame which consists of a central mixture jet and an annular air jet, is stabilized by the recirculation zone behind the thick annular burner rim. The thermochemical characteristics and the turbulent exchange of the flame were detailed in our previous papers⁽¹⁾⁽²⁾. The purpose of this study is to establish a model of the flame stabilization processes based on previous experimental results.

There are many investigation on the flame held behind a bluff body in a uniform mixture flow, since this is a typical flame stabilized by a recirculation zone. Though the ignition delay concept proposed by Zukoski et al.⁽³⁾, and improved by Cheng et al.⁽⁴⁾, Kundo et al.⁽⁵⁾ and others is one of the most acceptable theories for bluff body flames, this theory could not be applied to the double concentric jet flame, mainly because of an intense reaction in the recirculation zone⁽¹⁾. On the other hand, Longwell et al.⁽⁶⁾ tried to analyze the reaction in the recirculation zone behind the bluff body and to predict the blow-off limits. At present, however, his model is not accepted because no chemical reaction takes place in the bluff body recirculation zone where only burnt gases recirculate⁽⁷⁾. Further development of the model is well known as a PSR (perfect-

ly stirred reactor) which has produced a great deal of information on combustion phenomena⁽⁸⁾⁽⁹⁾.

One of the most important results, in our present study, is that the recirculation zone of the double concentric jet flames can be regarded as the PSR. Details of thermochemical data show that an intense reaction takes place in the recirculation zone, and that flame stabilization is dominated by the equivalence ratio of the recirculation zone. The equivalence ratio, which was determined by the result of mixing between the double concentric jets, was accurately predicted. The mass exchange between the recirculation zone and the outer flows was calculated from the mean residence time. The turbulent exchange processes determine both the thermochemical characteristics and the mass feed rate of the reactants in the recirculation zone. A blow-off mechanism was proposed based on the results mentioned above, and blow-off limits were predicted.

2. Nomenclature

B : collision factor
 d : inner diameter of burner tube
 E : global activation energy
 k : exchange area ratio = $(2d+3t)/(2d+t)$
 M : molecular weight
 m : molar fraction ratio of inert gas
 n : order of reaction
 P : pressure
 q : volumetric exchange velocity
 R : universal gas constant
 T_{RZ} : mean gas temperature in recirculation zone
 t : thickness of burner rim
 U : mean velocity
 V_{RZ} : volume of recirculation zone

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λ_{mix} , λ_{RZ} : air-fuel ratios of mixture and recirculation zone
 λ_{st} : theoretical air-fuel ratio
 τ_{re} : mean residence time in recirculation zone
 ϕ : excess air ratio
 ρ : density
 Subscripts
 A: air
 F: fuel
 mix: mixture
 RZ: recirculation zone
 (in): feed in
 (out): flow out
 0: initial state (room temperature)
 2: parallel air

3. Experimental Apparatus

The double concentric jet burner is schematically shown in Fig. 1. The central jet (8 mm in d.), propane-air mixture, is varied up to 70 m/s in mean velocity, and is surrounded by the annular air jet (55 mm in d.) which can be controlled up to 30 m/s in mean velocity. When the rim of the partition tube between those non-swirl coaxial jets is of sufficient thickness, the recirculation zone attached to

Fig. 1 Schematic of the recirculation zone.

Fig. 2 Temperature and gas components distribution in and around the recirculation zone, $U_{mix}=10.8$ m/s, $U_2=26.8$ m/s.

the rim stabilizes the flame in high velocity streams⁽¹⁾. Main interest in the present paper is focused on cases where the rim thickness t is larger than 3 mm.

Mean residence time in the recirculation zone in isothermal flow was measured by a light scattered technique, as described in our previous paper⁽²⁾. In measurement with combustion, a light emission from NaCl, which was introduced as an atomized solution into the flame, was applied. Magnesium oxide (MgO) powder was used for measurements both with and without combustion, so the adequacy of the light scattered and the emission technique was proved.

4. Thermochemical Characteristics of the Recirculation Zone

Typical temperature and gas components concentration contours of the recirculation zone are shown in Fig. 2. These relatively uniform distributions shown an intense mixing of the mixture and the air in the recirculation zone. Though the original fuel (C_3H_8) is dissociated in the inner exchange layer, carbon monoxide (CO) oxidation takes place mainly in the recirculation zone. A distribution of local air ratios ϕ_{local} calculated from gas concentrations is shown in Fig. 3. ϕ_{local} distribution is always remarkably uniform in the recirculation zone except in the case of 'reverse flame⁽¹⁾'. From the results, the recirculation zone can be regarded as a kind of PSR.

5. Mass Exchange Processes between the Recirculation Zone and the Outer Flows

The turbulent mass exchange process between the recirculation zone and the outer flows is also schematically shown in Fig. 1. Volumetric exchange ratio q_2/q_{mix} is in inverse proportion to the velocity

Fig. 3 Distribution of local air ratios.

ratio as shown in our previous paper⁽¹⁾.

$$q_{2(in)}/q_{mix(in)} = k(U_{mix}/U_2) \quad (1)$$

where k is the exchange area ratio calculated by assuming that the form of the recirculation zone is an isosceles triangle in cross section.

Several relations on the maximum supplied to the recirculation zone are immediately introduced as follows.

$$q_{mix(in)} = q_{Amix(in)} + q_{F(in)} \quad (2)$$

$$q_{Amix(in)}/q_{F(in)} = \lambda_{mix} \quad (3)$$

$$\phi_{mix} = \lambda_{mix}/\lambda_{st} \quad (4)$$

The mean air ratio of the recirculation zone ϕ_{RZ} can be defined as follows, because of the uniformity of ϕ_{local} .

$$\lambda_{RZ} = (q_{Amix(in)} + q_{2(in)})/q_{F(in)} \quad (5)$$

$$\phi_{RZ} = \lambda_{RZ}/\lambda_{st} \quad (6)$$

Consequently, the following equation is derived from Eqs. (1)-(3), and (5).

$$\phi_{RZ} = \left(\phi_{mix} + \frac{1}{\lambda_{st}} \right) k U_{mix}/U_2 + \phi_{mix} \quad (7)$$

Equation (7) can accurately predict ϕ_{RZ} both with and without combustion as described in our previous paper⁽¹⁾.

The relation between summation of volumetric exchange rates and the mean residence time of the gas in the recirculation zone is described as follows;

$$q_{mix(out)} + q_{2(out)} = V_{RZ}/\tau_{re} \quad (8)$$

The mean residence time τ_{re} must be obtained by measurement. The resulting τ_{re} for combustion flows is shown in Fig. 4 and expressed as Eq. (9).

$$t/\tau_{re} U_2 = \xi \sqrt{U_{mix}} \quad (9)$$

where

$$\xi = 1.46 \times 10^{-2} \text{ [m/s]}^{-0.5} \quad (10)$$

for combustion flows.

Fig. 4 Residence time.

6. Modeling of Blow-off Processes

The mean air ratio of the recirculation zone contours overlapped with flame-stability region is shown in Fig. 5⁽¹⁾. The stability of the flame evidently depends on ϕ_{RZ} rather than on ϕ_{mix} . This fact, which is caused by the intense chemical reaction in the recirculation zone, suggests that the existence of reaction in the recirculation zone is an indispensable condition for flame stabilization. Therefore, an impossibility of continuation of the reaction in the recirculation zone results in blow-off the same as in the case in PSR. In other words, when excess reactants are supplied to the recirculation zone, where the rate control is a chemical reaction in spite of diffusion by turbulent mass exchanges, the reaction is impossible by temperature reduction brought about by the reduction of the reaction efficiency, and the flame blows off due to lack of heat source.

Following assumptions are made for the modeling of the blow-off.

(1) The recirculation zone is a kind of PSR. Namely, in the zone, the air ratio is uniform and the reaction uniformly progresses (see Figs. 2 and 3).

(2) Rate limiting reaction is CO oxidation.

(3) A second order Arrhenius type reaction occurs.

Molecule oxygen consumption rate in the recirculation zone, $N_{O_2(c)}$, is written as follows⁽⁸⁾⁽⁹⁾.

$$N_{O_2(c)} = V_{RZ} B \sqrt{T_{RZ}} \{ \exp(-E/RT_{RZ}) \} \times (P/RT_{RZ})^\alpha x_{CO}^\alpha x_{O_2}^\beta \text{ [mol/s]} \quad (11)$$

where T_{RZ} means the dependence of collision factor B on temperature. x_{CO} and x_{O_2} are mole fractions of CO and O_2 respectively, α and β are their reaction order.

On the other hand, mole oxygen feed rate to the recirculation zone depends on turbulent mass exchange. This mass, which

Fig. 5 Flame stability limits and ϕ_{RZ} .

is exchanged in each exchange layer, must be conserved in a steady state condition. Relation between mass feed rate to and mass flow out rate from the recirculation zone is given in Eqs. (12) and (13).

On the inside (mixture side) layer;

$$\rho_{F_0} Q_{F(in)} + \rho_{A_0} Q_{A(mix(in))} = \rho_{RZ} Q_{mix(out)} \quad (12)$$

On the outside (annular air side) layer;

$$\rho_{A_0} Q_{2(in)} = \rho_{RZ} Q_{2(out)} \quad (13)$$

Mole oxygen feed rate to the recirculation zone, $\dot{N}_{O_2(in)}$, is obtained from total air feed rate to the recirculation zone $Q_{A(mix(in))} + Q_2(in)$.

$$\begin{aligned} \dot{N}_{O_2(in)} &= \dot{N}_{A(in)} / (m+1) \\ &= \rho_{A_0} (Q_{A(mix(in))} + Q_2(in)) / M_A (m+1) \quad (14) \end{aligned}$$

From Eqs. (2), (5), (7), (12) and (13), Eq. (14) is written as follows.

$$\begin{aligned} \dot{N}_{O_2(in)} &= \frac{\rho_{A_0}}{(m+1)M_A} \frac{\rho_{RZ} \lambda_{RZ}}{\rho_{F_0} + \lambda_{RZ} \rho_{A_0}} \frac{V_{RZ}}{\tau_{re}} \\ &[\text{mol/s}] \quad (15) \end{aligned}$$

The ratio of oxygen consumption rate $\dot{N}_{O_2(c)}$ (Eq. (11)) to feed rate $\dot{N}_{O_2(in)}$ (Eq. (15)) means the reaction (or oxygen consumption) efficiency η_{O_2} .

$$\begin{aligned} \eta_{O_2} &= \Phi (\dot{N}_{O_2(c)} / \dot{N}_{O_2(in)}) \\ &= \Phi (m+1) M_A (\rho_{F_0} + \lambda_{RZ} \rho_{A_0}) (P/RT_{RZ})^n \\ &\times B \{ \exp(-E/RT_{RZ}) \} x_{C_0}^2 x_{O_2}^2 \tau_{re} \\ &/ \rho_{A_0} \rho_{RZ} \lambda_{RZ} T_{RZ}^{-0.5} \end{aligned}$$

Putting the experimental equation (9) into the above equation yields

$$\begin{aligned} \eta_{O_2} &= \Phi (m+1) M_A (\rho_{F_0} + \lambda_{RZ} \rho_{A_0}) t \\ &\times (P/RT_{RZ})^n B \{ \exp(-E/RT_{RZ}) \} \\ &\times x_{C_0}^2 x_{O_2}^2 / \rho_{A_0} \rho_{RZ} \lambda_{RZ} T_{RZ}^{-0.5} \xi U_2 U_{mix}^{0.5} \quad (16) \end{aligned}$$

where Φ is an index function to eliminate the excess air at lean condition as follows;

$$\begin{aligned} \text{when } \phi_{RZ} \leq 1; \quad \Phi &= 1, \\ \text{when } \phi_{RZ} > 1; \quad \Phi &= \phi_{RZ}. \end{aligned}$$

The maximum feed rate and then the maximum consumption rate are given by

$$d(\dot{N}_{O_2(in)} / V_{RZ} P^n) / d\eta_{O_2} = 0 \quad (17)$$

at any T_{RZ} . When the feed rate exceeds the maximum, the reaction is interrupted. When t and U_2 are constant, Eq. (17) is rewritten as,

$$dU_{mix} / d\eta_{O_2} = 0 \quad (18)$$

and the blow-off mixture velocity is obtained. η_{O_2} changing with U_{mix} at a con-

stant ϕ_{RZ} is shown in Fig. 6. η_{O_2} decreases with an increase of U_{mix} . Though the temperature of the recirculation zone T_{RZ} decreases with a decrease in η_{O_2} , the consumption rate (Eq. (11)) increases with an increase in density term $(P/RT_{RZ})^n$, and then, a higher feed rate is allowed. After the maximum point (o in Fig. 6) of U_{mix} , however, the consumption rate decreases due to a decrease in Arrhenius exponent term $\exp(-E/RT_{RZ})$, so that excess feed can not be allowed and the reaction stops. Consequently, the dotted line in Fig. 6 has no physical sense.

The maximum U_{mix} (Eq. (18)) is given for any ϕ_{RZ} . Blow-off limits on the U_{mix} - ϕ_{mix} plane are obtained by plotting the maximum U_{mix} as a function of ϕ_{RZ} which is related to ϕ_{mix} by Eq. (7). Since the thermochemical parameters and the aerodynamic parameters as seen in Eqs. (7) and (10) are not independent of each other, the calculation for blow-off limits must be executed for each value of U_2 and t .

7. Procedure and Results of Calculation

The consumption rate given by Eq. (11) depends on the kinetic constants, B and E . The values proposed for C_3H_8 -air mixture by Clarke et al. (10) were used in this calculation, they are

$B = 2 \times 10^9 \text{ [m}^3/\text{K}^{0.5} \text{mol} \cdot \text{s]}, n=2, \alpha=\beta=1$. The activation temperature was assumed as $E/R=2000 \text{ K}$ and experimental constant ξ was given by Eq. (10). Eq. (16) can thus be written as,

$$\begin{aligned} \eta_{O_2} &= \Phi \times 2 \times 10^9 (m+1) M_A (\rho_{F_0} + \lambda_{RZ} \rho_{A_0}) t \\ &\times (P/R)^2 \exp(-20000/T_{RZ}) x_{C_0} x_{O_2} \\ &/ (1.46 \times 10^{-2} \rho_{A_0} \rho_{RZ} \lambda_{RZ} T_{RZ}^{0.5} U_2 U_{mix}^{0.5}) \quad (19) \end{aligned}$$

The mean temperature of the recirculation zone T_{RZ} was computed by an enthalpy balance for any ϕ_{RZ} , assuming that water-gas equilibrium was realized. Thermochemical data were taken from JANAF table (11). It was assumed that heat exchange, i.e. heat recovery, took place during turbulent mass exchange between burnt gas and fresh mixture (mixture and air). Recovery temperature of fresh mixture T_{rec} , raised from

Fig. 6 Relation between η_{O_2} and ϕ_{RZ} .

room temperature T_0 , was introduced into the enthalpy balance. It is too difficult, however, to predict T_{rec} because of the lack of knowledge on the microscopic structures of turbulence. Therefore, TrZ depends not only on η_{O2} and ϕ_{RZ} , but also on burner dimensions, velocities and T_{rec} .

The procedure which predicted the blow-off limits was as follows;

(1) TrZ data set was made as functions of η_{O2} , ϕ_{RZ} and U_{mix} at constant t , U_2 and T_{rec} . A flow chart of TrZ calculation is shown in Fig. 7.

(2) Relation between U_{mix} and η_{O2} was obtained by comparison of the assumed η_{O2} and the calculated η_{O2} by Eq. (19).

(3) The maximum U_{mix} which was given by Eq. (18) was determined for a certain ϕ_{RZ} . A flow chart of the computation procedure is shown in Fig. 8.

Blow-off limits predicted in some cases of t and U_2 are shown in Fig. 9. For three cases of T_{rec} , 800, 900 and 1000 K, blow-off limits were computed and the calculated results were compared with the experimental data. Most experimental data fitted within the predicted limits in the range of $T_{rec}=800-1000$ K. The higher

T_{rec} , the greater the maximum U_{mix} (at the peak of the curve). Difference of 100 K in T_{rec} brings about a 15 % deviation in the maximum blow-off mixture velocity, U_{mix} . Generally, the prediction was able to simulate the characteristics peculiar to the double concentric jet flame.

8. Discussion

There are several uncertain factors in the blow-off concept proposed here in detail, in spite of the good agreement with the predictions of the experiment.

First, it is not actually likely that T_{rec} is constant all over the blow-off limits. TrZ becomes high with an increase in U_{mix} along the blow-off limits. This means that T_{rec} must also increase with TrZ . Consequently, T_{rec} rises as the blow-off U_{mix} approaches the maximum blow-off U_{mix} , so a more precise prediction will be close to the experimental points. The experimental data shown in Fig. 9 clearly indicate this tendency.

Another uncertain factor is the value of the global activation energy E . It is shown that some deviation from the ideal

Fig. 7 Flow chart for TrZ calculation.

Fig. 8 Flow chart for blow-off U_{mix} calculation.

Fig. 9 Predicted flame stability limits comparing with experimental results.

PSR, that is imperfect mixing in the reactor, apparently brings about a higher activation energy⁽¹²⁾. The imperfectness of mixing process must come from the flow velocities and dimension of the zone.

The third problem is in the rate limiting step reaction, which was assumed CO oxidation in this paper, in rich ($\phi_{RZ} < 1$) region. Several hydrocarbons, as intermediate products, were detected in rich region, especially near the rich blow-off limits. These products suggest that the dissociation of the original fuel is involved in the rate limiting step. Better agreement with the experimental data might be obtained from more detailed information about these problems.

9. Conclusions

The blow-off processes of a flame stabilized by the recirculation zone formed behind the burner rim are simulated theoretically. The recirculation zone can be regarded as a kind of PSR, where the reaction dominates the flame stability. Mass exchange between the recirculation zone and the outer flows determines the actual air ratio of the recirculation zone ϕ_{RZ} and feeds the reactants to the region. The feed rate of the reactants with turbulent mass exchange can be determined by the measurement of the mean residence time in the recirculation zone⁽²⁾. The adequacy of the blow-off model is proved by the good agreement between the prediction and the experiment of the blow-off limits.

Other conclusions drawn from this study are summarized as follows;

(1) Intense reaction depending on the actual air ratio ϕ_{RZ} takes place in the recirculation zone and determines the temperature and the gas component concentrations in the zone, so that it dominates flame stability.

(2) Blow-off always occurs when the reaction in the recirculation zone is in-

terrupted. The reduction of the reaction efficiency due to excess supply of reactants causes the interruption.

(3) The mean residence time in the recirculation zone is considered to be a function of the burner dimension, the annular jet velocity and the mixture velocity.

(4) Reactants (mixture and air) are preheated by heat exchange with the turbulent mass exchange. The blow-off prediction yields good results when T_{rec} , which is the temperature of the preheated reactants, is assumed to range 800-1000 K.

(5) In order to improve the accuracy of the blow-off prediction, it is necessary to evaluate T_{rec} and the imperfectness of mixing in the recirculation zone, theoretically or experimentally.

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