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EXPERIMENTAL AND THEORETICAL STUDY ON THE FLAME STABILIZATION BY RECIRCULATION BEHIND A BLUFF-BODY

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ABSTRACT

An experimental investigation and analytical description have been carried out on the flame stabilization by recirculation behind a bluff-body flame holder. The blowout limits of flames and the length of the recirculation zone have been investigated for cylindrical and spherical bluff-body flame holders. Also, measurements of the influence of the flame holder geometry on the lean blowout limits as well as on the rich blowout limits have been carried out.

In the theoretical study, a two-dimensional flow model to describe the mechanism of the flame stabilization by recirculation behind a bluff-body has been developed. In this model, the process of flame stabilization is governed by the balance between the rates of turbulent mixing and chemical reactions in the shear layer at the recirculation zone boundary. The predicted blowout limits of flames have shown a qualitatively agreement with the observed ones.

NOMENCLATURE

b	: Width of the shear layer
C	: Constant in Eq. (12)
D	: Diameter of the bluff-body
E	: Activation energy
F	: Preexponential factor
h_s	: Stagnation enthalpy
L	: Length of the recirculation zone
ℓ	: Prandtl's mixing length
m	: Mass fraction
N	: Constant in Eq. (10)
p	: Pressure
R	: Universal gas constant
r	: Radial distance
r_w	: Radial distance from the wall, Eq. (10)
S	: Rate of generation
T	: Temperature
u	: Axial component of velocity
u_a	: Flow velocity at the upstream section
u_r	: Reverse flow velocity
v	: Radial component of velocity
x	: Axial distance
α	: Stoichiometric mass ratio of fuel to oxygen
ε	: Eddy diffusivity

μ_{eff} : Effective viscosity
ρ : Density
$\sigma_{h,eff}$: Effective Prandtl number
$\sigma_{m,eff}$: Effective Schmidt number
Φ : Equivalence ratio
ϕ : Combined mass fraction, Eq. (5)

Subscripts

ex : Outer boundary of the shear layer
fu : Fuel
i : i-th species
in : Inner boundary of the shear layer
ox : Oxygen
pr : Combustion products, or nitrogen

INTRODUCTION

Under sufficient fast flow conditions in modern propulsion engine combustors, a recirculation pattern of flow is established behind a bluff-body flame holders. The recirculation zone provides a station where reactions can take place. The recirculation zone and surrounding flow exchange materials and heat with each other. In this process, the unburned mixture is supplied continuously to the recirculation zone while hot combustion gas and radicals are supplied to the surrounding flow.

The attractive features of the flame stabilization due to the formation of recirculation flow zone involving both diffusion and premixed flame combustors have been studied by numerous investigators, [1] and [2]. According to Zukoshi and Marble [3], the fresh mixture entering the shear layer is ignited by the hot combustion products entrained therein from the recirculation zone. The burning mixture then flows downstream within the shear layer and, in turn, ignites neighbouring pockets of the fresh mixture. When the fully burned gases leave the shear layer, some portion recirculates back into the wake region, thereby providing a continuous source of ignition to the incoming fresh mixture. On the other hand, Lewis and von Elbe [1] tried to explain the blowout behaviour of flames from the critical stretching rates of the flames in the shear layer at the wake boundaries.

Weiss et al. [4] showed that the blowout limits of the bluff-body stabilized flames are well correlated to those of a well-stirred reactor for various fuels. Longwell and Weiss [5] have also showed that the blowout behaviour of a well-stirred reactor is governed by the balance between the rates of chemical reactions and fresh mixture supply.

The process of turbulent exchange behind a flame holder has been investigated experimentally by Bovina [6] and Winterfeld [7]. Their results show shat turbulent exchange is determined by the geometry of the recirculation zone and the residence time of the gas particles within this zone. The mean residence time, which is an indication of how fast the heat and mass of the recirculation zone are transferred to the shear layer, is found to be inversely proportional to the flow velocity. The residence time appears to be independent of mixture ratio and to decrease with main stream turbulence intensity. Levebvre et al.[8] have developed a method for estimating the fraction of mixture entrained into the recirculation zone of a bluff-body flame holder.

The mechanism of flame blowout for a spray flames of the within-recirculation zone fuel injection systems has been investigated experimentally by the author [9].

In this study, an experimental investigation and analytical description have been carried out on the flame stabilization by recirculation behind a bluff-body flame holder. The blowout limits and the length of the recirculation zone have been investigated for cylindrical and spherical bluff-body flame holders. Also, measurements of the influence of the flame holder geometry on the lean and rich blowout limits have been carried out.

A simplified analytical model of flame stabilization behind a bluff-body flame holder has been tried on the basis that the blowout behaviour is governed by the balance between the chemical kinetics and turbulent mixing in the shear layer at the recirculation zone boundary. In this model, the conservation laws for the turbulent flow field with chemical reaction are used in terms of elliptic partial differential equations. Also, the reverse flow region in the central part of the recirculation zone is treated as a well-stirred reverse flow region and the boundary layer approximation is applied to the forward flow region.

EXPERIMENTAL STUDY

A schematic diagram of the experimental apparatus is shown in Fig.1. Used air supplied by the air blower was controlled and measured through a control valve and metering orifice plate. The fuel, commercial grade butane, was supplied from the fuel vessel to the air-fuel mixing chamber through a pressure regulator, a control valve and a fuel flow-meter. The air-fuel mixture was then introduced at relatively flat velocity distribution through the combustion duct. The combustion duct was made from a pyrex glass tube with diameter of 75 mm, lined in its upper section with a thin steel liner tube. The test section was kept without steel liner to facilitate the experimental observations and photographing requirements. A stabilizer bluff-body flame holder suspended by a fine steel wire has been placed on the axis at the upstream section of the combustion duct. Three cylindrical and three spherical flame holders were used in this work. The cylindrical flame holders were made from a three steel bars of equal lengths, 12 mm, and with diameters of 6 mm, 10 mm, and 14 mm. The spherical flame holders were made from a three steel balls with diameters of 6 mm, 10 mm and 14 mm.

Critical equivalence ratios at lean and rich blowout limits of flames were determined by controlling the fuel supply flow rate with the air supply flow rate kept constant. The recirculation zone length was determined by applying the sodium chloride (NaCl) flame reaction technique. When the sodium cloride

Under these assumptions, the governing equations for the forward flow region are as the following:

Continuity equation;

$$\frac{\partial}{\partial x}(\rho u r) + \frac{\partial}{\partial r}(\rho v r) = 0 \qquad \ldots (1)$$

Momentum equation;

$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(r \mu_{eff} \frac{\partial u}{\partial r}\right) - \frac{\partial p}{\partial x} \qquad \ldots (2)$$

Species equation;

$$\rho u \frac{\partial m_i}{\partial x} + \rho v \frac{\partial m_i}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\mu_{eff}}{\sigma_{m,eff}} \frac{\partial m_i}{\partial r}\right) + S_i \qquad \ldots (3)$$

Energy equation;

$$\rho u \frac{\partial h_s}{\partial x} + \rho v \frac{\partial h_s}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\mu_{eff}}{\sigma_{h,eff}} \frac{\partial h_s}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left[r \mu_{eff}\left(1 - \frac{1}{\sigma_{h,eff}}\right)\frac{\partial (u^2/2)}{\partial r}\right] \ldots (4)$$

The suffix i takes a value of 1 or 2, representing fuel or the combined mass fraction ϕ, where ϕ is defined as;

$$\phi = m_{ox} - \alpha m_{fu} \qquad \ldots (5)$$

where m_{ox} and m_{fu} are the mass fraction of oxygen and fuel respectively, and α is the stoichiometric mass ratio of fuel to oxygen. The mass fraction of the combustion products (or nitrogen) m_{pr} is determined from the following relation;

$$m_{pr} = 1 - m_{fu} - m_{ox} \qquad \ldots (6)$$

The generating rate of fuel S_{fu} which appears in Eq. (3) is described in the following Arrhenius expresion;

$$S_{fu} = - F p^2 m_{fu} m_{ox} \exp(-E/RT) \qquad \ldots (7)$$

where F is the preexponential factor, p is the pressure, E is the activation energy, R is the universal gas constant and T is the temperature.

The eddy diffusivity model [10] is adopted to characterize the turbulence process. Then, the eddy diffusivity ε is given by the relation;

$$\varepsilon = k\, b \left| u_{ex} - u_{in} \right| \qquad \ldots (8)$$

where the eddy diffusivity ε is assumed to be uniform in a cross section except in the near-wall regions. The width b of the

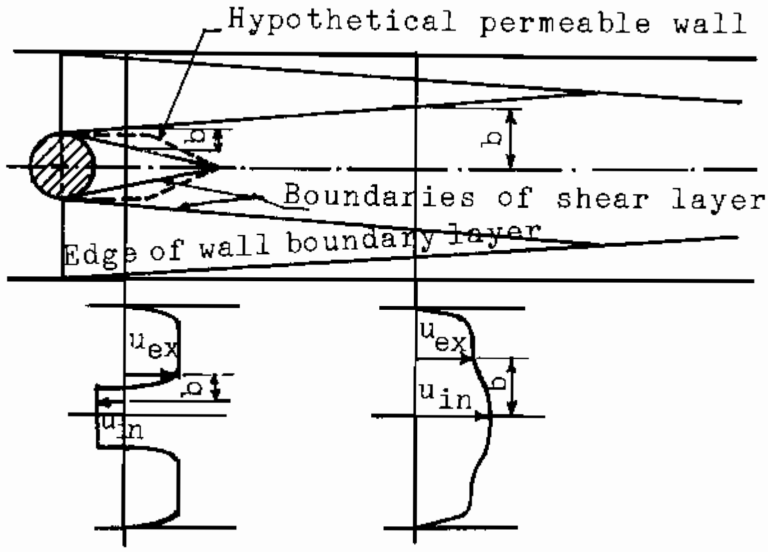


Fig. 4 Definition of the shear layer parameters

shear layer and the velocities u_{in} and u_{ex} at its inner and outer boundaries respectively, are defined as shown in Fig. 4. The constant k is taken = 0.002.

The eddy diffusivity in the boundary layer on the duct wall is estimated from the Prandtl's mixing length hypothesis;

$$\varepsilon = \ell^2 / (du/dr) \qquad \ldots (9)$$

where ℓ , the mixing length, is defined as;

$$\ell = N\, r_W \qquad \ldots (10)$$

where the constant N is taken = 0.345 and r_W is the distance from the wall.

The effective viscosity μ_{eff} is estimated from the following relation;

$$\mu_{eff} = \rho\, \varepsilon \qquad \ldots (11)$$

Numerical analysis was carried out using a modified version of the GENMIX 4 program of Patankar and Spalding[11] for boundary layer models. The calculations were carried out for specific values of the flow velocity u_a (uniform distribution), equivalence ratio Φ and the temperature T_a in the initial cross section of the bluff-body center. The wall temperature T_W, the reverse flow velocity u_r and the recirculation zone length L are also incorporated. The thermodynamic properties and reaction parameters employed are taken from Ref.[12]. The first approximation of the state (values of h_s, m_{fu} and ϕ) in the reverse flow region is taken equal to the equilibrium state of the approaching mixture. When integration step reaches the end of the reverse flow region, the state in this region is reestimated considering the exchange of enthalpy and species between this region and the surrounding stream through their boundaries.

If the reestimated state coincides with the first approximation, integration is continued downstream. If not, the same procedure is repeated replacing the first assumption with the just reestimated state. In this analytical model, the parameters pertaining to the reverse flow region, such as the length L and the reverse flow velocity u_r, can not be determined theoretically. In the present study, the values of the recirculation zone length were taken from the experimental results. The mean value of the reverse velocity was estimated using the next relation;

$$u_r = C\, u_a \qquad \ldots (12)$$

where C is a constant taken = -0.5.

RESULTS AND DISCUSSIONS

The experimental results of the variation of the values of the recirculation zone length L for the used cylindrical and spherical bluff-body flame holders are shown in Figs. 5 and 6. Figure 5 shows the effect of the flow velocity on the length of the recirculation zone. From this figure, it can be noted that the length of the recirculation zone is significantly influenced by the geometry of the bluff-body and the flow velocity. The recirculation zone is increased by either increasing the size of the bluff-body or the velocity of the flow. Fig. 6 shows the effect of the equivalence ratio Φ on the length of the recirculation zone. The equivalence ratio has no noticeable effect on the length of the recirculation zone, although the length is decreased slightly around the stoichiometric ratio. Also, the length of the recirculation zone is slightly higher with cylindrical bluff-body flame holders rather than with sperical ones.

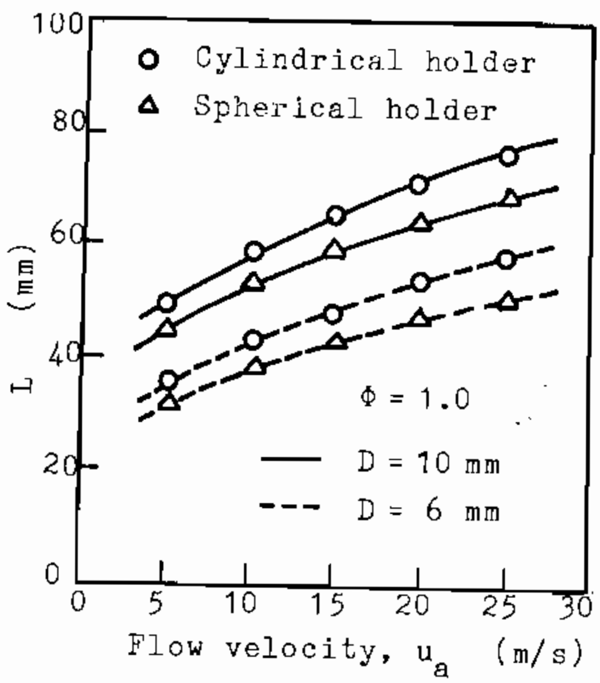


Fig. 5 Effect of flow velocity on the length of the recirculation zone.

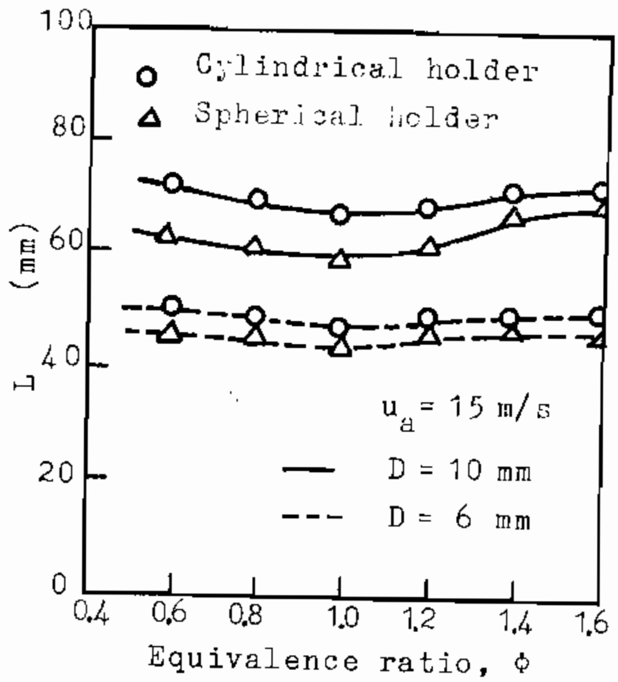


Fig. 6 Effect of equivalence ratio on the length of the recirculation zone.

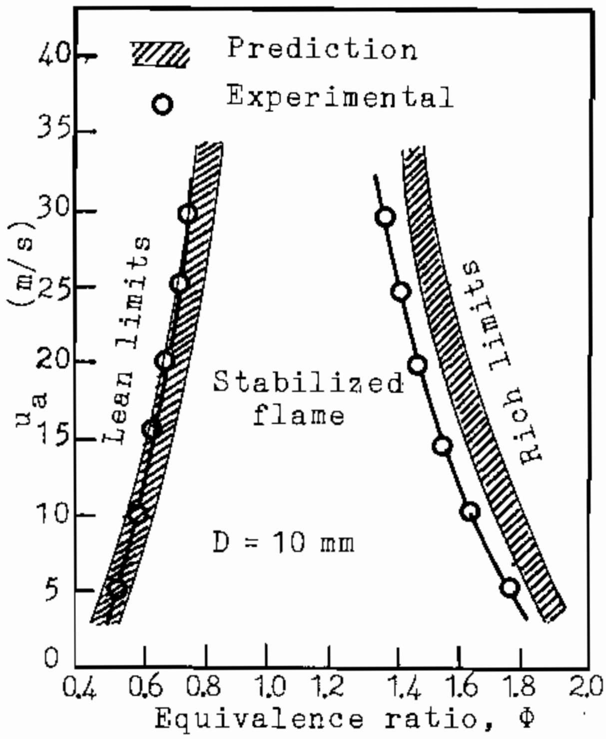


Fig. 7 Predicted and observed blowout limits with a cylindrical flame holder.

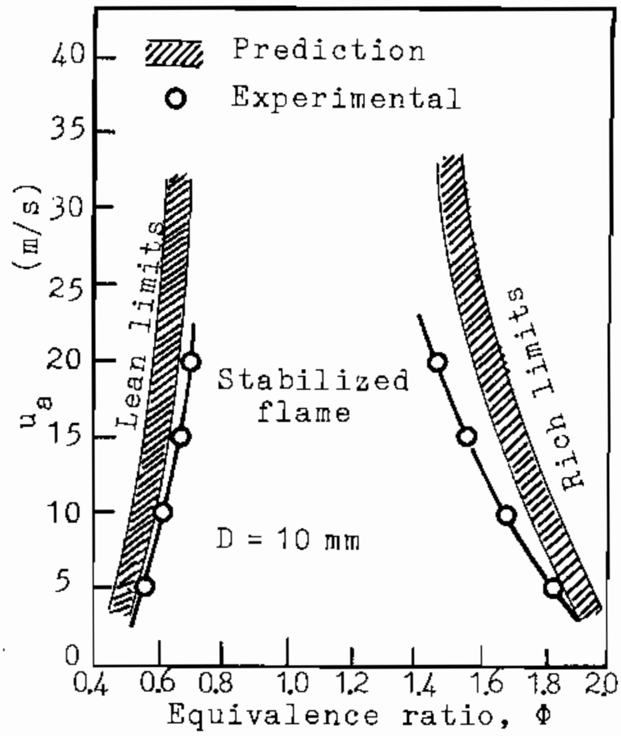
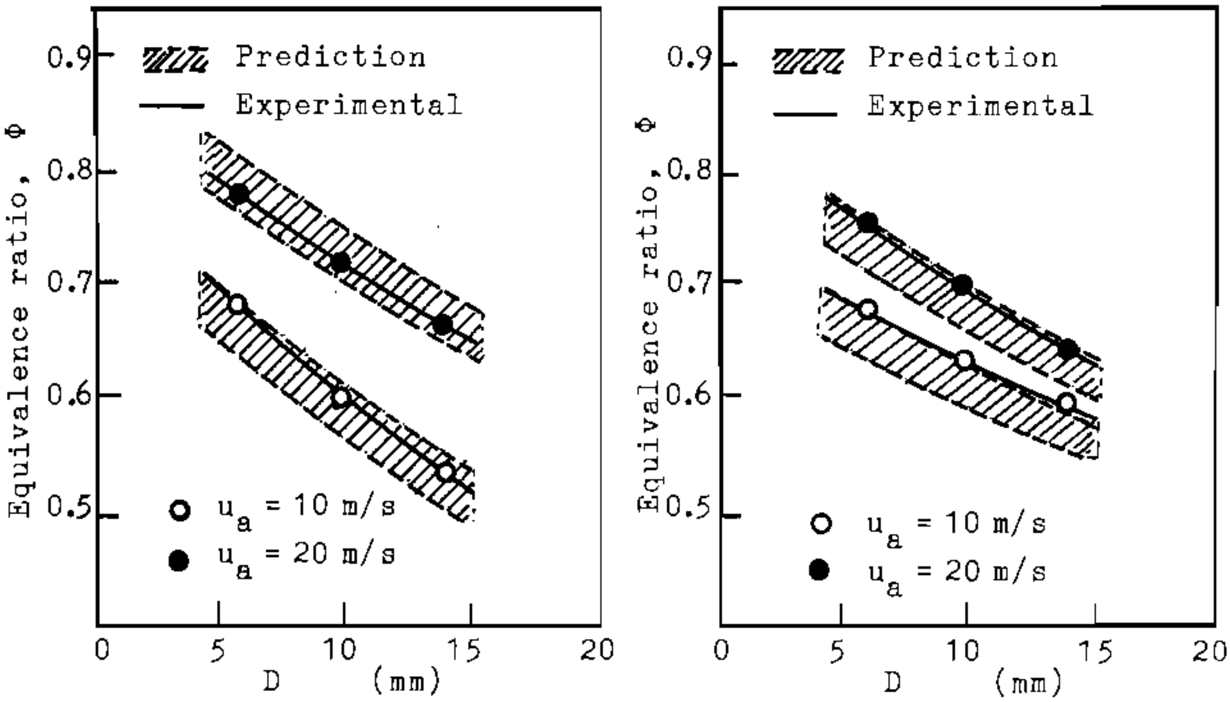


Fig. 8 Predicted and observed blowout limits with a spherical flame holder.

A comparison between the predicted and experimentally observed blowout limits for the used cylindrical and spherical bluff-body flame holders is shown in Fig. 7 and Fig. 8, respectively. In the analytical model, the blowout limits of a flame have been determined by the criterion whether the combustion efficiency continues to increase downstream of the recirculation zone or not. The width of the dashed areas in the figures is corresponding to the steps of the blowout limits searching process.

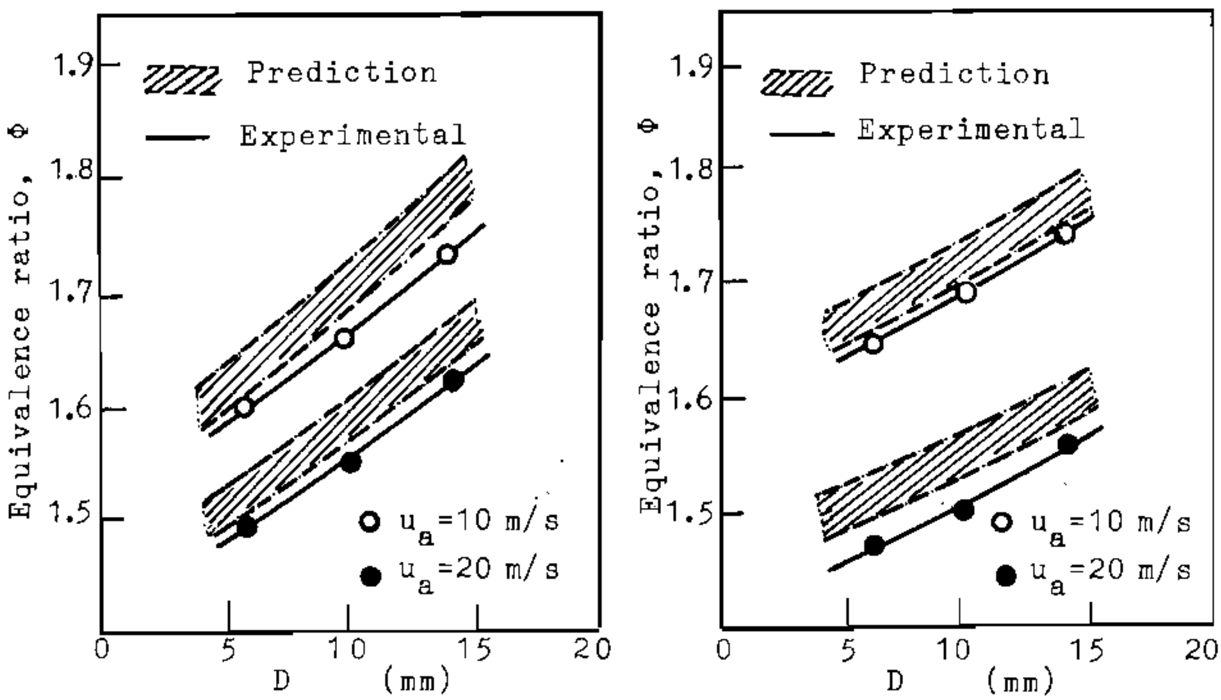
Although a simplified analytical model has been adopted in this study, the predicted blowout behaviour shows a remarkable agreement with the observed one. This result seems to suggest the validity of the concept that the flame stabilization behind a bluff-body is governed by the balance between the rates of turbulent mixing and chemical reaction in the shear layer at the recirculation zone boundary. However, the hypothesis that the blowout behaviour of flames depends on the eddy stretching within the turbulent mixing zone should be involved for more accurate predictions.

Also, predicted and experimentally measured influence of the used bluff-body flame holder geometry on lean blowout limits and rich blowout limits is shown in Fig. 9 and Fig. 10 respectively. From both figures, it can be noted that the



(a) Cylindrical flame holders (b) Spherical flame holders

Fig. 9 Predicted and observed influence of flame holder geometry on lean blowout limits.



(a) Cylindrical flame holders (b) Spherical flame holders

Fig. 10 Predicted and observed influence of flame holder geometry on rich blowout limits.

blowout limits are extended by increasing the flame holder size. Increasing of flame holder size will improve stability hy extending the residence time of the reactants in the recirculation zone. Flame holders that deflect the flow to the greatest extent produce the longest residence times and the widest stability limits.

CONCLUSIONS

An experimental and theoretical study on the flame stabilization by recirculation behind a bluff-body flame holder have been carried out. The length of the recirculation zone and the blowout limits of flames have been investigated for cylindrical and spherical flame holders. A two-dimensional axisymmetric flow model has been developed where both transport processes and a finite-rate one-step reaction are taken into account simultaneously. The predicted blowout limits of flames show an excellent qualitative agreement with the observed ones. Although several problems are left unsolved, such as the turbulent transport coefficients, chemical reactions in a turbulent flow field and so on, at least the essential mechanism of flame has been made clear.

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