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

S. H. El-Emam *

ABSTRACT

An experimental investigation and analytical description have been carried out on the flame stabilization by recirculation behind a bluff-body flame holders. The blowout limits of flames and the length of the recirculation zone have been investigated for cylinderical 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.

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* Lecturer, Department of Mechanical Power Engineering, Mansoura University, El-Mansoura, Egypt.

INTRODUCTION

Under sufficiently 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 contiuously 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 Zukowski 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 neighoring pockets of 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 reaction 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 that turbulent exchange is detemined 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. Lefebvre 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 holders. The blowout limits and the length of the recirculation zone have been investigated for cylinderical and spherical bluff-body flame holhers. 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 behined 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, control valve and fuel flow-meter. The air-fuel mixture was then introduced at relatively flat velocity distribution

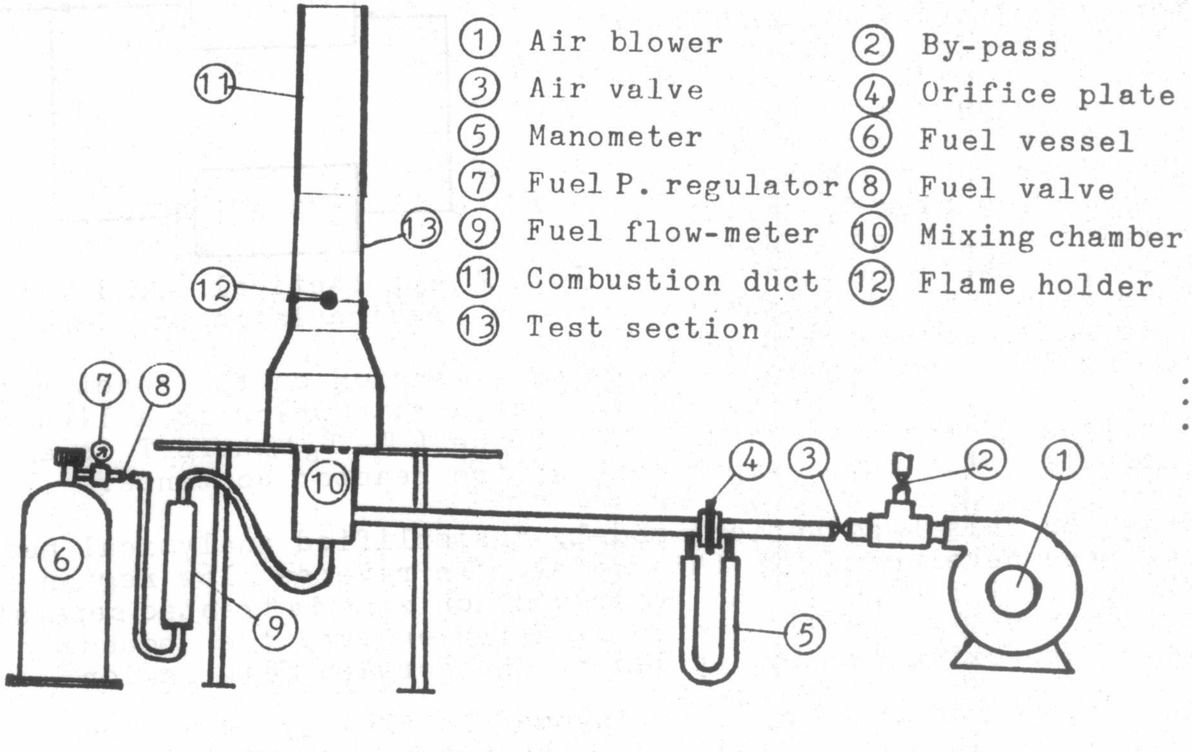


Fig. 1. Experimental apparatus

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 observation and photographing requirements. A stabilizer bluff-boddy flame holder suspended by a fine steel wire has been placed on the axis at the upstream section of the combustion duct. Three cylinderical and three spherical flame holders were used in this work. The cylinderical 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 steel balls with diameters of 6 mm, 10 mm and 14 mm.

Critical equivatence 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 the sodium chloride ($NaCl$) flame reaction technique. When the sodium chloride solution was injected downstream of the end of the recirculation zone, no luminescence was observed in the recirculation zone. But when the solution was injected in the recirculation zone, the luminescence spread over the recirculation zone. The transition point is corresponding to the end of the recirculation zone.

THEORETICAL STUDY

A hypothetical model of a longitudinal mixer and reactor associated with recirculation regime is shown in Fig. 2. A mass flow rate $\dot{m}_s$ of the fresh reactants at a temperature T_s enters into the mixer to mix well with a mass flow rate $\dot{m}_r$ of the reactor output at temperature T_r. The resultant mixture of $\dot{m}_s + \dot{m}_r$ at T_m spilts into two branches one of which is fed into the reactor. Focusing attension on the reactor, heat is lost by it to the mixture at a rate which is a linear function of the temperature difference ($T - T_s$) where T is a characteristic mean temperature of the reactor contents.

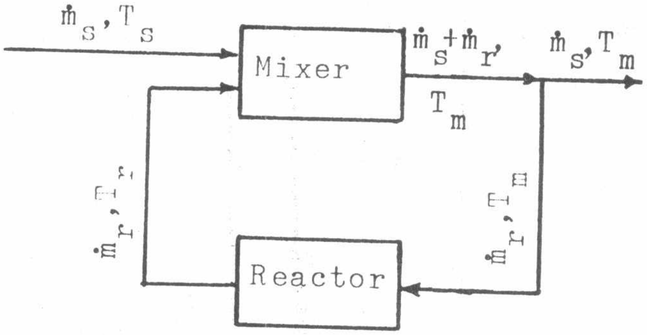


Fig. 2 Hypothetical model for recirculation/mixing.

Based on this hypothetical model, a simplified analytical model has been developed. In this model, the reverse flow region in the central region of the recirculation zone is treated separately as a well-stirred reverse flow region and the boundary layer approximation is applied to the forward flow region.

The analytical model of an axisymmetric flow field around a bluff-body is shown in Fig. 3. The reverse flow region in the wake of the bluff-body is covered with a hypothetical permeable wall which is transparent to mass and heat exchanges. A recirculation flow is formed around this region by effusing out the recirculated burned gas and taking in a part of the surrounding stream. Then the flame is stabilized by this recirculating flow. The reverse flow region is treated as a well-stirred reactor in which the temperature and composition are uniform and in an equilibrium state of estimated combustion efficiency.

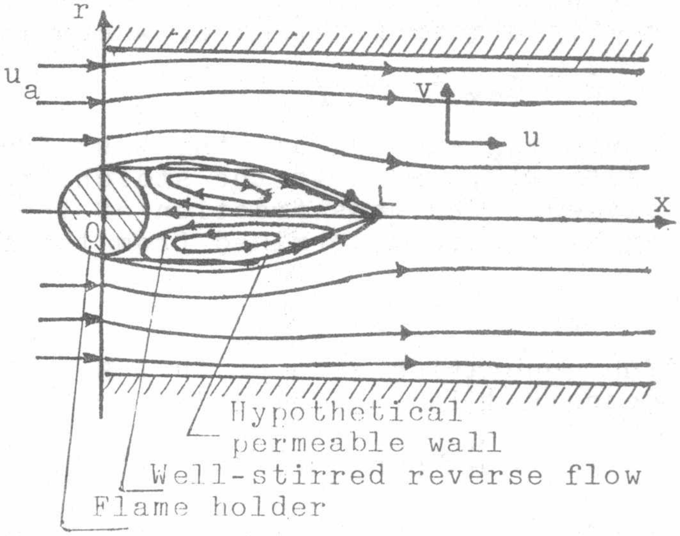


Fig. 3 Analytical model

The following assumptions are introduced:

(1) No reverse flow occurs outside the reverse flow region and the boundary layer approximation is applied to the forward flow region.
(2) The combustion reaction is of one-step, to which Arrhenius rate law in terms of time-mean values of temperature and species concentrations is applied.
(3) Turbulent diffusion predominates over the molecular one.
(4) The effects of radiative heat transfer and buoyancy are small.
(5) No pressure gradient exists in radial direction .
(6) The effective Lewis Number is unity.

Under these assumptions, the governing equations for the forward region are as 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;

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

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;

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

The generation rate of fuel S_{fu} which appears in Eq. (3) is described in the following Arrhenius expression as follows;

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

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 turbulent process. Then, the eddy diffusivity ε is given by the relation;

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

where the eddy diffusivity is assumed to be uniform in a cross section except in the near-wall regions. The width b of the shear layer and the velocities u_{in} and u_{ex} at its inner and outer boundaries respectively, are defined as shown in Fig. 4, and 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;

$$\varepsilon = \ell^2 / (du/dy) \qquad \dots (9)$$

where ℓ (the mixing length) is defined as;

$$\ell = K\, Y_W \qquad \dots (10)$$

The constant K=0.435 and Y_W is the distance from the wall.

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

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

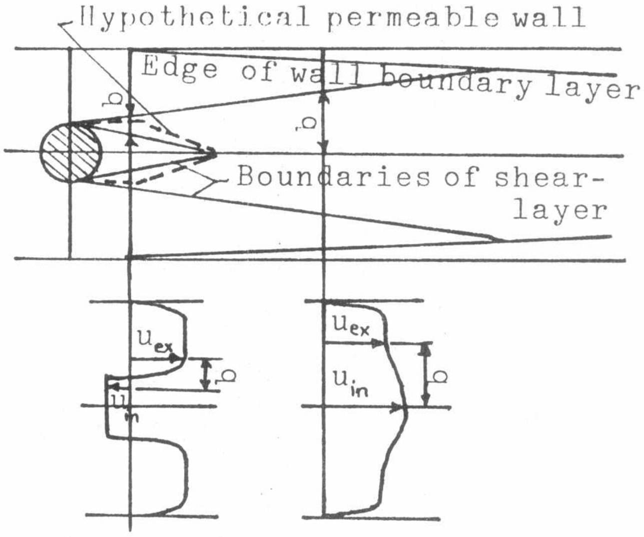


Fig. 4 Definition of the shear layer

Numerical analysis was carried out using a modified version of the GENMIX 4 program of Patankar and Spalding [11] for boundary layer models. The calculation 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.

In this study, the recirculation zone length L values were taken from the experimental results. The reverse flow velocity was estimated from the relation;

$$u_r = -0.5\, u_a \qquad \ldots (12)$$

RESULTS AND DISCUSSIONS

The variation of the length of the recirculation zone for the used cylinderical and spherical bluff-body flame holders are shown in Figs. 5 and 6. Fig. 5 shows the effect of the flow velocity on the length of the recirculation zone. From this figure it can be noted that the recirculation zone length 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 on the length of the recirculation zone. The equivalence ratio has no noticable effect on the length of the recirculation zone, although the length decreases slightly around the stoichiometric ratio. Also the length of the recirculation

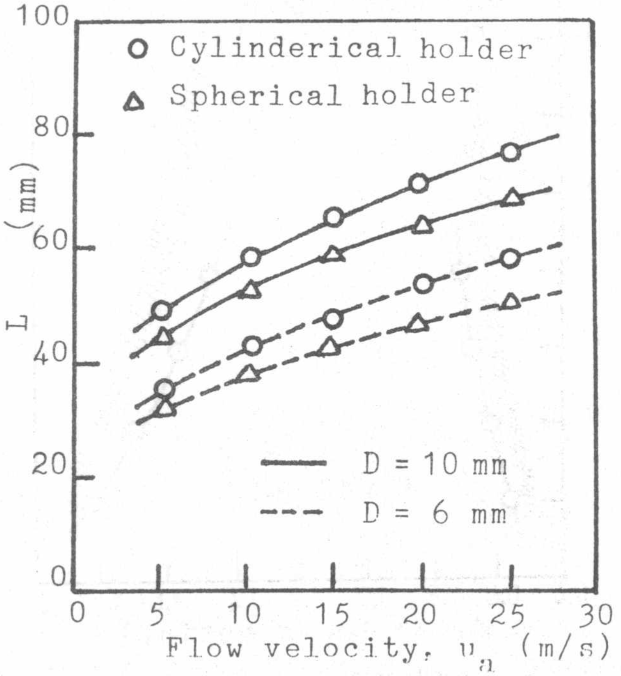


Fig. 5 Effect of flow velocity on the length of the recirculation zone.

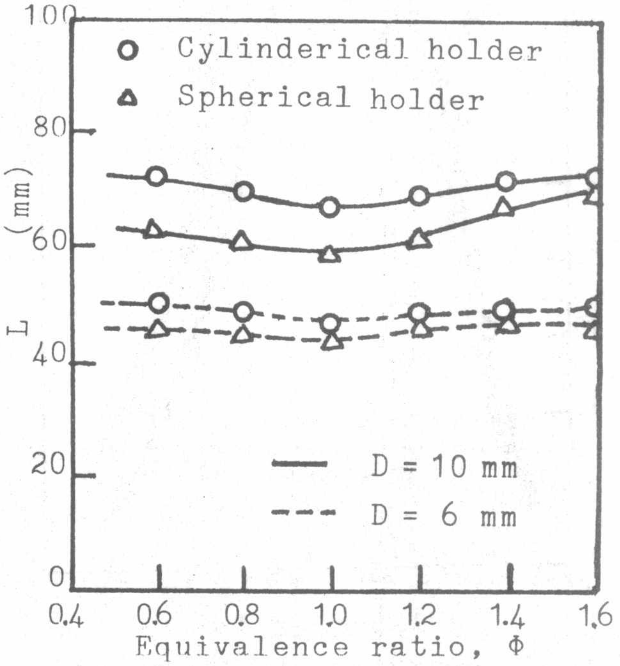


Fig. 6 Effect of equivalence ratio on the length of the recirculation zone.

zone is slightly higher with cylinderical flame holders rather than with spherical flame holders.

A comparison between the predicted and observed blowout limits for the used cylinderical 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 searching blowout limits process.

Predicted and experimentally measured influence of flame holder geometry on lean blowout limits and rich blowout limits is shown in Fig. 9 and Fig. 10 respectively. It can be noted that, the blowout limits are extended by increasing the flame holder size. Increasing of flame holder size will improve stability by 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.

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 rated of turbulent mixing and chemical reaction in the shear layer at the

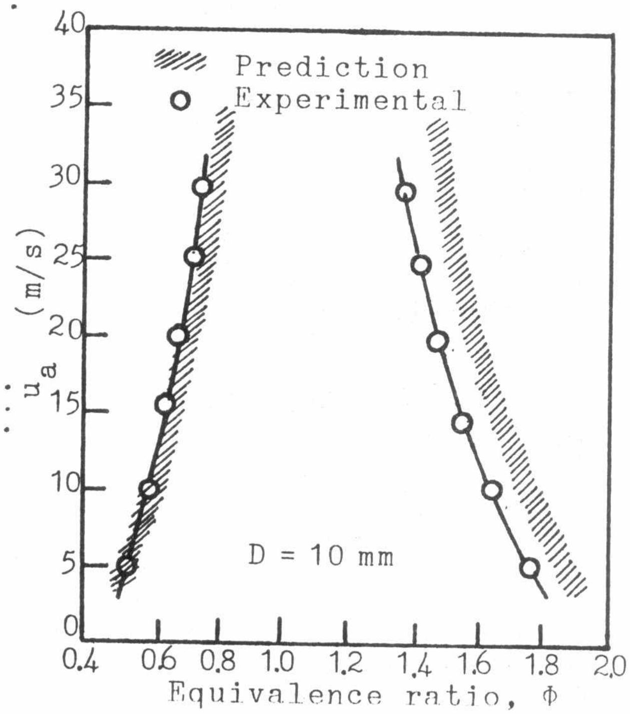


Fig. 7 Predicted and observed blowout limits with cylinderical flame holder.

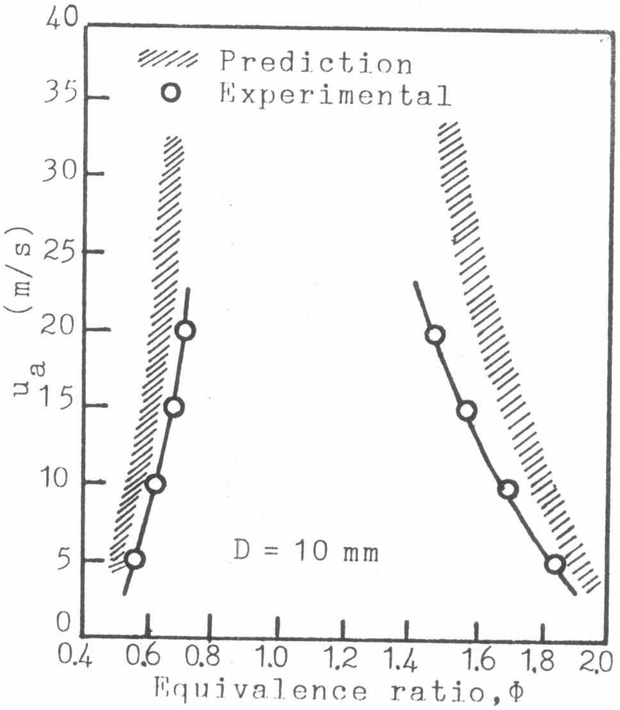
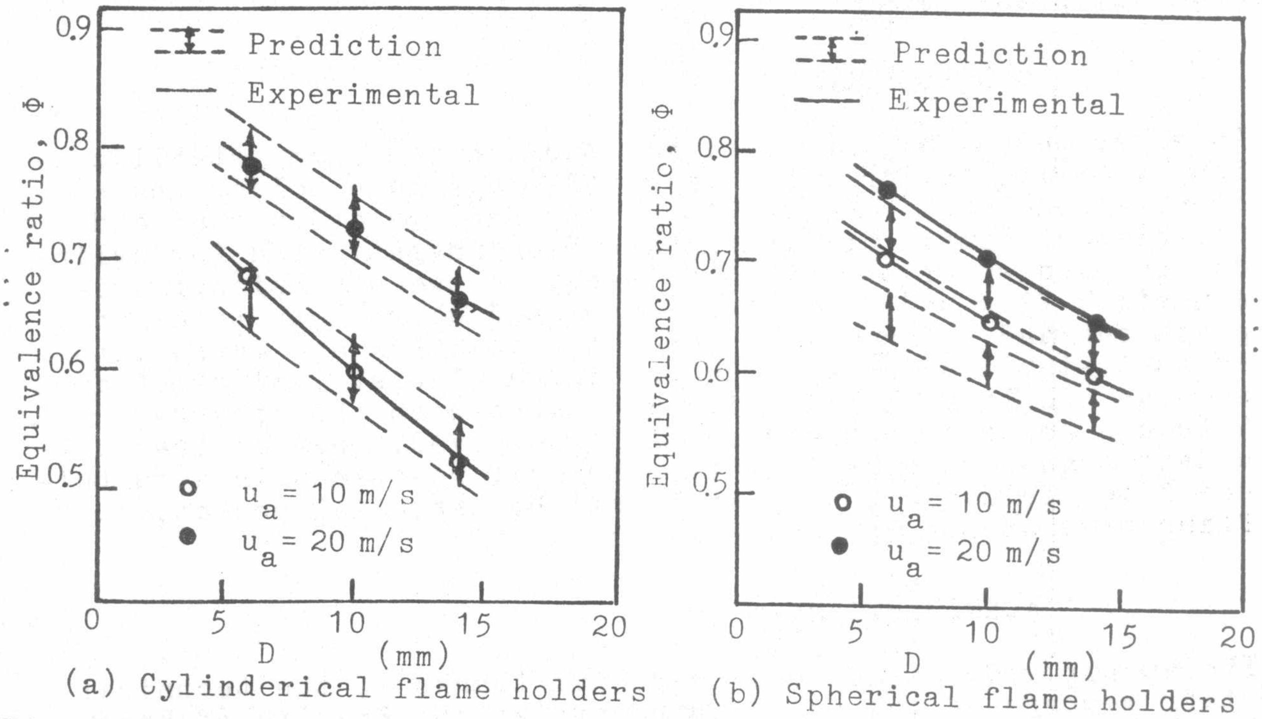
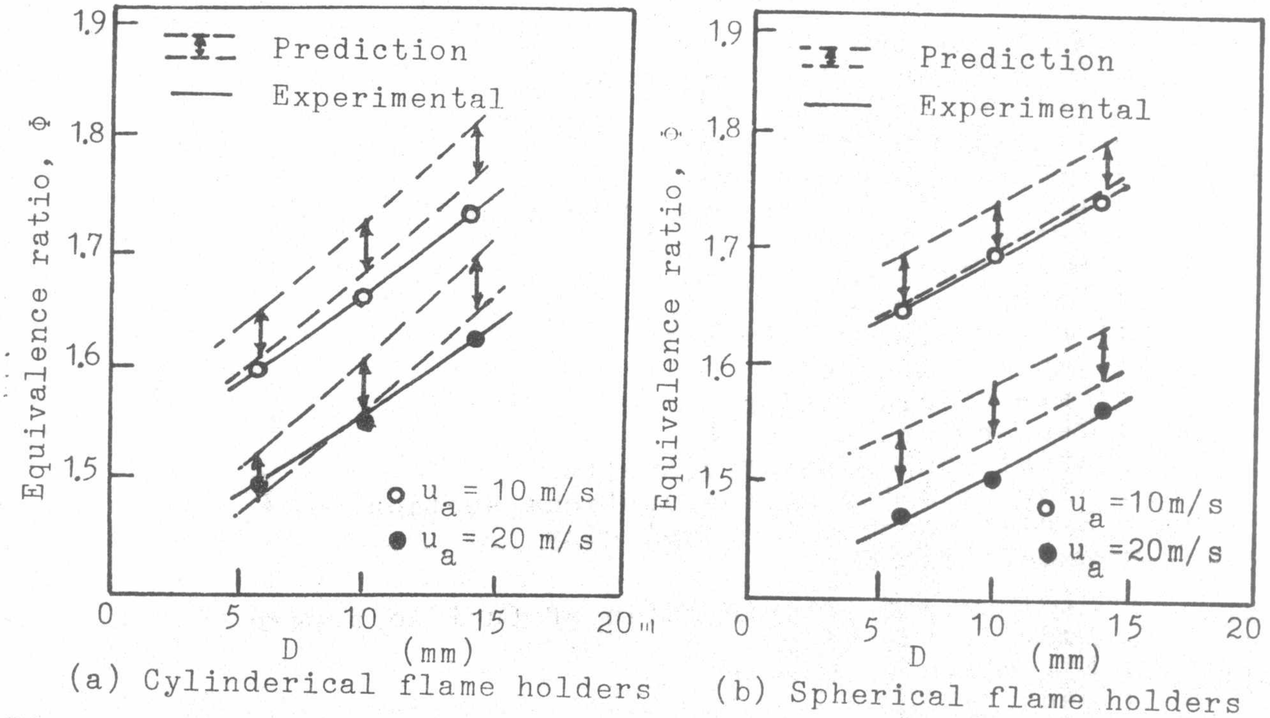


Fig. 8 Predicted and observed blowout limits with spherical flame holder.



(a) Cylinderical flame holders (b) Spherical flame holders

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



(a) Cylinderical flame holders (b) Spherical flame holders

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

recirculation zone boundary. However, the hypotheses that the blowout behaviour of flames depends on the eddy stretching within the turbulent mixing zone should be involved for more accurate predictions.

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 cylinderical 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 turbullent transport coefficients, chemical reactions in a turbulent flow field and so on, at least the essential mechanism of flame blowout has been made clear.

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NOMENCLATURE

b : Width of the shear layer
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
p : Pressure
R : Universal gas constant
r : Radial distance
S : Rate of generation
T : Temperature
u : Axial component of velocity
u_a : Flow velocity at the upstream section
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)
r : Reverse flow

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