AN EXPERIMENTAL INVESTIGATION FOR THE INFLUENCE OF FLAME HOLDER GEOMETRY ON FLAME STABILITY OF PREMIXED MIXTURE

Reda I. El-Ghnam, Khairy H. El-Nagar, Eed A. Abdel-Hadi., and Ismail M.M. ElSemary

Benha University, Faculty of Engineering at Shoubra, Mechanical Department

ABSTRACT

The objective of reaching stable combustion has led to intensive studies of the processes involved in flame stabilization using flame holders. In the present work flame stabilization using flame holders is investigated to study the flame stability limits for a free jet premixed flame using a central flame holder burner. The stability limit (blow off) is examined through changing some parameters in particular flame holder geometry (disc and cone of 90°and 120°apex angle) with different diameters, blockage ratio of the flame holder and the burner exit velocity. The effect of these parameters on the flame stability, recirculation zone length and residence time is discussed. An experimental test rig is constructed to fulfill these objectives and different measurements are recorded and analyzed. The study showed that the flame holder has an impact on the recirculation zone, which leads to an improvement in the residence time of the hot gases, and also an increase in the heat and mass exchange between hot gases and reactants, and hence improving the flame stability. The blockage ratio gives a noticeable improvement on the flame stability limit. Disc flame holder showed better behavior than the cone flame holder regarding flame stability limit under the different operating conditions.

Keywords: flame stability limits; flame holder; disc and cone geometries; premixed flame; recirculation zone; residence time.

1. INTRODUCTION

Flame stability in combustion chambers of gas turbines and industrial furnaces is a very important factor to achieve better performance. The stability limit of the premixed flames has been studied by many investigators. The effects of the different parameters on flame stability presented by the previous investigators aresummarized in the following part.

Longwell [1] has mentioned in an early study that the reaction zone behind a flame holder is considered as a homogenous chemical reactor that helps in flame stability. After examining heat release from this zone and comparison with the estimated heat released by turbulent flame fronts, it was concluded that the reaction zone would have to be almost a continuous turbulent combustion wave to release the observed energy. Although his proof is not rigorous, his contention is that the fluid mechanical mixing rates of gases in the reaction volume are much higher than the chemical reaction rates.

Fastre[2] studied experimentally the mechanism of flame stabilization by bluff bodies. In this investigation the geometry of the flame in the stabilization region is examined by means of photographic and probing techniques. The results of the studies showed conclusively that a constant blockage ratio, the wake geometry scales behave linearly with the flame holder size. The observed square root dependence on the characteristic wake length, and hence on the blow off velocity, is shown to be directly dependent on the blockage effects.

Radhakrishnan et al. [3] had performed an experimental work on a constant cross-sectional area tubular combustor. The primary variables varied were the reference velocity, mixture temperature and the length over which the fuel and air were allowed to mix. The aim of varying the premixing length was to study the effects of small-scale concentration non-uniformities on the lean ignition and blow off limits. It was mentioned that the length of the recirculation zone downstream of a flame holder is a more appropriate length scale for defining the flame stability characteristics than its geometric size, although the latter is a more easily measurable quantity.

Tabaczynski et al. [4] had developed a correlation for the blow off velocity using flame holderstabilized premixed turbulent flames. An important obtained conclusion from their study is that the velocity in the plane of maximum flame holder blockage is a better measure than the approach flow velocity for determining stability. Also, the length of the recirculation zone is a more appropriate length scale for defining the flame holder stability characteristics than its geometric size..

Maria and Fernandez [5] had determined the lean combustion limits for a premixed pre-vaporized propane air mixture with flat plate flame stabilizers. Experiments were conducted in a constant area flame tube combustor utilizing flame holders of varying percentages of blockage and downstream counter bore. They concluded that an increase in mixture velocity causing increase in the equivalence ratio blow off limits, despite the flame holder geometry or the percentage of blockage. This necessity for richer mixtures is attributed to faster mixing rates and smaller residence times.

Gil et al. [6] have studied experimentally the flame stabilization and flow field characteristics of premixed flames in an axisymmetric curved-wall jet burner. Results showed that the blow off velocity is much higher and the flame height is reduced significantly as compared with the tube jet burner. It is noticed that the condition of maximum blow off velocity occurs when the mixture is rich and the equivalence ratio increases as the nozzle exit area decreases.

Chaparro and Cetegen [7] investigated the flow field characteristics of flame holderstabilized conical premixed propane air flames. This experimental finding on the blow off characteristics of conical premixed flames anchored at their apex by three different flame holders' rod, disk, and cone in the presence of upstream velocity oscillations. Velocity measurements were made for different mixture velocities with the three flame holder. Upstream velocity oscillations were introduced to determine the flame blow off characteristics under oscillatory flow conditions. At flow oscillation frequencies of 200 to 400 Hz, the flame breaks into coherent structures starting at about two bluff body diameters downstream of the flame holder. Instantaneous strain rate along the flame front shows highly varying positive and negative strain rates whose magnitude can be as high as 15000 s^{-1} for mixture approach velocity of 15 m/s.

Swetaprovo et al. [8] performed experiments to determine the blow off equivalence ratios for lean premixed conical flames for different mixture approach velocities ranging from 5 to 16 m/s in the presence of spatial mixture gradients and upstream velocity modulation. Conical flames were anchored on a disk shaped flame holder that was attached to a central rod in the burner nozzle. A combustible propane air mixture was flowed through a converging axisymmetric nozzle with a concentric insert, allowing radial mixture variation by tailoring the composition in the inner and outer parts of the nozzle. The radial mixture profiles were characterized near the location of the flame holder by laser Reyleigh light scattering. Additionally, a loudspeaker was fixed at the nozzle base allowing introduction of periodic velocity oscillations with amplitude of 9% of the mean flow velocity up to a frequency of 350 Hz. Similar investigations were reported by many other authors as given in references [9] to [16].

2. EXPERIMENTAL TEST RIG

The main target of the current study is to investigate experimentally the effect of the burner exit velocity, the blockage ratio, and the flame holder geometry on the flame stability of the premixed gaseous flames when stabilized behind flame holder. To accomplish the above needs, a test rig is designed and manufactured here to carry out the experiments using the suitable instrumentation.
The test rig used in the present study is shown schematically in Fig. 1. The experimental work was carried out on a constant cross-sectional area tubular combustor. The experimental facility was designed to generate data to study flame stability and blow off limits for premixed fuel-air mixtures. The test rig is made up of a burner with controlled air and fuel supply systems, as well as the measuring devices.

2.1 Burner

The burner consists of a pipe made of cast steel with an outer diameter of 60 mm and an inner diameter of 50 mm and length of 1250 mm open to atmosphere. The burner is provided with a fuel injection system located at the entrance of the pipe. The burner is provided with a concentric flame holder. The flame holders used in the present experimental work are made of cast steel with different shapes mainly the cone and disc. To ensure co-axial symmetry, the flame holder is mounted on a steel rod of 4 mm diameter at the center of the tube. The steel rod is adjusted in the center of the burner by two groups of steel bolts. The cone flame holders have two different cone angles mainly 120° and 90°. The flame holders diameters and blockage ratios are shown in table (1) where the blockage ratio (BR) represents the total area blocked by the flame holder at the burner exit to the burner area and can be presented by the following equation:

$$B.R. = \frac{A_{flameholder}}{A_{burner}}.$$

This percentage defines on the other hand, the total area available for the air at the burner exit. Fig.(2) shows a schematic diagram of the burner used here.

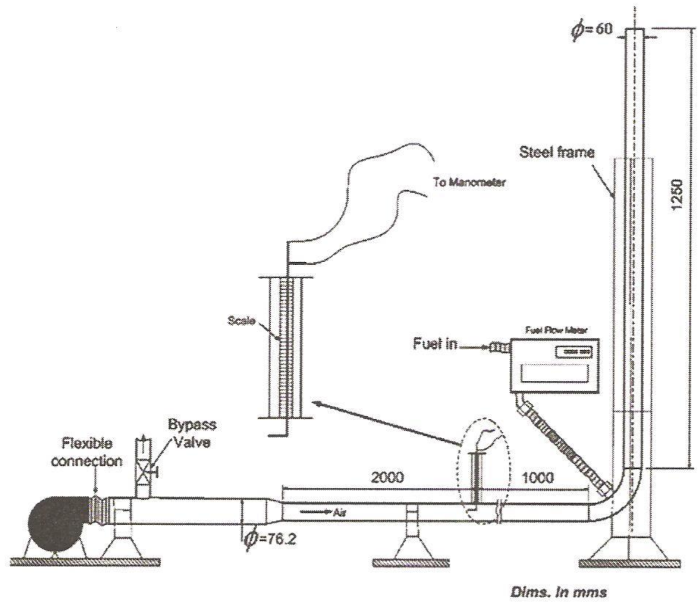
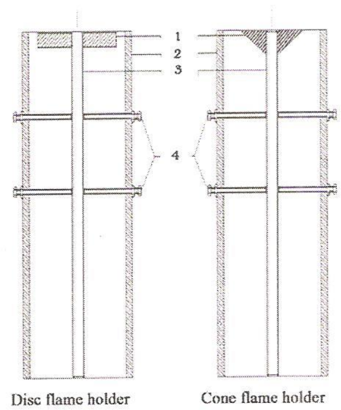


Figure (1) Schematic diagram of experimental test rig

Table (1) Flame holders geometrical details

Bluff Body Shape	Disc, Cone 120° and Cone 90°					
Diameter (mm) (for each shape)	12.5	17.5	22.5	27.5	32.5	37.5
Blockage Ratio (for each shape)	0.0625	0.1225	0.2024	0.3025	0.4225	0.5625



1-Flame holder.
2-Pipe (50 mm diameter).
3-Steel rod (4 mm Diameter).
4-Two groups of three fixation bolts.

Figure (2) schematic of the burner.

2.2 Air Supply and Control System

A controlled quantity of air is supplied to the test section by centrifugal blower (5.5 hp, 2880 rpm) through a pipe line which is branched into two lines; one of them is directed to the measuring device and then to test section and the other is connected to bypass valveas shown in Fig. 1. The two branches are integrated with manual gate valves to achieve the desired volume flow rate. The air mass flow rate is measured by measuring air velocity, V_a, through a Pitot tube, which is placed at distance of 2250mm from the control valve. The Pitot tube readings are measured by a multi tube manometer that determines the total and static pressures. The airflow line is provided with a layer of wire mesh located at the exit of the control valve, to ensure homogeneity of flow. The air mass flow rates, $\dot{m}_a$, are calculated as:

$$\dot{m}_a = \rho_a V_a A$$

Where:

$$V_a = \sqrt{2\, g\, h_a}$$

$$\rho_a = \frac{P_a}{R T_a}$$

The uncertainty of the air mass flow rate was estimated to be ±0.8%.

2.3 Fuel Supply and Control System

Natural gas is used here and preferred for its low wastes and the high flammability limits. A natural gas fuel was injected into the air stream at sufficient distance before the flame holder to provide uniform homogeneous gas mixture flowing into the burner as shown in Fig.1. The use of a gaseous fuel avoids the problem of pre-vaporization (especially for operation at room temperature). The amount of fuel is determined and controlled by using a fuel volume flow meter which is provided with a control valve to adjust the fuel flow rate. The fuel flow meter is connected to the fuel injection point through a flexible gas tube. Table (2) shows the properties of the natural gas used in the present study.The fuel mass flow rates,$\dot{m}_f$, are calculated as:

$$\dot{m}_f = \rho_f \dot{Q}_f$$

Where:

$\dot{Q}_f$ Fuel volume flow rate

$$\rho_f = \frac{P_f}{R_f T_f}$$

The uncertainty of the fuel flow rate was estimated to be ±1.7%.

All the experimental work was done with stream wise injection. To ensure homogeneous formation of the mixture, a premix tube (burner) is placed after the fuel injection system. The length to diameter ratio of this tube is chosen to be approximately 25 to avoid any influence of the premixing on the weak extinction.The measurements of air and fuel mass flow rates are used to calculate the equivalence ratio ∅as:

$$\emptyset = \frac{\left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{act}}{\left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{th}}$$

With uncertainty of ±0.92%.

Table (2) Properties of the gaseous fuel used in the present study, Data sheet from Cairo gas company (PETROGAS)

Calorific value	42852 kJ/kg
Density	0.754 kg/m^3
Correct (A/F)	17.2
Molecular weight	18.87

2.4 Flame Length, Recirculation Zone Length and Flame Blow Off Limits

In addition to measurements of air and fuel flow rates, extra parameters are needed to be measured to study the flame stability limits. These parameters are the flame length, recirculation zone length and the flame blow off limits. The length of the flame and the recirculation zone length aremeasured by the direct photographs taken during experiments using a digital camera and a screen divided into mms located behind the burner, as indicated in Fig. 3. The recirculation zone is the zone behind the flame holder as depicted in Fig. 4. Flame blow off is observed by simple visual observation. The usual practice in determining the lean blow off limit is to decrease the fuel flow rate until the flame blows off. The uncertainty of the recirculation zone length was estimated to be ±6.7%.

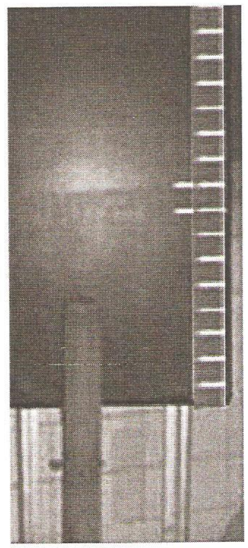


Figure 3 Measurements of flame length

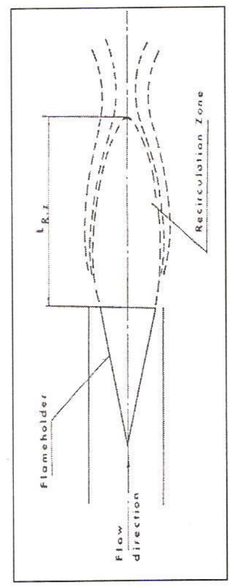


Figure 4 Recirculation zone configuration

2.5. Test Procedures

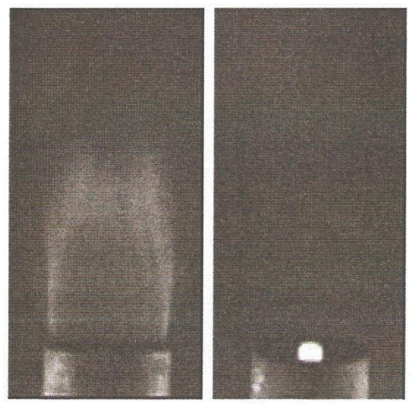
The air mass flow rate is adjusted and recorded. The fuel mass flow rate is recorded and the mixture is ignited at first by a flame torch until the flame is established behind the flame holder. Then the air mass flow rate is gradually increased and recorded until the blow off occurs. For each recorded air mass flow rate a direct photography of the flame is taken. In order to study the effect of the blockage ratio, and flame holder shape on the weak extinction limit, the blockage ratio is varied from 0.06 to 0.56. For each blockage ratio, there are two flame holder shapes disc and cone with a cone angle of 120° and 90° respectively and air velocity rang from. 4.678 m/s to 16.985 m/sare examined.

3. RESULTS AND DISCUSSION

In the present study, the effect of some parameters on the flame stability of premixed mixture is intensively investigated. These include different flame holder geometries, burner exit velocity, and blockage ratio. These parameters have a direct effect on flame stability, recirculation zone length and residence time. In the following subsections detailed discussions of the results based on the experimental measurements are presented. In this study the flame holders have different diameters of 12.5 mm, 17.5mm, 22.5mm, 27.5mm, 32.5mm and 37.5mm. The geometries include disc flame holder and cone flame holders with two different cone anglesof120° and90°.

3.1 Flame Stabilization

The meaning of flame stabilization given in this study is the flame that can be visualized and seemed stable for some extent. Fig. 5 shows a comparison between two flames, Fig. 5.a represents a stable flame where the flame has a certain height and width and can be organized or visualized, while Fig. 5.b represents unstable flame which cannot be detected either visually or has regular dimensions.



Stable flame (a) Unstable flame (b)

Figure (5) Stable and unstable flames

3.1.1 Effect of burner exit velocity on the equivalence ratio Φ

Figure 6 shows the variation of the equivalence ratio (ϕ) with the burner exit velocity (V_{exit}) for different blockage ratio (BR). It is clear form the figure that for the same blockage ratio, as the burner exit velocity increases the equivalence ratio decreases; this attributed to that the increase of the airflow rate passing through the burner for same blockage ratio increases the exit velocity and in the same time decreases the equivalence ratio. It is clear that as the blockage ratio increases, which means that the exit area allowing the flow of the premixed mixtures through it decreases, the exit velocity increases keeping same operating conditions and this is the case in all geometries used in this study. The flammability limits at higher velocities has improved with the increase in the blockage ratio.

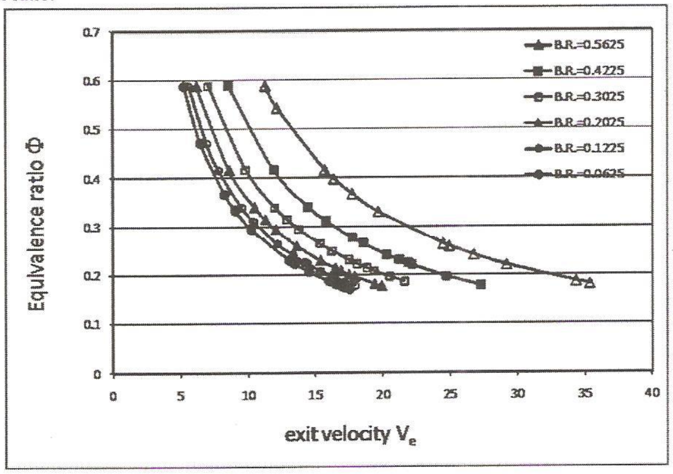


Figure.(6) Variation of equivalence ratio with exit velocity for different blockage ratios

3.1.2 Effect of flame holder geometry on the blow off equivalence ratio

In order to indicate the change in performance of the different geometries of the flame holder on flame stability, the blow off limit for the three geometries are plotted as a relationship between the blow off equivalence ratio ($\phi_{\text{at blow off}}$) and blockage ratio as given in Fig. 7. It is obvious that as the blockage ratio increases the blow off equivalence ratio decreases for all flame holders. For the same blockage ratio the lowest value of the blow off equivalence ratio occurs with using disk flame holder. The improvement occurred in the case of the disc flame holder which shows the best behavior compared to the two other cone flame holders. The improvement shown can be attributed to that the disc flame holder makes the stream lines of the combustible mixture exhibit larger divergence, so the recirculation zone formed behind the flame holder body becomes bigger and this leads to two factors which affect the weak blow off limit: first, increasing the residence time of the hot gases and so improving the flame stability and the second, increasing the surface area and shear layer of the recirculation zone and so increasing the rate of heat and mass exchange between the hot gases and the reactants, which improve stability of the flame.

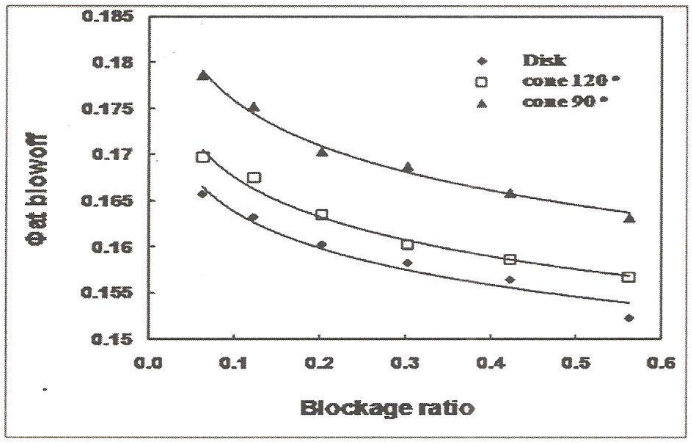


Figure.(7) Variation of equivalence ratio at blow off with blockage ratio for different flame holders

3.2 Recirculation Zone

The recirculation zone formed behind the flame holder is considered as a heat source to ignite the combustible mixture. The recirculation zone volume is a very important parameter; its length is useful parameter, which can be utilized to obtain some interesting information. The total flame height and the recirculation zone height are measured directly as indicated in figure (8).

It was found as mentioned by Radhakrishnan et al. [3] that the flame recirculation zone height depends on the flame holder geometry in both cold and hot flows. According to his investigation, the recirculation zone heights can be considered as a representative parameter to differentiate between different flame holder effectiveness. The following correlations are adapted in the present work to calculate the recirculation zone heights according to that mentioned by Krishnan Radhakrishnan et al. [3].

$$L_{eff} = L_{R.Z}$$

For cone flame holder an effective length of the recirculation zone (L_{eff}) is equal to the length of the wake formed behind the flame holder ($L_{R.Z}$) plus quarter of flame holder height (h) as shown in figure 8.

$$L_{eff} = L_{R.Z} + h/4$$

Figures (9.a to 9.c) show the variation of the circulation length with the exit velocity at different blockage ratio using disc flame holder, cone flame holder 120° and cone flame holder 90° respectively. It is clear that for different flame holders, as the exit velocity increases, the

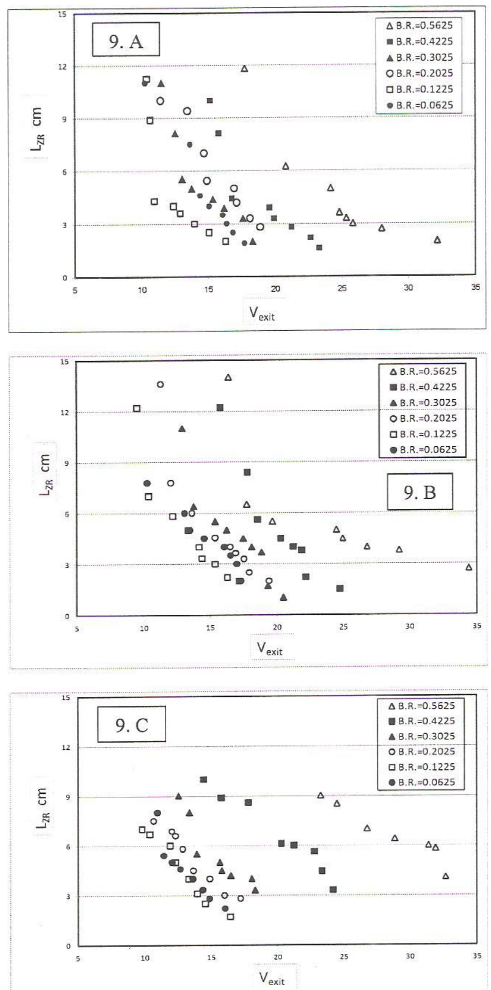
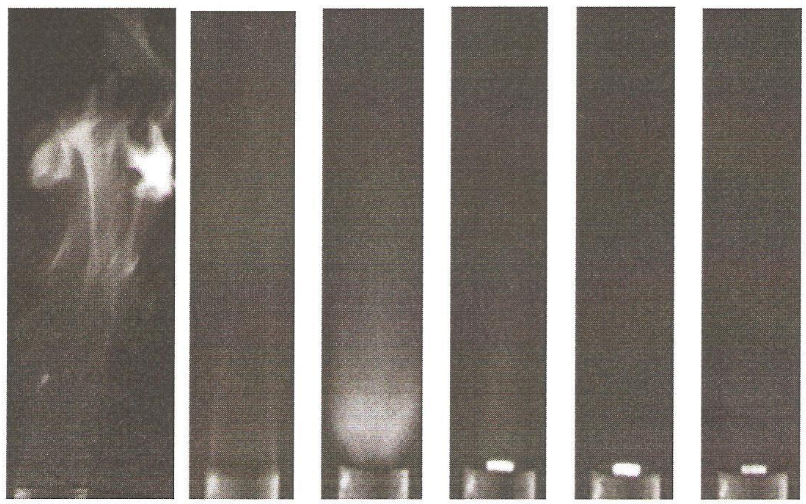


Figure (9) Effect of exit velocity on circulation zone length for different blockage ratios, using a) disc flame holder. b) Cone flame holder 120 ° c) cone flame holder 90 °

circulation length decreases because of the lean mixture. Higher velocities with less fuel consumption can be achieved for the same flame length with increasing the blockage ratio. For the same range of flame length it is observed that wider range of velocities can be reached for higher blockage ratios, which means that the chance of achieving the flame stability is improved as the blockage ratio increases.

Details of the recirculation zones length for disc flame holder at different equivalence ratios are shown in figure (10). The figure represents a series of photographs displaying the effect of reducing fuel to air ratio down to the point at which the extinction is about to occurs for the case of disc flame holder of B.R.=0.2025.



Φ=0.588004 Φ=0.415782 Φ=0.262963 Φ=0.236266 Φ=0.2053989 Φ=0.185943

Figure (10) A series of photographs displaying the effect of reducing fuel to air ratio down to the point at which the extinction is about to occurs in case of disc bluff body of B.R.=0.2025.

3.3 Residence Time (τ)

It is defined as the time available for the combustible mixture and the combustion products to reside the recirculation zone [3]. This time (τ) can be given by the following relation:

$$\tau = \frac{L_{eff}}{V_{exit}}$$

According to the above definition, it is obvious that as the residence time increases a better chance is obtained to ignite the mixture efficiently. Figure (11) shows the variation of the equivalence ratio with the residence time for different geometries of the flame holders used for the same blockage ratio. It can be seen that for residence time higher than 4 milli-seconds the increase in residence

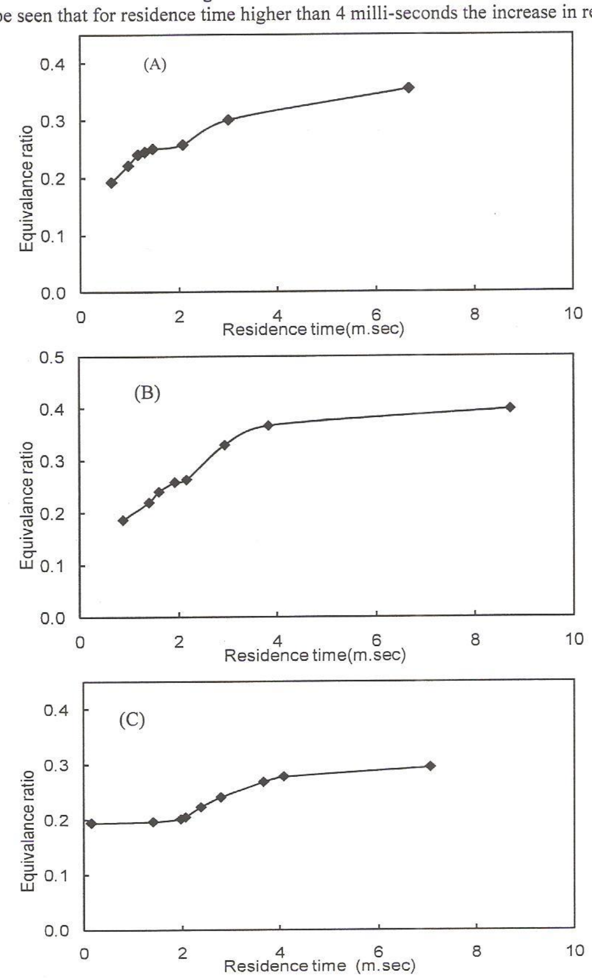


Figure (11) variation of the equivalence ratio with residence time at blockage ratio B.R.=0.5625 for (A) disc, (B) cone 120°, (C) cone 90° flame holders.

time has insignificant effect on the equivalence ratio for all flame holders. For residence time from 2-4 milli-seconds as the residence time increases the equivalence ratio increases.

4. CONCLUSIONS

The main objective of this work is to study the effect of flame holder geometry with different blockage ratios on the flame stability for a free premixed flame of Natural Gas. For this reason a burner with central flame holder is installed. Different shapes of the flame holders mainly; disc (with different diameters) and cone (with different diameter and apex angles) have been used as flame holders. For each flame holder with a specified blockage ratio, tests are done at different air to fuel ratio and measurements are performed for recirculation zone length by photographic technique.

Based on the different experimental runs performed here and the discussion of the results, the following conclusions are obtained:

1) The flame holder has an impact on the recirculation zone, which leads to an improvement in the residence time of the hot gases, and also an increase in the heat and mass exchange between the hot gases and reactants, which improve the flame stability.
2) There is a noticeable improvement in the stability limits by increasing the blockage ratio for higher velocities of the premixed mixture.
3) The flame holder shape has an effect on the stability limit; the percentage change of blow off limit is approximated to be within 5%.
4) Disc flame holder is proved to be more efficient for flame stability under the different operating conditions performed here.

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NOMENCLATURE

D	burnerdiameter	m
d	flame holder diameter	m
$A_{flameholder}$	cross section area of flame holder	m^2
A_{burner}	cross section area of burner	m^2
B.R.	blockage ratio $B.R. = A_{flameholder} / A_{burner}$	---
$\dot{m}_a$	air mass flow rate	kg/s
V_a	air average velocity$V_a = \sqrt{2\ g\ h_a}$	m/s

ρ_a	air density $\rho_a = P_a/(RT_a)$	Kg/m^3
A	cross section area of pipe	m^2
G	gravitational acceleration	m/s^2
h_a	average air head	m
P_a	air static pressure, $P = P_{at} + P_{st}$	Pa
T_a	air temperature	K
R	gas constant for air where	J/kg. K
$\dot{m}_f$	fuel mass flow rate	kg/s
P_f	static pressure of the fuel	Pa
T_f	fuel temperature	K
R_f	fuel gas constant $R_f = \overline{R}/M$	kJ/kg K
$\overline{R}$	universal gas constant	kJ/kmol K
M	molecular weight of the fuel	kg/kmol
$\emptyset$	equivalence ratio $\emptyset = \left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{act} / \left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{th}$	----
$\left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{act}$	measured fuel to air ratio	----
$\left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{th}$	theoretical fuel to air ratio	----
h	cone flame holder height	m
L_{eff}	effective length of the recirculation zone	m
$L_{R.Z}$	recirculation zone length	m
V_{exit}	burner exit velocity	m/s
τ	residence time $\tau = \frac{L_{eff}}{V_{exit}}$	s