A STUDY OF FLAMMABILITY LEAN LIMIT FOR A BLUFF BODY STABILIZED FLAME

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Abstract

An experimental investigation has been carried out on the effect of mainstream velocity, blockage ratio, and flameholder shape on the lean limit of flammability. These tests employed different blockage ratio (0.25 and 0.5) and different shapes of bluff body (cone, flat plate, cylinder and sphere). The approach stream velocity was varied up to 15 m/s. The fuel employed was natural gas. The results showed that increasing the mainstream velocity has an adverse effect on lean limit of flammability, increasing the blockage ratio widens the range of stability for cylindrical and spherical stabilizers, but has an opposite effect in case of cone and plate, and the shape of bluff body affects the lean limit of flammability through its effect on the recirculation zone shape and size.

Keywords: flame stability.

Introduction

One of the main problems encountered in jet engine afterburners and most of practical combustion systems is that of maintaining a stable flame in a fast flowing stream and over a wide range of operating conditions. The usual method of surmounting this problem is to create a sheltered zone of low velocity in which flame speeds are greatly enhanced by imparting a high level of turbulence to the primary mixtures and by arranging for hot combustion products to recirculate and mix with the incoming mixture.

A widely used method of stabilizing flames in combustible mixture flowing at high velocities is by insertion of bluff objects — such as cones, V-gutter or other shapes — in the flow field. The flame is stabilized by the recirculation zone (RZ) formed in the wake of the bluff body. It plays an important role in the process of flame stabilization that is achieved by heat and mass exchange between the recirculation zone and the mainstream. This recirculation zone serves a triple purpose: (i) producing a region of low velocity, (ii) providing long residence time for the flame to propagate into the incoming fresh mixture, and (iii) serving as a heat source of continuous ignition for the incoming combustible mixture. The stability of a generated flame is maintained if heat exchange (loss) from the recirculation zone to combustible stream is balanced by the heat gained by the recirculation zone from the flame. The recirculaton zone produced by the bluff body is affected by its geometry (aerodynamic effect), the type of fuel and the equivalence ratio (chemical effect) and its confinement in the combustor (pressure gradient effect). Thus a complex aerodynamics, chemistry, pressure gradient interaction is present in reactive recirculatory flow fields.

Much interest is now being shown in the lean, premix/prevaporize (LPP) concept as a mean of controlling exhaust emissions of nitric oxides and smoke. By avoiding droplet combustion and by operating the combustion zone at a lean equivalence ratio, nitric oxide formation is drastically reduced due to the low reaction temperature and the absence of hot spots in the combustion zone. In practice this implies that over a large proportion of the engine operating range the equivalence ratio in the combustion zone must lie close to the weak extinction value.

The practical importance of the bluff body stabilization process has given rise to a large number of theoretical and experimental studies. Much of our present understanding of the flame stabilization process is due to the pioneering studies carried out in 1950's by LONGWELL et al. (1949,1950), WILLIAMS et al. (1949) and WRIGHT (1959). Also more recent studies are carried out by PAN et al. (1992A, 1992B), BAXTER and LEFEBVRE (1992), BALLAL and LEFEBVRE (1979), RAO and LEFEBVRE (1982), BALLAL et al. (1989), EL-FEKY et al. (1988), KUNDU et al. (1980), PLEE and MELLOR (1979). *Table (1)* present summary of the literature review. During these studies most of the factors affecting flame stabilization behind bluff bodies — such as stabilizer dimension, blockage ratio, equivalence ratio, pressure, temperature, velocity and turbulence — were investigated.

During the studying of the literature, one may notice that most of these studies were carried out at low blockage ratios (smaller than 0.4) and using conical bluff body and sometimes flat plate. The effect of higher values of blockage ratio was not tested and the other shapes of flameholder were not investigated. Also sometimes there is a contradiction in the influence of bluff body shape and blockage ratio on the flame stability range and there is no comparison between the different shapes of the stabilizer. So the present work attempts to investigate the effect of high blockage ratio (0.5) as well as a small one (0.25) and to compare between them. Also the effect of stabilizer geometry (cone, flat plate, cylinder and sphere) on the lean limit of flammability will be studied.

Table 1
Summary of the Literature Review

Reference	Experimental data	Measuring technique	Results
Longwell et al. (1949)	$BR = 0.02$ to 0.23, cylinder, cone and V - gutter $U = 69$ to 274 m/s $T = 339$ to 533 k $P = 0.1$ to 3.2 atm Naphtha/air	Visual observation	- increasing U, decreasing T and/or d and streamlining trailing edge of baffle decreases stability range. - pressure: unimportant
Williams et al. (1949)	$BR = 0.0005$ to 0.17 rod, V-gutter and flat plate $U = 6$ to 107 m/s $Tu = 0.4$ to 80 % $T = 300$ to 340 k Natural gas/air	visual observation HWA	- increasing U or Tu decreasing BR and/or cooling the flameholder decreases the stability range. - baffle shape: unimportant.
Wright (1959)	$BR = 0.03$ to 0.25 flat plate $U = 37$ to 185 m/s $P = 1$ atm. gasoline/air	visual observation schlieren photography	- the flame speed and geometry depend on blockage. - the blowout velocity was given by: $U = \left(\frac{BR}{C_1+C_2 \cdot BR}\right) \cdot \frac{h}{r}$ which predicted that max. blowout speed would be C_1/C_2: for plate 0.35 cylinder 0.56 - the chemical time does not depend on flameholder.
Lefebvre et al. (1966)	$BR = 0.11$ to 0.44 cones $U = 41$ to 134 m/s $T = 293$ to 774 k butane/air	visual observation	- increasing U, decreasing T and/or increasing BR increases $\dot{M}_E/\dot{M}$ - for certain BR, pipe and baffle diameter unimportant. $\frac{\dot{M}_E}{\dot{M}} = 0.65\left(\frac{U}{T^{0.75}}\right)\left[\frac{BR}{(1-BR)^{0.5}}\right]^{1.5}$
Ballal and Lefebvre (1979)	$BR = 0.04$ to 0.34 cones $U = 10$ to 100 m/s Tu : up to 15 % $T = 300$ to 575 k $P = 0.2$ to 0.9 bar propane/air	visual observation	- increasing U and/or Tu increases Φ, while increasing BR and/or T has an adverse effect. - pressure: unimportant $\Phi = \left\{\frac{2.25\cdot[1+0.4\cdot U\cdot(1+0.1\cdot Tu)]}{P_0\cdot T\cdot e^{T/150}\cdot d\cdot(1-BR)}\right\}^{0.16}$

Reference	Experimental data	Measuring technique	Results
Walburn (1968)	$BR = 0.083$ to 0.167 cylinders $U = 100$ to 400 ft/s propane/air	gas chromatography	– the experimental results demonstrated the heterogeneity of the reaction zone and a progressive increase in reaction efficiency downstream of the stabilizer.
Kundu et al. (1980)	$BR = 0.11$, 0.25 and 0.54 plate, wedge and cylinder propane/air	direct photography	– recirculation strength $\dot{M}_r/\dot{M}$ increases linearly with BR and depends on the shape of bluff body – $\dot{M}_r/\dot{M}$ was max. for plate – RZ boundary is not function in U and/or Φ
Roa and Lefebvre (1982)	$BR = 0.1, 0.2$ and 0.3 v-gutters $\theta = 30$ to 180 deg $U = 30$ to 220 m/s $T = 373$ to 565 k $P = 4.2$ to 35.2 kpa kerosene, water/air	visual observation	– the flame stability improves as BR and θ increase – if U increases Φ inereases. – stability must not be based on the geometrical width of the gutter but on the width of the wake formed behind it.
El-Feky et al. (1988)	$BR = 0.3$ to 0.75 cones $\theta = 30, 45$ and 60 deg. U: up to 15 m/s T: up to 373 K butane, propane/air	visual observation direct photography	– increasing U, decreasing T and/or decreasing θ increases the low limit of flammability. – the best stabilizer $BR = 0.5$ and $\theta = 60$ deg $\Phi \propto \frac{U^{0.142} \cdot L^{0.8} \cdot (BR-0.5)^2 + C}{d^{0.6} \cdot (T \cdot e^{T/150})^{0.16} \cdot \theta^{0.034}}$
Ballal et al. (1989)	$BR = 0.31$ solid cone, $\theta = 45$ deg $U = 10$ m/s, $\Phi = 0.7$ Tu: $u'/U = 4$ % $v'/U = 2.8$ % methane/air	2-component LDA system	– combustion accelerates U but damps Tu. – L is nearly doubled due to combustion. – large scale eddies carrying fresh mixture are entrained into the high shear region surrounding RZ.
Pan et al. (1992A)	$BR = 0.25$ solid cone, $\theta = 45$ deg $U = 20$ m/s Tu: $u'/U = 4$ % $v'/U = 2.8$ % $\Phi = 0.65, 0.8$ and 1.0 methane/air	3-component LDA system	– RZ elongated due to combustion and it is shorterim confined flame than in open one. – $\dot{M}_r$ increases by 30 % due to confinement. – highly strained flame is observed at the max. width of RZ and at the stagnation point.
Pan et al. (1922B)	$BR = 0.13$ to 0.25 solid cones $\theta = 30$ to 90 deg $U = 10$, 15 and 20 m/s $Tu = 2$ to 22 % $\Phi = 0.56, 0.65, 0.8$ and 0.9 methane/air	2-component LDA system	– increasing BR slightly decreases L but increases the shear stress and TKE. – increasing s produces slightly large RZ. – increasing Tu shortens L to its cold flow value.

Reference	Experimental data	Measuring technique	Results
Baxter and Lefebvre (1992)	$BR = 0.125$ to 0.32 v-gutter $Mn = 0.18$ to 0.26 $T = 650$ to 850 k $W = 25.4$ to 65.1 mm $\theta = 45$, 60 and 90 deg aviation kerosene, JP5/air	visual observation	- increasing U decreases the stability range. - stability improves due to increasing the gutter width. - the shape of bluff body affects its stability characteristics. - any increase of T widens the range of stability.

Test Rig

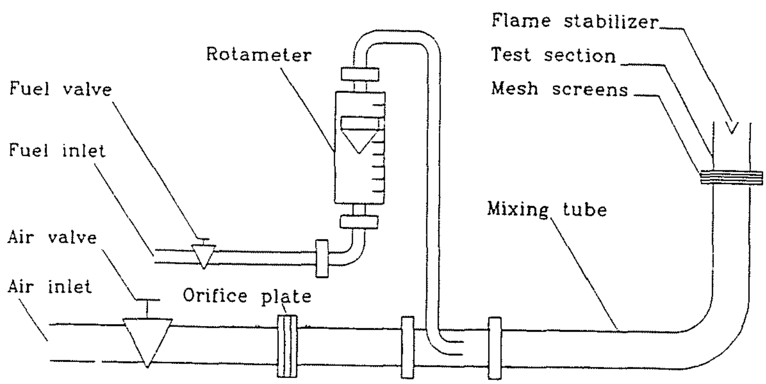

Fig. 1. Schematic diagram of the test rig

A schematic diagram of the test facility used in the present work is shown in *Fig. 1*. The basic system consists of an air supply at atmospheric pressure connected to a pipe of 50.8 mm inside diameter. The air flow rates were controlled by a valve and measured by a standard orifice plate having an area ratio of 0.262 and D and $D/2$ tapping. The pressure difference across the orifice was measured by a simple U-tube water manometer. The fuel employed was natural gas. Its flow rates were controlled by an accurate valve and measured by a pre-calibrated rotameter. To ensure a homogeneous formation of the mixture a premixed tube (about 2 m long) was connected after the fuel injection place and before the test section. For the same reason and to avoid the secondary flow caused by the bend 3 fine mesh screens were used just before the test section. Eight flameholders with different shapes and two blockage ratios were manufactured. During the experiments the stabilizer was adjusted axi-symmetrically with the test pipe and just at the open end of it.

The Present Work Data

Mainstream average velocity:	up to 15 m/s
Blockage ratio:	0.25 and 0.5
Flameholder shapes:	flat plate, cone with 60 deg included angle, cylinder and sphere.
Flameholder dimensions:	for plate, cone and sphere: $d = 25.4$ mm ($BR = 0.25$) $d = 35.9$ mm ($BR = 0.5$) for cylindrical bluff body: $d = 17$ mm, $l = 30$ mm ($BR = 0.25$) $d = 25.3$ mm, $l = 40$ mm ($BR = 0.5$)
Type of fuel:	natural gas which has a volumetric composition as follows: CH_4 99 %, C_2H_6 0.8 %, C_3H_8 0.1 % and C_4H_{10} 0.1 %

Test Procedure

The test procedure used in the present study was quite simple. For any given flameholder the air flow rate was adjusted and recorded. The fuel control valve was opened and the mixture was ignited by an electric torch until the flame was established behind the bluff body. After each ignition the spark plug was withdrawn to avoid disturbance to the flowing stream. Then the fuel flow rate was gradually reduced and recorded until extinction occurs. The flame blowout was noticed by simple visual observation.

Results and Discussions

During all the experiments if one repeats the test more than one time for the same upstream velocity the flame does not blow out at the same value of fuel to air ratio (equivalence ratio); but always there are higher than one value; as shown in *Fig. 2*; so the mean values of the equivalence ratio will be used at the rest of figures.

The velocity of the combustible mixture as it approaches the flameholder is a flow parameter of importance to weak extinction limits. The

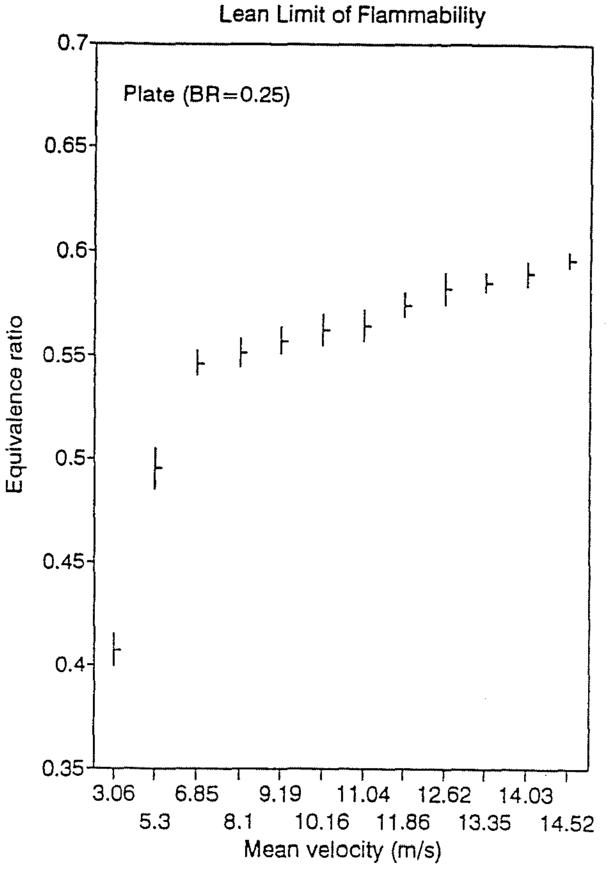

Fig. 2. The equivalence ratio versus the mean velocity

experimental results show that any increase in approach stream velocity has an adverse effect on flame stability by reducing the residence time (τ) of the reactants in the recirculation zone (BAXTER, 1992). This effect is illustrated in *Fig. 2* to *8* for different geometrical bluff bodies and different blockage ratios

$$\tau = L/U$$

The influence of flameholders' shapes on flame blowout is shown in *Fig. 3, 4*. The four curves in these two figures represent four different shapes of bluff bodies (plate, cone, sphere and cylinder) having the same blockage ratio of 0.25 and 0.5, respectively. The shape of the stabilizer affects its stability characteristics through its influence on the size and shape of the wake region (RZ) formed behind it. Any change (increase or improve) in the size

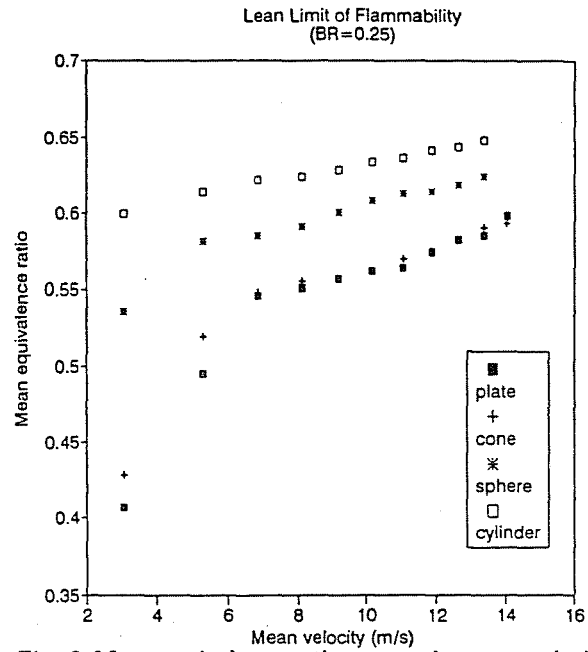

Fig. 3. Mean equivalence ratio versus the mean velocity

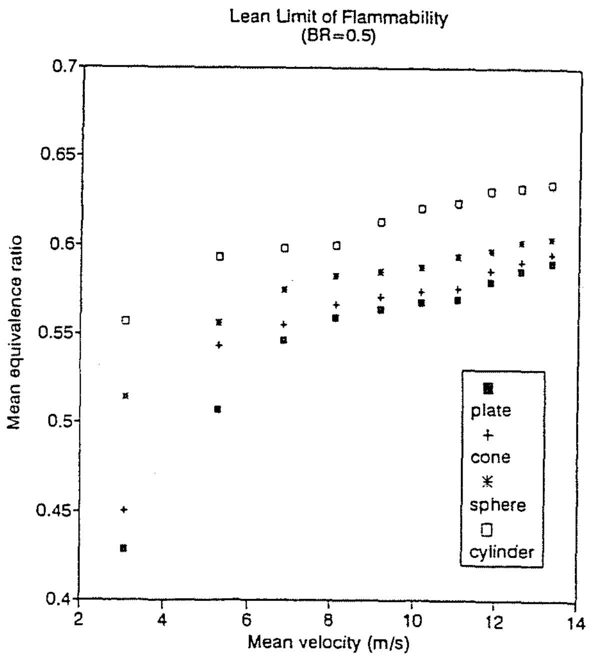

Fig. 4. Mean equivalence ratio versus the mean velocity

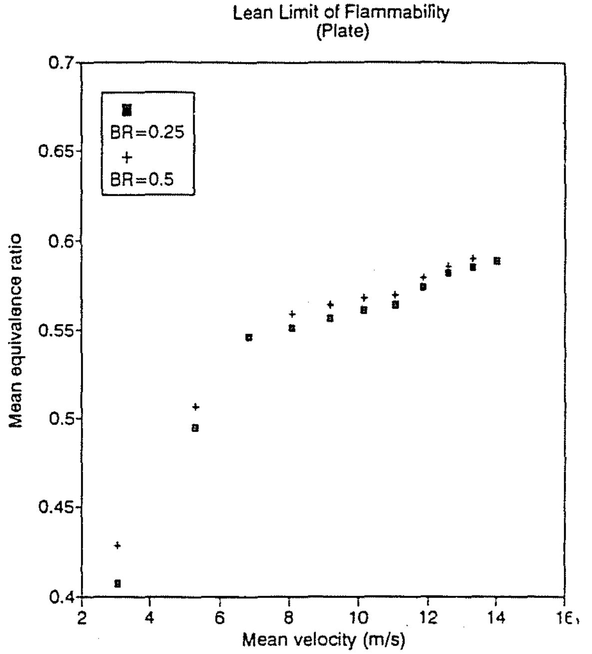

Fig. 5. Mean equivalence ratio versus the mean velocity

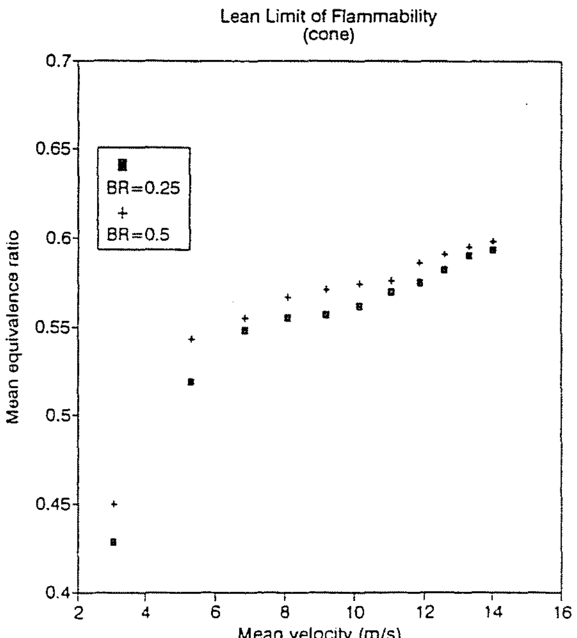

Fig. 6. Mean equivalence ratio versus the mean velocity

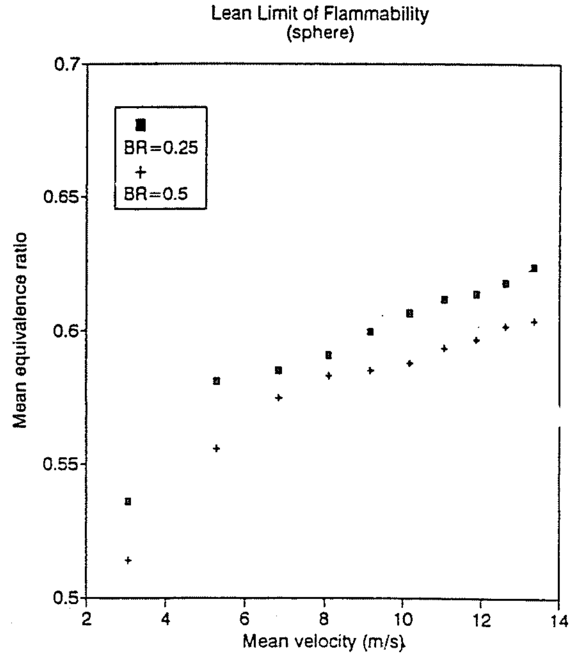

Fig. 7. Mean equivalence ratio versus the mean velocity

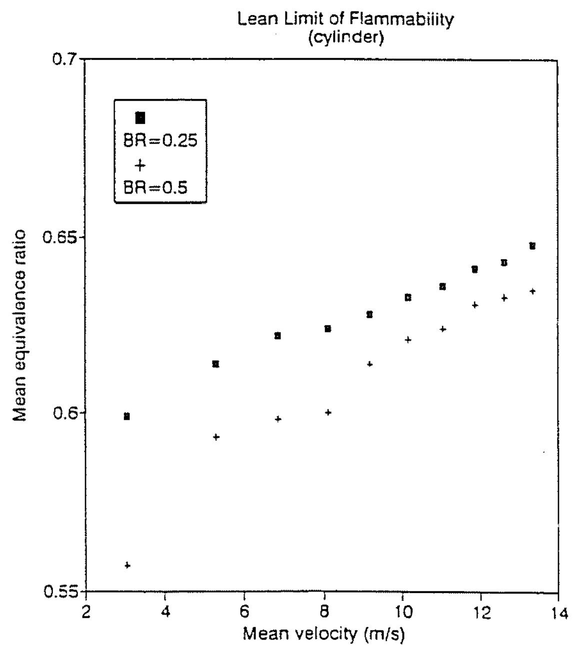

Fig. 8. The mean equivalence ratio versus the mean velocity

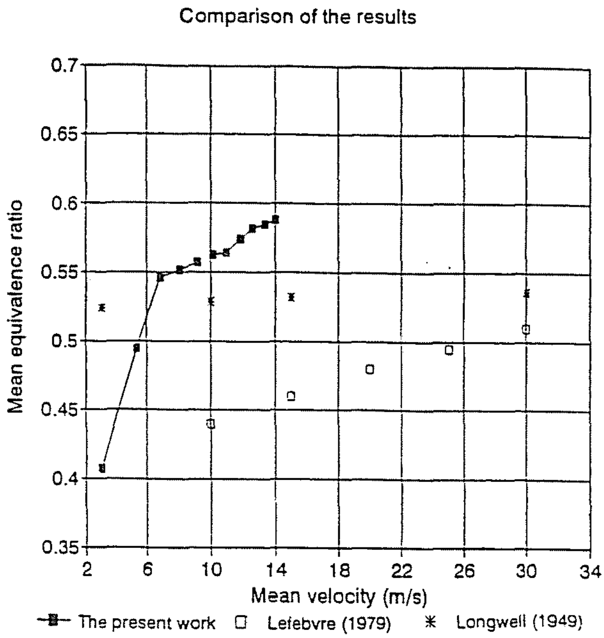

Fig. 9. Mean equivalence ratio versus the mean velocity (results comparison)

of the recirculation zone extends the residence time and consequently improves stability. It is clear from these figures that the flat plate is the best shape of flameholder, the same result was found by KUNDU et al. (1980).

The effect of flameholder size (blockage ratio) on stability lean limit is illustrated in *Fig. 5* to *8*. For cylindrical and spherical stabilizers as the blockage ratio increases from 0.25 to 0.5 — for the same mainstream velocity — the weak extinction equivalence ratio (Φ) decreases; which means that the stability is improved due to the enlargement of the recirculation zone and the increase in the residence time. But the opposite trend is observed for plate and conical stabilizers; for any given mainstream velocity as the blockage ratio increases the equivalence ratio increases; so the lower blockage is better than the higher one. The reason behind this phenomenon is the increase in the annular velocity around the stabilizer due to the blockage increase that has an opposite effect on the stability range. It means that 0.25 blockage ratio is the best for plate and cone, while for cylinder and sphere 0.5 is the best one (WRIGHT, 1959).

Fig. 9 shows a comparison between the results of the present work and the results of LONGWELL, (1949) and LEFEBVRE, (1979). It is clear from this figure that there are some differences in the lean extinction equivalence ratio for the same mainstream velocity. There are two reasons for these differences. The first one is the flameholder shape and the blockage ratio employed; in the present work the shape of the stabilizer is a flat plate and the BR is 0.25, while there was a special design with BR 0.23 for Longwell and for Lefebvre the stabilizer was cone with BR 0.34. The second reason is the fuel used-natural gas; solvent naphtha and propane, respectively.

Conclusions

From the analysis and discussion of the experimental results, it is concluded that the lean limit of flammability is governed by the residence time. The residence time depends on the upstream velocity and on the shape and dimension of the flame stabilizer. Thus, for the same mainstream velocity, the larger recirculation zone the longer residence time and consequently lower value of the lean limit of flammability. So the best flameholder is the flat plate because it has the lower value of lean extinction equivalence ratio. The best blockage ratio is different according to the shape of the bluff body; for plate and cone the best one is the smaller (0.25) while it is the bigger (0.5) for cylinder and sphere.

Nomenclature

A = pipe cross-section area
a = bluff body projected area
BR = blockage ratio (a/A)
C_1, C_2 = constants
D = pipe diameter
d = baffle diameter
h = duct height
L = recirculation zone length
LPP = lean, premix/prevaporize
l = flameholder length
$\dot{M}$ = mixture mass flow rate
$\dot{M}_E$ = entrainment mass flow rate
Φ = equivalence ratio
$\dot{M}_r$ = recirculation mass flow rate
Mn = Mach number
P = inlet air pressure
RZ = recirculation zone
T = inlet air temperature
Tu = turbulence intensity
TKE = turbulence kinetic energy
U = mainstream velocity
u', v' = velocity fluctuation
W = flameholder width
t= residence time
θ = cone included angle

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