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ENHANCEMENT OF FLAMMABILITY LIMITS OF THE NATURAL GAS BY THE USE OF BLUFF BODY

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Abstract

An experimental investigation has been carried out to study flammability limits of the natural gas and the effect of flame holder position, in the burner tube, on it. These tests employed two shapes of bluff body: disk and cone (60° included angle) with blockage ratio of 0.42. The fuel used was natural gas and the upstream air velocity was varied up to 26 m/s. The flame holder location was varied from 12 mm inside the burner tube, with respect to the burner mouth, to 12 mm downstream and outside it (h/d from -0.44 to $+0.44$). The results showed that the flammability limits are widened due to the use of bluff body and it depends largely on the flame holder shape and position in the burner tube. The results showed also that the best position of the flame holder is not the same for all shapes of the bluff bodies, but it depends on the shape of the flame holder and on the nature of study (lean limit or rich limit). For the lean limit of flammability, it is concluded that the best position of the flame stabilizer is at 6 mm inside the burner tube ($h/d = -0.22$) for disk bluff body and 12 mm outside it ($h/d = 0.44$) for the conical one. For the rich limit the best position is 6 mm outside ($h/d = 0.22$) for disk and 12 mm outside also ($h/d = 0.44$) for cone.
Keywords: flammability limits and flame stability.

Introduction

The boundary of a flammable mixture such that a change in one direction gives a flammable mixture, and in the other a nonflammable mixture, is called the flammability limit. The two distinctly separate flammability limits, lean and rich, correspond to the minimum and maximum amount of the combustible that will support flame propagation. The flammability limits are believed to be physico-chemical constants of flammable gases and vapours of flammable liquids. These constants were determined for static mixtures in large vessels with ignition at the vessel base and at constant pressure. The actual flammability limits are usually determined by visual observation of flame propagation in wide vertical tubes [1].

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Because of the buoyancy and convection effects flame propagation upward in a vertical tube is somewhat easier than downward propagation. Thus it appears that the limits of flammability may not be fundamental properties of a gas mixture. However, in practice they are fairly well-defined, and knowledge of them is important for safety consideration, to enable one to predict whether or not a mixture is likely to be explosive [2, 3].

Also, flame stabilization is of fundamental importance in the design efficient performance and reliable operation of high speed propulsion systems. In gas turbines and other combustion equipment, the velocities at which the gases flow are much higher than the maximum flame speeds of practical fuels. (The blowoff velocity defined as the maximum velocity for which the flame continues to propagate into the mainstream.) Therefore, an ignition energy source and region of low velocity must be provided within the combustor to stabilize or anchor the flame.

The use of bluff bodies as flame holders is an effective flame stability technique. The wake flow downstream of the flame holder consists of a recirculating region bounded by free shear layers [4]. The presence of the recirculation zone (RZ) serves as a continuous source of energy and active species for igniting the fresh combustible mixture. The mechanism of flame spread to other regions of the flow is by the transport of heat and active species from the shear layer that surrounds the recirculation zone to the adjacent fresh mixture [5].

Research conducted during the past three decades indicates that the wake flow structure behind the bluff body is directly related to the flame holding performance. The stabilizing performance of a bluff body flame holder is usually described either in terms of the range of equivalence ratios (φ) over which stable combustion can be achieved (flammability limit), or by the maximum velocity that the system can tolerate before the flame extinction occurs. However, the wake flow contains the complexities of separation and recirculation, mass and momentum transport across the shear layers and the vortex shedding [6].

The previous work in this topic was summarized at EL-FEKY and PENNINGER [7]. During the study of the literature it was found that the location of the flame holder in the burner tube was not studied. The same remark was concluded by KATSUKI and WHITELAW [8]. So the present work attempts to investigate the effect of flame holder position, with respect to the mouth of the burner, on the flammability limits. This study includes not only the lean limit of flammability but also the rich one. It is concluded from [7] that the best flame holder shapes are plate (disk) and cone, so this study is carried out by the use of these two shapes of bluff body with a blockage ratio of 0.42.

Test Rig

A schematic diagram of the test facility used in the present work is shown in *Fig. 1.* Its construction and the importance of each part were explained at [7]. There are some important changes in the test rig construction:

1. The fuel volumes were measured by a gas meter and the time by a stop watch, and the volume flow rates were calculated, $(\Delta V/\Delta t)$. The fuel flow through the gas meter is more stable than that through the rotameter.
2. To ensure a short flame and a wide range of the investigated flow velocity, the burner tube was replaced with a smaller one with a diameter of 27.6 mm.
3. To study the effect of flame holder location on the flammability limits, a special construction was used to change its position from 12 mm inside the burner tube, with respect to the burner mouth, to 12 mm outside it (h/d from −0.44 to +0.44).

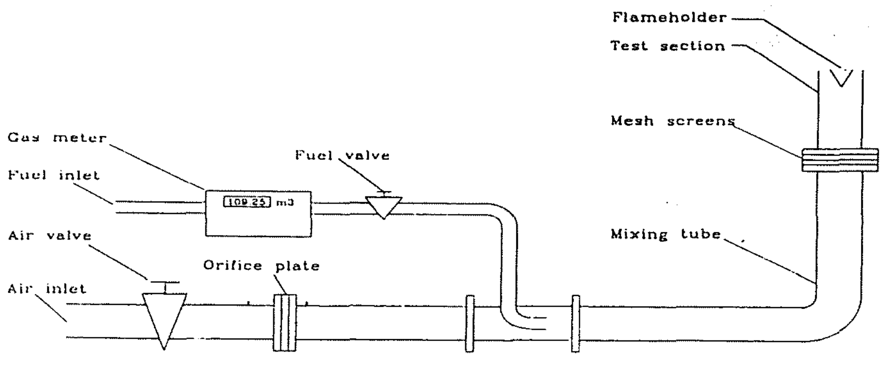

Fig. 1. Schematic diagram of the test rig

The Present Work Data

Mainstream average air velocity (u)	up to 26 m/s
Flame holder shapes	plate and cone with 60° included angle
Blockage ratio (BR)	0.42
Pressure (p)	atmospheric pressure
Temperature (T)	room temperature

Flame holder position (h)	from 12 mm upstream to 12 mm downstream (h/d from −0.44 to +0.44)
Type of the fuel	natural gas with 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 work was quite simple. For a given flame holder location, the air flow rate was adjusted, measured 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 the flame disturbance. Then, in case of lean limit of flammability study, the fuel flow rate was gradually reduced and recorded until extinction occurs, while, in case of rich limit study, the fuel flow rate was gradually raised and recorded until the flame starts to oscillate and extinction occurs. In each case the flame blowoff was noticed by simple visual observation.

Results and Discussion

During the present study numerous experiments were carried out, and each experiment was repeated many times to emphasize that the results are surely lying within a certain range of equivalence ratio, and to calculate the mean value of it (φ) for each test. *Figs. 2 – 5* show the relation between the mean equivalence ratio and the mainstream average air velocity for different flame holder positions. As it was concluded by El-Feky and Penninger [7], Baxter and Lefebvre [9], Ballal and Lefebvre [10], Rao and Lefebvre [5] and Longwell et al. [11], for the lean limit of flammability, the extinction equivalence ratio increases as the mainstream velocity increases. While the opposite effect of flow velocity is noticed for the rich limit, however, the rich extinction equivalence ratio decreases as the air velocity increases.

Fig. 2 shows the stability loops (flammability limits) for the natural gas when the flame was stabilized behind a bluff body (disk), each panel for a specific position of the flame stabilizer (h/d from −0.44 to +0.44). It may be noticed from this figure and from *Fig. 3* that as the flame holder moved downstream (outside of the burner tube) the stability loop is widened specially from the rich limit side. The effect of each position is quite clear for

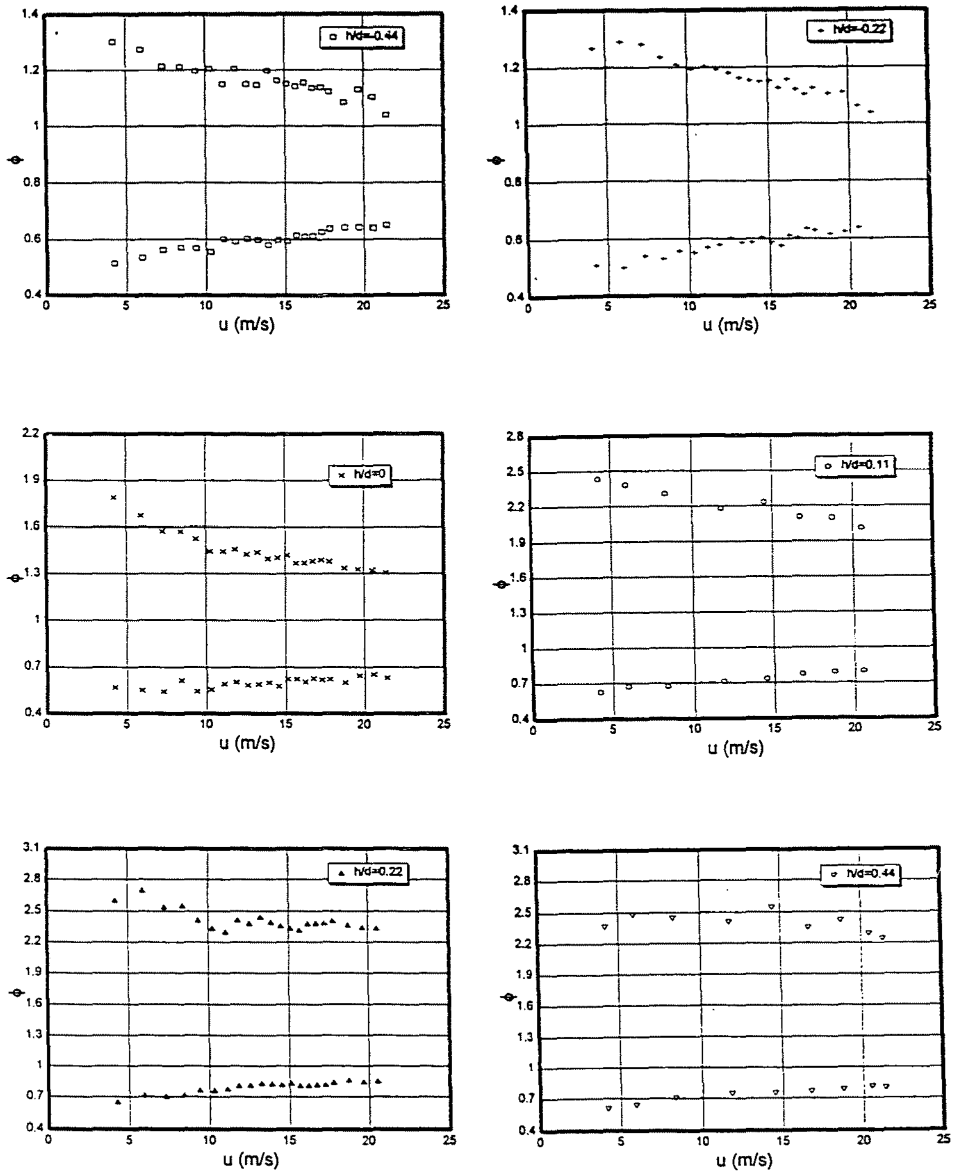

Fig. 2. Effect of flameholder position on flammability limits for disk bluff body with BR = 0.42

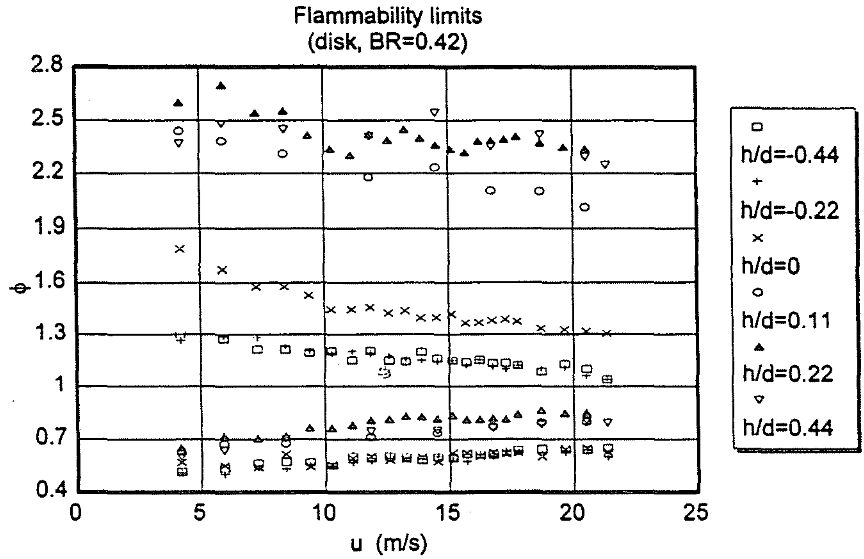

Fig. 3. Natural gas flammability limits variation with stabilizer position (disk)

the rich limit, but it is not so clear for the lean one. The reason behind this result is: when the flame holder moved out of the burner tube the recirculation zone enlarged without any restriction due to the absence of the walls [12].

It is well known that as the recirculation zone volume increases the residence time and the rates of heat and mass transfer between the recirculated hot products and the fresh mixture increase; which means stable flame for richer mixtures. Also there is the effect of the burning velocity that becomes higher for the rich mixture. Unfortunately there are an adverse effect of the entrainment air, that increases as the flame holder moves downstream, and the burning velocity; which rapidly reduces, at the limits, as a result of the change in mixture composition, that becomes nonflammable [13–15]. MANSON [16] mentioned that it had been emphasized by MALLARD that for a given gaseous mixture the flame velocity may be very different upon the confinement (open tubes, closed vessels) of the mixture.

The same results of the flammability limits were noticed, from *Figs. 4* and *5* for the conical flame stabilizer, of course with some variations in the values of the equivalence ratios; that depends on the shape of flame holder.

The influence of flame holder position on the weak extinction equivalence ratio is illustrated also in *Fig. 6* for disk bluff body and in *Fig. 8* for the conical one. It is clear from these figures that the best position of the

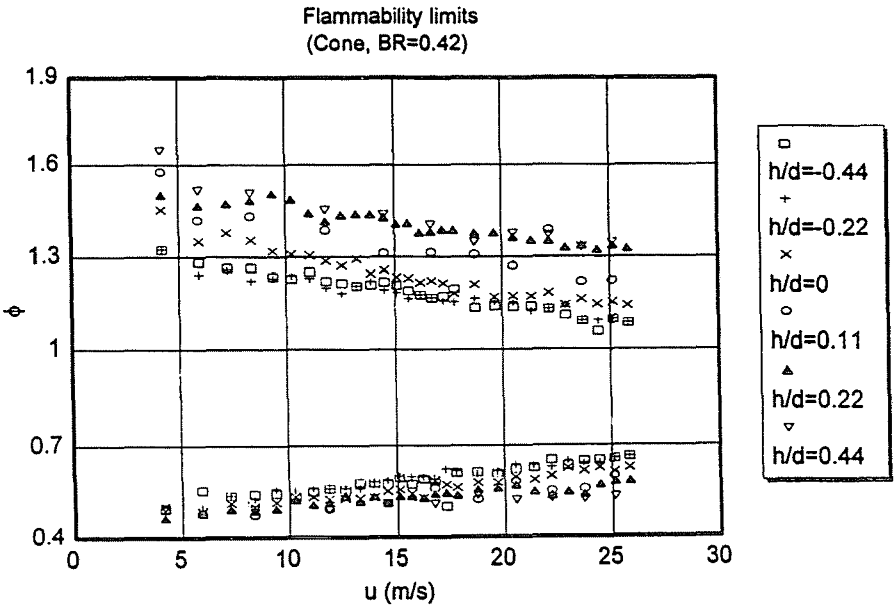

Fig. 4. Influence of stabilizer position on the natural gas flammability limits (cone)

disk flame holder (that achieved a minimum weak extinction equivalence ratio) is at $h/d = -0.22$, while the best position for the conical one is at $h/d = 0.44$.

The effect of flame holder position on the rich limit of flammability is illustrated in *Fig. 7* for disk stabilizer and in *Fig. 9* for the conical one. It is noticed from these figures that the best position of flame holder (that achieved a maximum rich extinction equivalence ratio) is at $h/d = 0.22$ for disk shape and at $h/d = 0.44$ for the conical one.

All of these results and observations are affected and controlled by numerous interference aerodynamics and chemical kinetics parameters, which consequently influences the mechanism of flame stabilization and the mechanism of flame extinction. Flame extinction may be due to heat loss, convection and/or buoyancy, chemical kinetics, flame stretch and preferential diffusion [17–19].

The aerodynamic structure and turbulence characteristics of the recirculation zone formed behind the flame holder is affected by the flow velocity, the shape and position of the bluff body and by the presence of the walls (confinement) [20, 21]. They are also influenced by the vibration of the flame holder; that causes an oscillation of the recirculation zone [22]. The rate of reaction and the chemical kinetics are affected by the heat and mass transfer occurs within the recirculation zone and between the shear

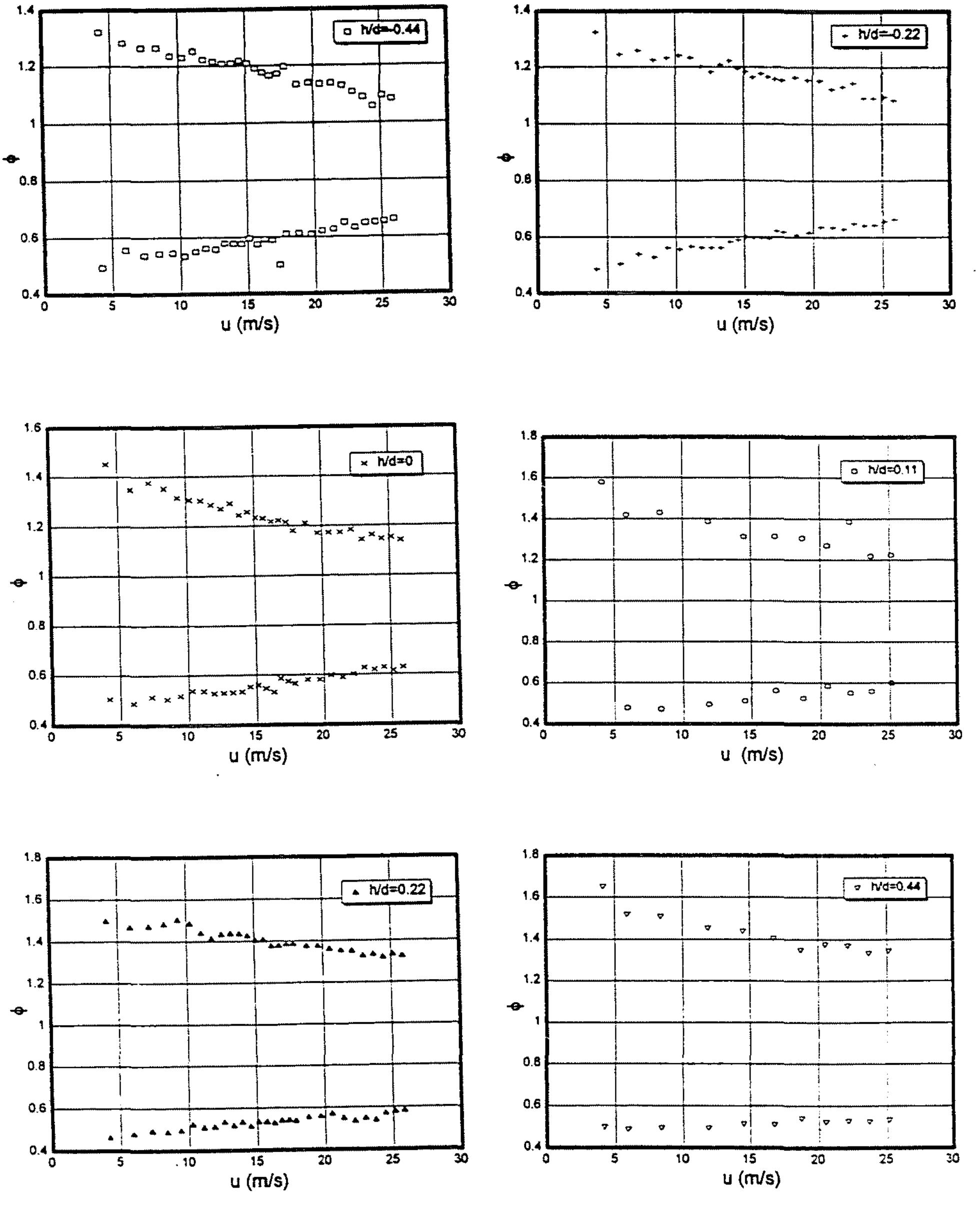

Fig. 5. Effect of flameholder position on flammability limits for conical bluff body with BR = 0.42

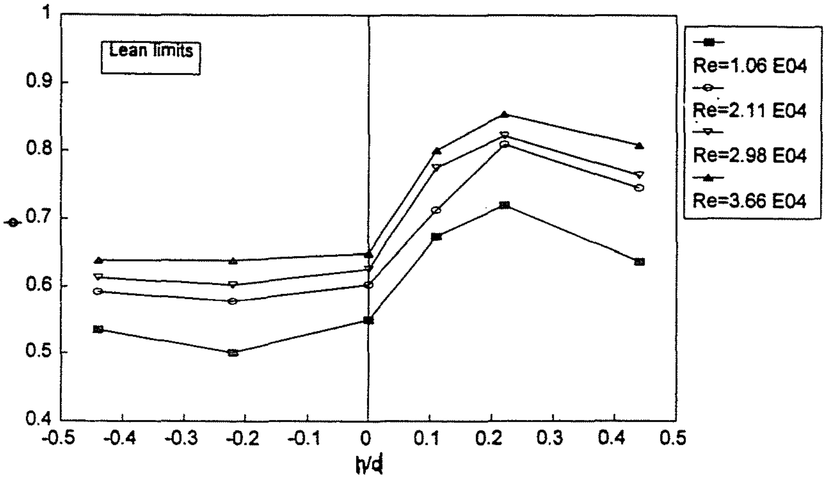

Fig. 6. Mean equivalence ratio versus the flame holder position for some selected flow velocity, (disk, BR = 0.42)

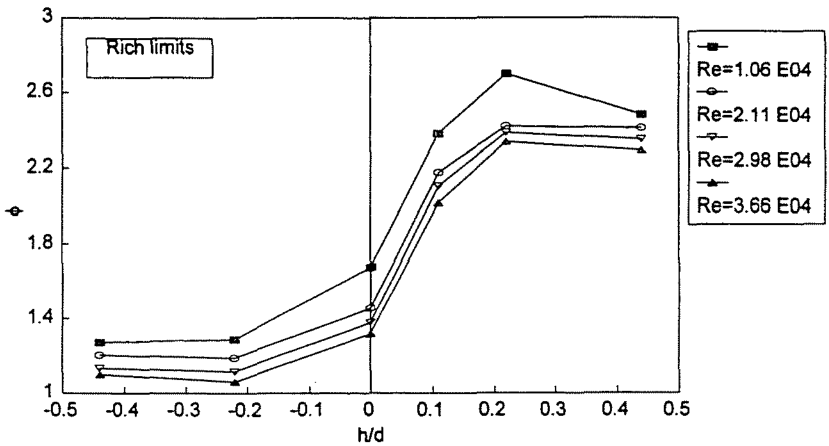

Fig. 7. Mean equivalence ratio versus the flame holder position for some selected flow velocity (disk, BR = 0.42)

layer bounded it and the adjacent mainstream flowing mixture [23]. It is also affected by the wall quenching and by the presence of the entrainment air in unconfined flames.

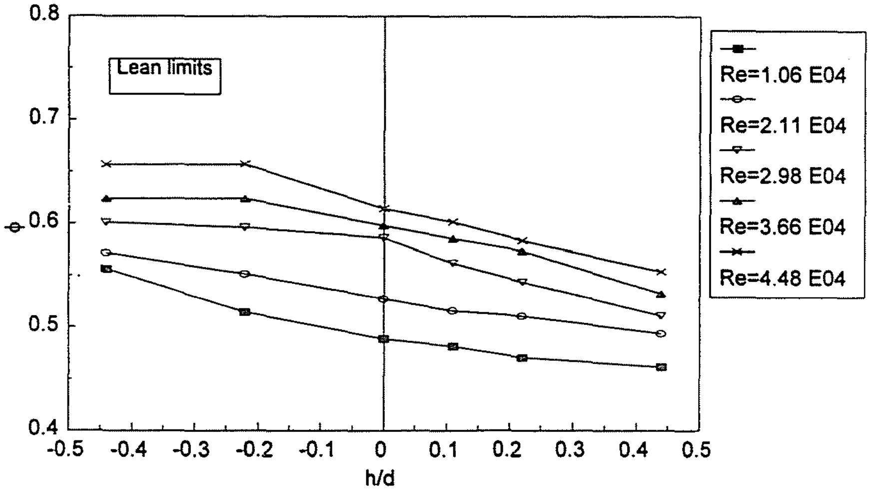

Fig. 8. Mean equivalence ratio versus the flame holder position for some selected flow velocity, (cone, BR = 0.42)

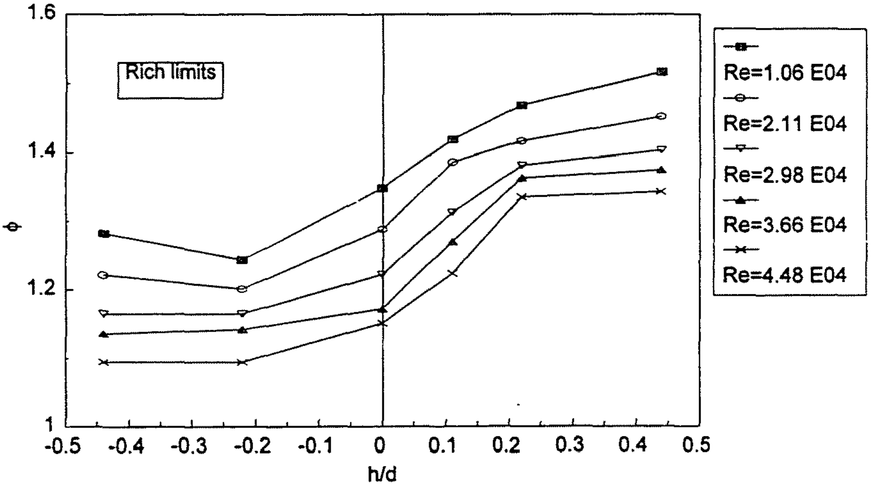

Fig. 9. Mean equivalence ratio versus the flame holder position for some selected flow velocity, (cone, BR = 0.42)

Conclusions

From the analysis and discussion of the experimental results, it is concluded that the flammability limits are widened, specially from rich limit side, due to the use of bluff body and it depends on the position of the flame holder. It is also concluded that the best position of the flame holder — with respect to the burner mouth — is not a fixed value but it depends not only on the shape of the bluff body but also on the nature of study (lean limit or rich limit). For lean limit the best position of the disk flame stabilizer is at 6 mm inside the burner tube ($h/d = -0.22$), while it is 12 mm outside it ($h/d = 0.44$) for the conical one. For the rich limit the best position is 6 mm outside the burner tube ($h/d = 0.22$) for the disk and 12 mm outside it ($h/d = 0.44$) for the cone. It is concluded also that it is important to study the nature of the recirculation zone (its aerodynamics structure and turbulence characteristics), and the exact effect of the flame holder position and the presence of the confinement on it. Also, it is necessary to study the effect of the entrainment air on the results of such open (unconfined) flame measurements; i. e. its effect on combustible mixture dilution, on the percentage of the recirculated mass and on the heat loss from the flame.

Nomenclature

BR blockage ratio
d burner tube diameter
h flame holder location
h/d dimensionless group for flame holder position
P mixture pressure
Re Reynolds number ($u \cdot d/\nu$)
RZ recirculation zone
T mixture temperature
Δt the time interval
u mainstream air velocity
ΔV the volume of fuel flow
φ equivalence ratio
τ residence time
ν kinematic viscosity of air

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