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Article

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Mapping stability of natural gas of concentric flow slot burner by generation different mixing field environments

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Abstract:-

This study experimentally investigates the effects of mixture inhomogeneity and flow configuration on the stabilization of partially premixed flames using different stabilization strategies. Particular attention is given to the combined influence of the mixing length ratio (L/D), fuel flow rate, and burner configuration on flame stability limits. The investigated approaches include the incorporation of a conical stabilizing element, the application of co-flow, and the modification of fuel–air distribution through stratified injection. The results reveal that flame stabilization is strongly governed by the interaction between the local mixture composition and the aerodynamic characteristics of the flow. Among the examined techniques, the conical element exhibited the highest stabilization capability, primarily owing to the formation of a recirculation zone that enhanced reactant residence time and facilitated flame propagation. Co-flow also contributed substantially to flame stabilization by improving flame attachment and reducing unsteady flame behavior. Fuel stratification demonstrated a considerable influence, particularly at relatively low fuel flow rates, where its effectiveness was associated with the modification of the local fuel–air distribution. Moreover, the comparative performance of fuel-inner/air-outer and fuel-outer/air-inner arrangements varied with the stabilization strategy and operating conditions, demonstrating that no single injection configuration provides optimal stability across the entire operating range. These findings establish that flame stability cannot be adequately characterized by global operating parameters alone, since the spatial organization of the mixture and its local composition are equally important. Accordingly, the results provide the experimental basis for developing a mixture-fraction-based stability diagram, which offers a more comprehensive approach to correlating mixing-field characteristics with flame stability limits and interpreting the physical mechanisms governing partially premixed combustion.

Keywords: Partially premixed combustion; Stability Factor; Flame stabilization; Mixture inhomogeneity; Fuel stratification; conical flame holder; Co-flow; Mixture fraction.

Introduction:-

Natural gas represents one of the major energy resources supporting modern industrial and power-generation sectors. Its widespread utilization is attributed to its relatively high calorific value, convenient transportation and distribution, controllable combustion characteristics, and lower

carbon dioxide emissions per unit of energy compared with coal and many petroleum-based fuels. These characteristics make natural gas particularly attractive for industrial heating applications, including furnaces, boilers, kilns, and food-processing equipment, where continuous heat supply and reliable burner operation are essential. Furthermore, the increasing demand for natural gas in industrial processes and electricity generation highlights the importance of developing combustion technologies capable of improving thermal efficiency, operational flexibility, and environmental performance [1]. Nevertheless, the practical utilization of natural gas involves several combustion-related challenges, including flame instability, flashback, flame lift-off, blow-off, and the formation of nitrogen oxides under high-temperature operating conditions. Therefore, the development of burner configurations that provide reliable flame stabilization over a wide range of operating conditions remains an important research objective [2–5].

Flame stabilization is governed by the interaction between chemical reaction rates, turbulent transport, heat transfer, and the aerodynamic structure of the reacting flow. Depending on the fuel and oxidizer injection arrangement, combustion systems can operate under premixed, non-premixed, or partially premixed conditions. Among these configurations, partially premixed combustion has received considerable attention because it combines the characteristics of premixed and diffusion flames and allows the formation of different local mixture compositions within the same combustion region. In practical burners, complete fuel–air homogenization is not always achieved before ignition, resulting in spatial variations in equivalence ratio and mixture fraction. These variations can influence local flame propagation, reaction-zone development, and resistance to extinction. Consequently, controlling the degree of premixing and the spatial distribution of the reactants provides an additional mechanism for manipulating flame structure and stability [6–9].

The influence of mixture stratification on flame stabilization has been investigated using different burner configurations and fuel–air injection strategies. Experimental and numerical investigations of stratified turbulent flames have demonstrated that variations in the local fuel–air ratio can modify the flame structure and its response to aerodynamic disturbances. In particular, the presence of locally enriched and lean regions can establish different flame-propagation conditions within the same reaction zone. Mitsopoulos et al. [5] investigated the influence of inlet mixture stratification on turbulent, prevaporized n-heptane–air flames stabilized behind a bluff body. Their findings demonstrated that changes in the incoming equivalence-ratio distribution and mixing-layer topology affect the flame characteristics and stabilization process. In a related study, Arndt et al. [10] examined the influence of fuel staging on thermoacoustic oscillations in a premixed stratified gas-turbine combustor, further highlighting the importance of fuel distribution in determining the dynamic response of stratified combustion systems. Similarly, investigations of turbulent methane–air mixtures have shown that compositional inhomogeneity can modify the combustion response and, under appropriate conditions, improve flame stability and heat-release characteristics [11]. These observations emphasize that global equivalence ratio alone cannot adequately represent the combustion behavior of stratified mixtures, since the local mixture composition and its spatial distribution also contribute to the stabilization mechanism.

In addition to mixture composition, the aerodynamic characteristics of the burner play a fundamental role in establishing stable combustion. Bluff bodies and other flame-holding elements are widely employed to generate low-velocity regions and recirculation zones downstream of the

burner outlet. These regions provide a mechanism for transporting hot combustion products and chemically active species towards the incoming reactants, thereby promoting ignition and maintaining continuous flame propagation. Wang et al. [2] investigated the ignition, propagation, and stabilization mechanisms of premixed jet flames generated by a bluff-body burner. Their results demonstrated the importance of the recirculation region and surrounding hot gases in determining the flame-development process. Zhang et al. [3] further examined partially premixed ignition using a bluff-body flame holder under different inlet and ignition conditions, highlighting the influence of flow-field characteristics on the development of the reaction zone. These investigations established that the effectiveness of a flame holder depends not only on its physical geometry but also on its interaction with the incoming mixture and the resulting flow structure. The influence of operating conditions and fuel characteristics on combustion stability has also been investigated in premixed natural-gas and methane-based burners. Cadavid et al. [4] examined the effects of atmospheric humidity and natural-gas composition on combustion behaviour under unstable operating conditions. Their findings indicated that fuel composition and the presence of water vapor can modify flame structure and combustion instability. Butz et al. [6] investigated turbulent methane–air flames operating in different combustion regimes using combined Raman/Rayleigh spectroscopy and conditional velocity-field measurements. Their results demonstrated that flame stabilization was strongly associated with the recirculation of hot combustion products and the interaction between different combustion regimes. In a complementary investigation, Elbaz et al. [7] characterized the mixing fields of natural gas and propane in highly turbulent planar flames using Rayleigh scattering. Their results demonstrated that the mixing-field structure is strongly dependent on fuel composition, Reynolds number, equivalence ratio, and premixing length. Together, these studies demonstrate the importance of combining scalar-field measurements with aerodynamic information to obtain a more comprehensive understanding of turbulent flame stabilization. The development of alternative aerodynamic stabilization techniques has also received considerable attention. Gani and Saravanan [8] numerically investigated partially premixed butane–air flames in a tubular burner, examining the effects of primary aeration, co-flow, and co-swirl on flame behavior. Their findings showed that the influence of secondary airflow depends on its interaction with the primary flow and the resulting recirculation structures. In particular, co-swirl improved stabilization through the formation of a favorable recirculation region, whereas co-flow could adversely affect stability under certain conditions because of increased flame stretching and aerodynamic quenching. These findings indicate that secondary-flow injection cannot be considered universally beneficial; its effectiveness depends on the operating conditions and the aerodynamic interaction with the main flame. Further investigations have explored the role of burner geometry and heat recirculation in extending the stable operating range of natural-gas combustion systems. Hamed et al. [12] examined different hollow bluff-body configurations for natural-gas–air premixed flames. Their results revealed that the shape, blockage ratio, and internal geometry of the stabilizing element significantly affect the wake-flow structure, residence time, and flame stability limits. In a related investigation, Hamed et al. [13] studied the characteristics of hollow bluff-body-stabilized flames incorporating heat recirculation. Their findings showed that suitable geometric arrangements can enhance preheating and flow reversal, resulting in improved flame stabilization and wider operating limits. These investigations demonstrate that modifying the burner geometry provides an effective means of controlling the aerodynamic environment and enhancing the interaction between the incoming reactants and the recirculated combustion products.

Other investigations have focused on the relationship between mixture inhomogeneity and combustion performance. Studies conducted using constant-volume combustion chambers have demonstrated that stratified methane–air mixtures can produce different combustion responses depending on the background equivalence ratio and the degree of compositional variation [11]. Experimental investigations of lean premixed methane–air combustion in divergent porous burners have also demonstrated that modifying the burner structure can extend the blow-off limit and improve flame stability while maintaining relatively low pollutant emissions [14]. In addition, experimental studies of turbulent methane–air and oxygen-enriched flames have shown that fuel-injection configuration, aerodynamic conditions, and oxidizer composition influence flame structure, emissions, and stability [15]. These results reinforce the importance of investigating the combined effects of injection arrangement, mixing characteristics, and burner geometry rather than considering each parameter independently. Recent research has further extended the investigation of mixture inhomogeneity to multi-fuel and alternative combustion systems. Experimental studies examining methane–ammonia blends have demonstrated that the mixing process and the resulting flame structure are important factors governing flame stability and emissions [16]. Furthermore, investigations of methane combustion under different dilution conditions have shown that the addition of diluent species can modify flame propagation and combustion instabilities through combined thermal and chemical effects [9]. These findings are particularly relevant to natural-gas-based combustion systems because they demonstrate the sensitivity of flame behavior to changes in mixture composition and local thermochemical conditions. Complementary findings were reported by Al-Bulqini et al. [17], who investigated the combined effects of mixture inhomogeneity and turbulence on flame-front curvature and flame surface density in turbulent natural-gas flames. Their study highlighted the importance of considering both the spatial distribution of the mixture fraction and the turbulent flow characteristics when describing flame-front structure and its evolution. A more detailed understanding of partially premixed flame structure was provided by Khedr et al. [18], who experimentally investigated the mixing field and reaction-zone structure of turbulent planar flames at different levels of mixture inhomogeneity. Using a concentric flow slot burner, they demonstrated that increasing the mixing length reduces the degree of mixture inhomogeneity and modifies the structure of the reaction zone. Their observations revealed a transition between different reaction-zone configurations, emphasizing the importance of controlling the upstream mixing process. In a separate investigation, Liu et al. [19] examined methane–air combustion in hot co-flow conditions using bluff-body and non-bluff-body configurations. Their findings demonstrated that the bluff body generates a recirculation region that enhances mixing and affects combustion stability, while the temperature and oxygen concentration of the surrounding co-flow influence the resulting combustion characteristics. The importance of burner structural parameters has also been demonstrated in natural-gas-fired systems. Experimental and numerical investigations of multi-port natural-gas burners have shown that the fuel-injection arrangement and burner geometry can influence local temperature distributions, flame stability, and nitrogen oxide formation [20]. Similarly, numerical investigations of water-cooled premixed natural-gas burners have demonstrated that structural modifications and operating parameters affect heat transfer, flame stability, and the tendency towards flashback [21]. In addition, studies of methane micromix combustion have shown that the interaction between impinging jets and the surrounding flow can enhance near-field turbulence and improve flame anchoring by modifying the local flame-stretching characteristics [22]. These results highlight the importance of burner geometry as a design parameter that can be used to control both the aerodynamic and thermal environments of the flame. Further insight into the

interaction between premixed and non-premixed combustion regimes has been obtained through numerical investigations of multi-regime methane–air burners. Hikkimath and Patel [23] demonstrated that the interaction between lean and rich reactant streams and the associated recirculation structures can substantially influence flame development and stabilization. Moreover, experimental investigations of stratified swirl burners have demonstrated that modifying bluff-body geometry can affect both nitrogen oxide emissions and the overall combustion characteristics [24]. These findings indicate that the relationship between fuel stratification and aerodynamic stabilization is highly dependent on burner configuration and should be evaluated under a range of operating conditions. More recently, Mansour et al. [25] investigated the mixing-field structure and its relationship with flame stabilization in turbulent, inhomogeneous, partially premixed natural-gas–air flows using a concentric flow slot burner. High-resolution Rayleigh scattering measurements were employed to quantify the mixture-fraction distribution and its spatial gradients under different Reynolds numbers, equivalence ratios, and mixing length ratios. A three-axis regime diagram was developed using the mean mixture fraction, its fluctuation range, and the maximum scalar gradient to characterize the degree of mixture inhomogeneity. Their findings demonstrated that the mixing length ratio and equivalence ratio exert a significant influence on mixture stratification and scalar-gradient intensity, whereas the Reynolds number has a comparatively weaker influence on the overall mixing-field characteristics. The study also established a relationship between steeper mixture-fraction gradients, thinner mixing layers, and flame stabilization, providing a quantitative approach for characterizing the influence of local mixing conditions on combustion behavior. Despite the considerable progress achieved in understanding turbulent partially premixed combustion, the combined effects of mixture inhomogeneity, fuel–air injection configuration, and aerodynamic stabilization techniques remain insufficiently characterized. In particular, the relative effectiveness of conical flame stabilization, co-flow introduction, and fuel stratification under different fuel flow rates and mixing conditions requires further experimental investigation. The influence of reversing the fuel and air positions between the inner and outer slots also deserves particular attention, since this modification changes the local momentum distribution, mixing-layer development, and spatial organization of the reactants. Furthermore, the effectiveness of an individual stabilization technique may vary with the mixing length ratio and fuel flow rate, suggesting that an optimum stabilization configuration cannot be identified independently of the operating conditions.

To address these research gaps, the present study experimentally investigates the stability characteristics of partially premixed natural-gas flames generated using a concentric flow slot burner (CFSB). The experimental program systematically examines the effects of the mixing length ratio (L/D), fuel flow rate, and fuel–air injection arrangement, together with the implementation of three stabilization approaches: a conical stabilizing element, secondary co-flow, and controlled fuel stratification. Both fuel-inner/air-outer and fuel-outer/air-inner configurations are considered to establish how the spatial arrangement of the reactants influences the stable operating range. Particular emphasis is placed on identifying the conditions under which each stabilization strategy becomes most effective and explaining the physical mechanisms responsible for the observed differences. The main contribution of this work is the systematic comparison of these stabilization approaches within a unified experimental framework, providing a direct assessment of the interaction between mixture inhomogeneity, injection configuration, and aerodynamic flame holding. The resulting stability measurements also provide the experimental foundation for developing a mixture-fraction-based stability diagram, which can establish a

quantitative relationship between local mixing-field characteristics and the stability limits of partially premixed natural-gas flames.

2. Experimental setup:-

The experimental investigations presented in this study were conducted using a Concentric Flow Slot Burner (CFSB), which was originally designed by Mansour et al. [25]. The burner was developed to produce turbulent planar flames with controlled levels of fuel-air inhomogeneity. Compared with the earlier concentric flow conical nozzle burner (CFCN), the slot geometry minimizes the influence of nozzle curvature on the mixing process, flame structure, and combustion stability. A schematic illustration of the burner is presented in Fig.1 (a) and Fig.1 (b), showing its two concentric rectangular flow passages. The burner operates in an inverse diffusion flame (IDF) configuration [5-25], where the oxidizer is introduced through the central rectangular slot while the fuel is supplied through the two outer slots. The central air-slot width is represented by a, whereas the width of each outer fuel slot is represented by b. A photograph of a representative flame produced by the burner is shown in Fig. 1(c). A distinguishing feature of the CFSB is the adjustable recess distance, L, between the exit planes of the inner air slot and the outer fuel slots, as illustrated in Fig.1 (a). This recessed section serves as a premixing region, allowing the degree of fuel-air mixing to be varied before the reactants leave the burner. Consequently, the level of mixture inhomogeneity at the burner exit can be controlled by changing the premixing length. Throughout this work, the premixing length is expressed in a normalized form using the burner hydraulic diameter at the exit, D = 17.14 mm. The exit nozzle maintains a constant rectangular cross-section of 10 mm × 60 mm, as indicated in Fig.1 (b). The burner geometry is characterized by the ratio of the air-slot area (A_a) to the total fuel-slot area (A_f), commonly referred to as the area ratio (A_R). In the present configuration, the air-slot width is 6 mm, while each fuel slot has a width of 1 mm. Since the air and fuel slots have identical lengths, the area ratio depends only on their respective widths and is defined as eq (1).

$$A_R = \frac{A_a}{A_f} \qquad (1)$$

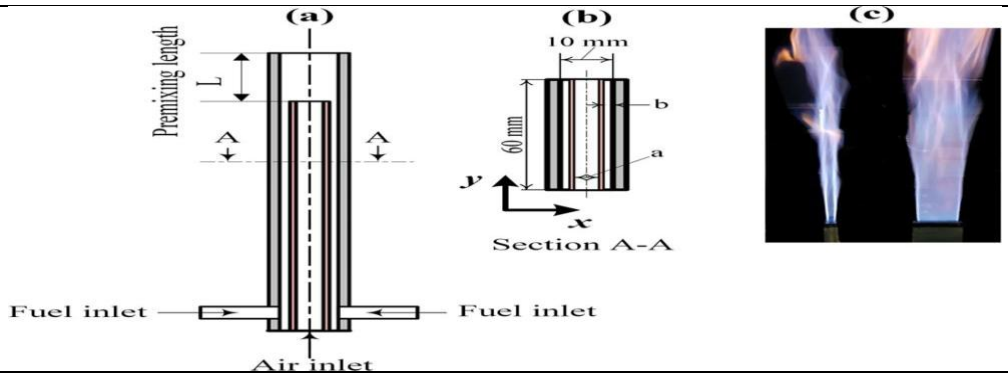


Figure 1 (a) Schematic diagram of the CFSB burner while and also refer to places that air and fuel can enter burner (b) A sectional view A-Ashowing the arrangements of air and fuel slots with dimensions (c) side and front of developed planar flame from left to right.

3. Methodology

Flame stability characteristics of the Concentric Flow Slot Burner (CFSB) over a broad range of normalized premixing lengths (L/D). The objective is to examine how different stabilization methods influence the operating limits and overall flame behavior under partially premixed conditions. The study begins with the burner operating without a stabilization cone, providing a reference case for evaluating subsequent modifications. Three stabilization cones of different dimensions are then introduced to determine the influence of cone size on flame attachment, blow-off resistance, and the extent of the stable combustion region. A detailed comparison is performed among all configurations to identify the advantages and limitations of each design. Based on the observations obtained from these experiments, an alternative stabilization strategy is proposed and assessed under the same operating conditions. The effectiveness of this new approach is evaluated by comparing its stability performance with that of the conventional burner and the three cone configurations. The results presented in this chapter provide a systematic assessment of how burner geometry and premixing length affect flame stability, offering useful insights for improving the design and operation of CFSB systems over a wide range of combustion. The flame stability experiments were conducted in the Engines Laboratory at the Cairo University using the Concentric Flow Slot Burner (CFSB). Compressed air was supplied from the laboratory air distribution system and delivered to the central slot of the burner. The supply pressure of 10 bar was reduced to a regulated pressure of 3 bar (gauge) before entering the flow control system. The air flow rate was adjusted using a precision needle valve and measured by a Sergio 3500 digital flow meter with an operating range of 0–250 L/min. The instrument provides a measurement accuracy of ± (0.8% of the reading + 0.2% of full scale), ensuring reliable control of the oxidizer flow. Natural gas was introduced through the two outer fuel slots from the laboratory gas supply network. Similar to the air line, the fuel flow was regulated by a precision needle valve before passing through a Sergio MF3500 digital mass flow meter, which operates over a range of 0–100 L/min with an accuracy of ± (0.8% of the reading + 0.2% of full scale). The outputs of both flow meters were continuously transmitted to a data acquisition system, allowing real-time monitoring and calculation of the Reynolds number and the global equivalence ratio throughout the experiments as shown in figure 2. To provide well-defined inlet conditions and reduce the influence of external disturbances, the burner was installed inside a wind tunnel having a square exit section of 250 mm × 250 mm. A blower supplied a uniform co-flow air stream around the burner. In addition, a series of honeycomb elements and fine-wire mesh screens were mounted upstream within the wind tunnel to suppress turbulence, remove large-scale eddies, and promote a nearly uniform velocity profile. This arrangement ensured stable boundary conditions and enhanced the repeatability and accuracy of the flame stability measurements. IN this section, the flame stabilization strategies investigated for the Concentric Flow Conical Burner (CFCB) are presented and discussed in detail. As illustrated in Figure 3, several stabilization techniques were implemented to investigate flame stability over a broad range of operating conditions and mixing field environments. Each strategy is described separately, with emphasis on its operating concept, implementation, and effect on flame behavior. The investigated configurations include the fuel-outer/air-inner arrangement, the fuel-inner/air-outer arrangement, the mixture-outer/air-inner

arrangement, cone-assisted stabilization, and co-flow-assisted stabilization. All experiments were performed using Egyptian natural gas as the fuel under identical test conditions (88% CH4, 7.8%C2H4, 1.9%CO2, and 1.2% N2 another are hydrocarbon and hydrogen). Flame stability was evaluated by determining the extinction limit, where each stability point represents the operating condition at which the flame was extinguished. A comparison among the investigated strategies is presented to identify the most effective method for extending the stable operating range and enhancing the overall combustion performance of the CFCB.

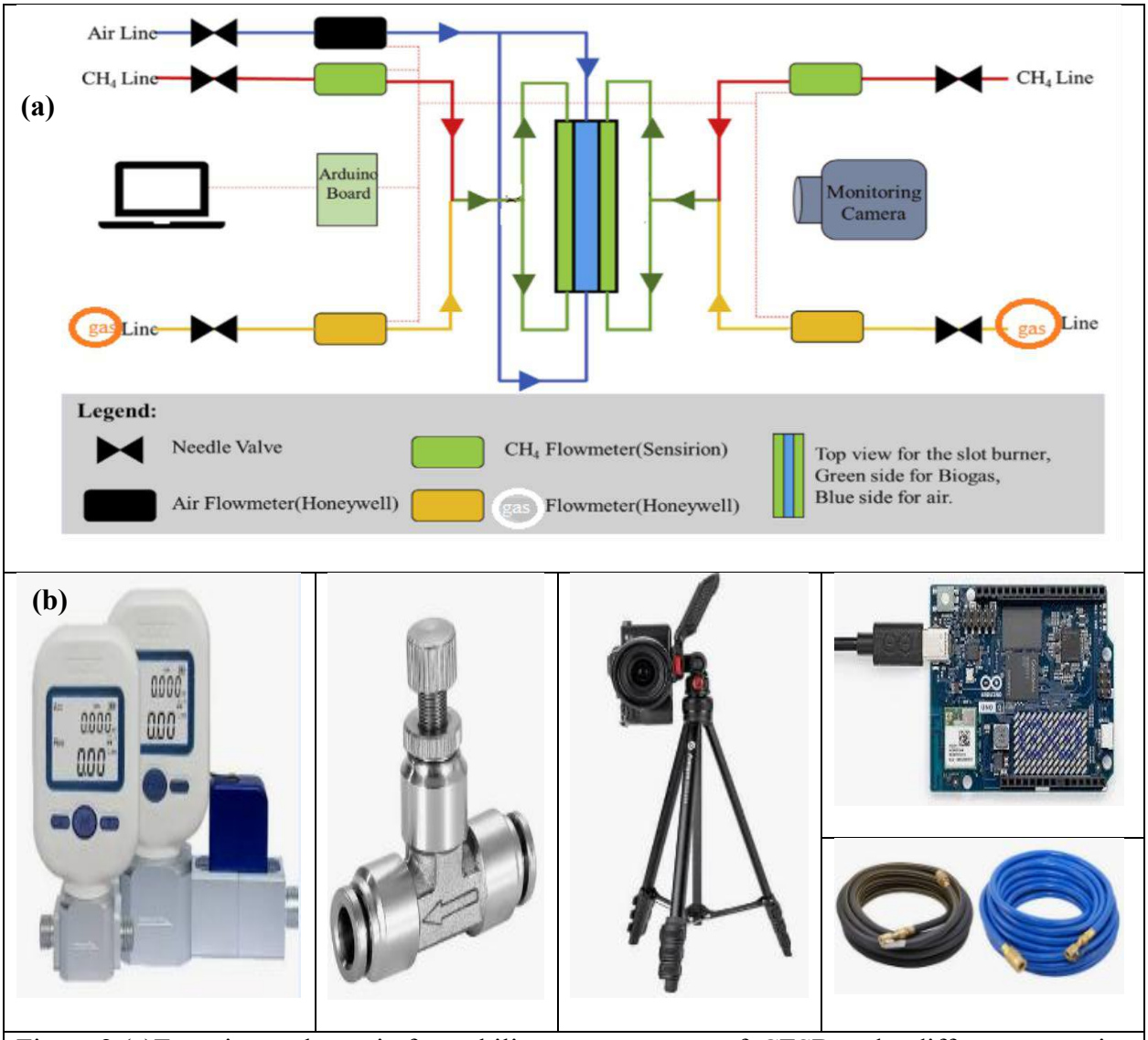


Figure 2.(a)Experimental test rig for stability measurements of CFSB under different strategies (b) real images of test rig components from left to right MF3500 flow meter, needle valve for flow control, tripod and digital camera monitoring, arduino board and pneumatics hoses

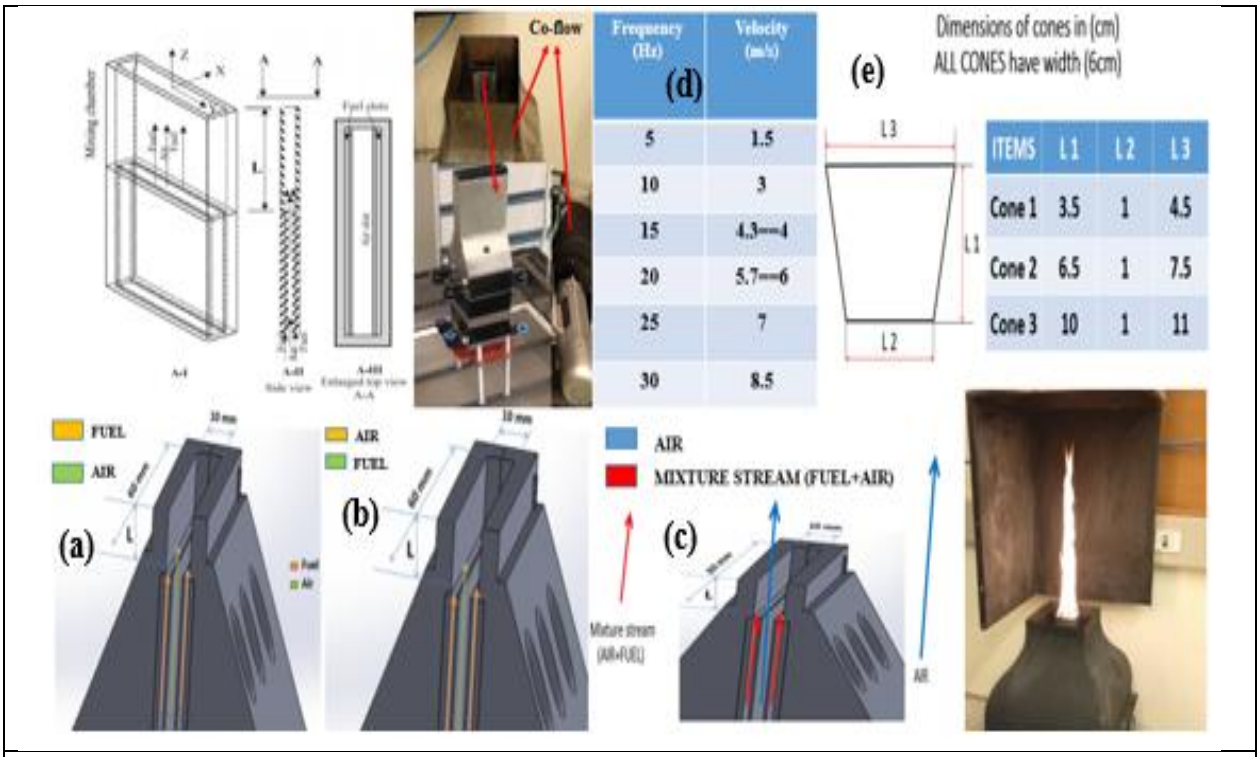


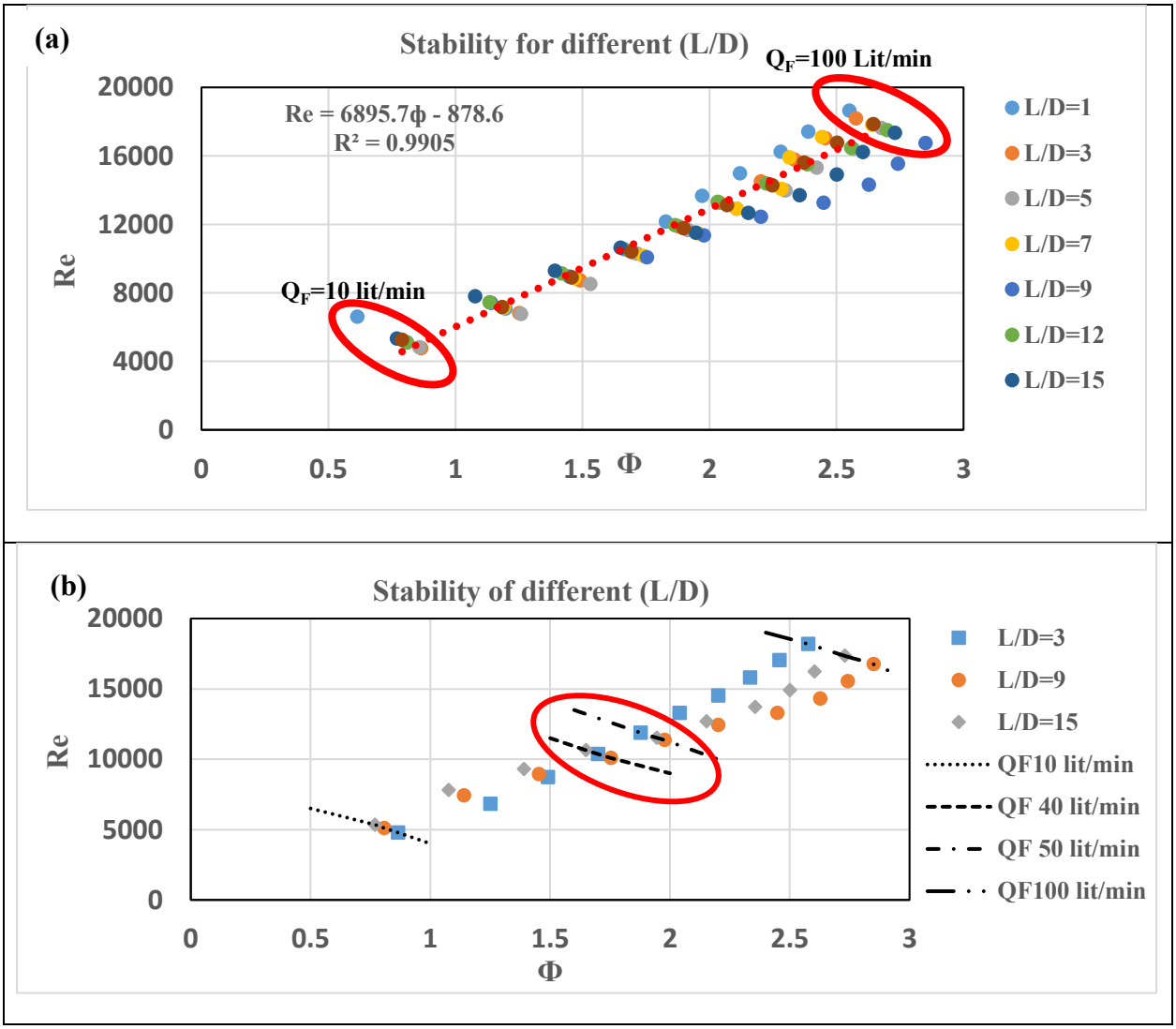
Figure 3:- different stability strategies for CFSB,(a)-(fuel out-air in)-(b)-(fuel in –air out)- (c)-(mixture out air in)-(d)-(fuel out air in, co flow) –(e)-(fuel out air in, cone stability)

4. Results and discussion.

In this section, the flame stabilization strategies investigated for the Concentric Flow Conical Burner (CFCB) are presented and discussed in details. Each of these strategies can generate new mixing field environment as illustrated in Figure 3, several stabilization techniques were implemented to improve flame stability over a broad range of operating conditions. Each strategy is described separately, with emphasis on its operating concept, implementation, and effect on flame behavior. The investigated configurations include the fuel-outer/air-inner arrangement, the fuel-inner/air-outer arrangement, the mixture-outer/air-inner arrangement, cone-assisted stabilization, and co-flow-assisted stabilization. All experiments were performed using Egyptian natural gas as the fuel under identical test conditions. Flame stability was evaluated by determining the extinction limit, where each stability point represents the operating condition at which the flame was extinguished. A comparison among the investigated strategies is presented to identify the most effective method for extending the stable operating range and enhancing the overall combustion performance of the CFCB.

4.1. (Fuel out-Air in) mixing field

In this approach, flame stability was evaluated by gradually increasing the fuel flow rate from 10 L/min to 100 L/min. For the burner used in this investigation, the resulting air-to-fuel area ratio is A_R = 3, providing the desired flow distribution between the oxidizer and fuel streams. For each selected fuel flow rate, the air flow rate was progressively increased until flame extinction occurred. The relationship between the Reynolds number (Re) and the equivalence ratio was then established to examine the stability limits at different levels of mixture inhomogeneity (L/D). The resulting stability maps, presented in Figure 4, illustrate the effect of inhomogeneity on the extinction boundaries and provide a basis for comparing the flame stabilization characteristics under the investigated operating conditions.



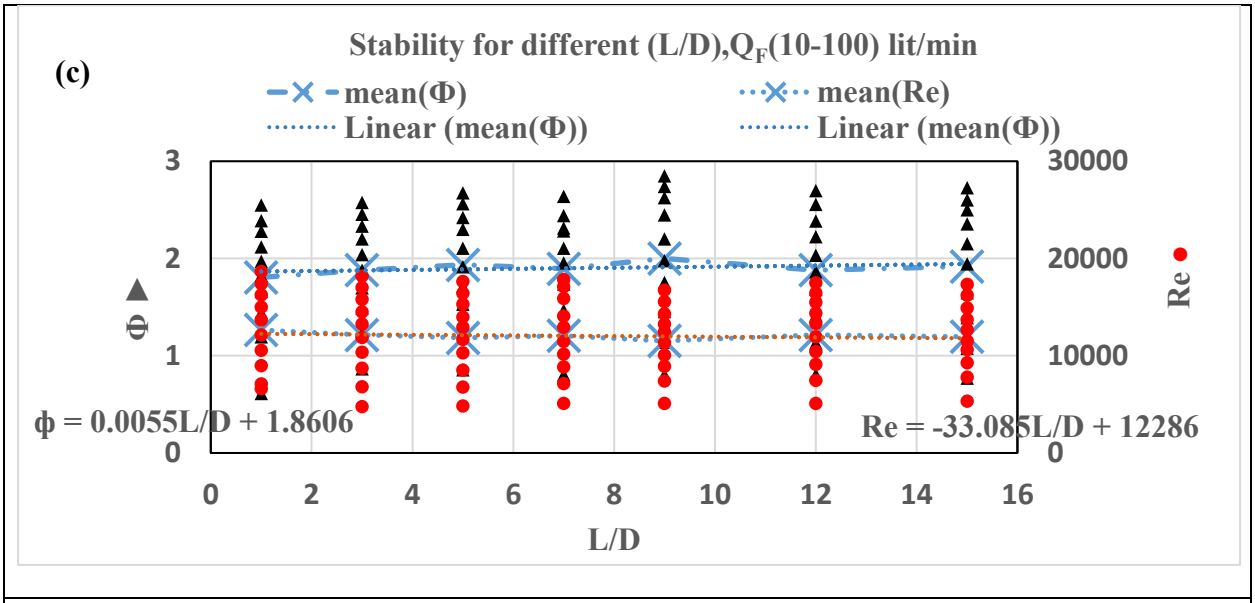


Figure 4 :- (a) represent stability for different (L/D=3 to 15] from low amount of fuel(10Lit/min) to high amount of fuel reach to 100 Lit/min ,(b) Represent how stability change at certain value of fuel red circle,(c)represent values of Re and ϕ for fuel from 10-100 lit/min for each L/D.

It is noticeable that, under lean mixture conditions, increasing the level of mixture inhomogeneity generally improves flame stability. However, beyond a certain fuel flow rate ((Q_F)), the stability curves intersect, indicating that higher inhomogeneity becomes less stable than lower inhomogeneity levels. This behavior is illustrated in Figures 4(a) and 4(b). The influence of increasing the inhomogeneity level through a larger L/D ratio on the Reynolds number and equivalence ratio trends is presented in Figure 4(c).

To provide a more comprehensive interpretation of the stability characteristics, the stability curves were divided into several distinct regions, as illustrated in Figure 5 for the different L/D values and this provide us with complete view about mixing field environment and its effect about stability. Flame extinction is achieved by increasing the jet velocity. In the concentric flow burner, two modes of flame extinction occur: blow-off from attached conditions or blow-out from lifted conditions, as discussed in details in our previous study [12]. Figure 5 illustrates the sequence of a flame extinction from blow-out, the second mode. The flame starts as attached, then by increasing the jet velocity at the same equivalence ratio, the flame is lifted to near blow-out and then blow-out. This is different than extinction from attached, defined as blow-off. The conical nozzle stabilizes the jet flame at the bottom of the conical nozzle which prevent lifting or blow- off extinction. In figure 6 all these stability points registered to imitate actual flame extinguish and finite point (A) as showed in figure 6b and this point represents main point for flame stability transitions .Equivalence ratio and Re of this point are plotted versus different L/D to finite this

relation of stability with flame conditions and also to compare this burner with another burner Concentric Flow Conical Burner.

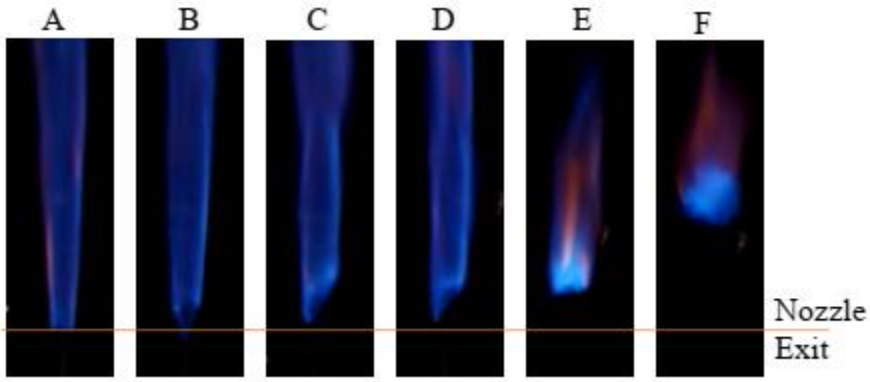
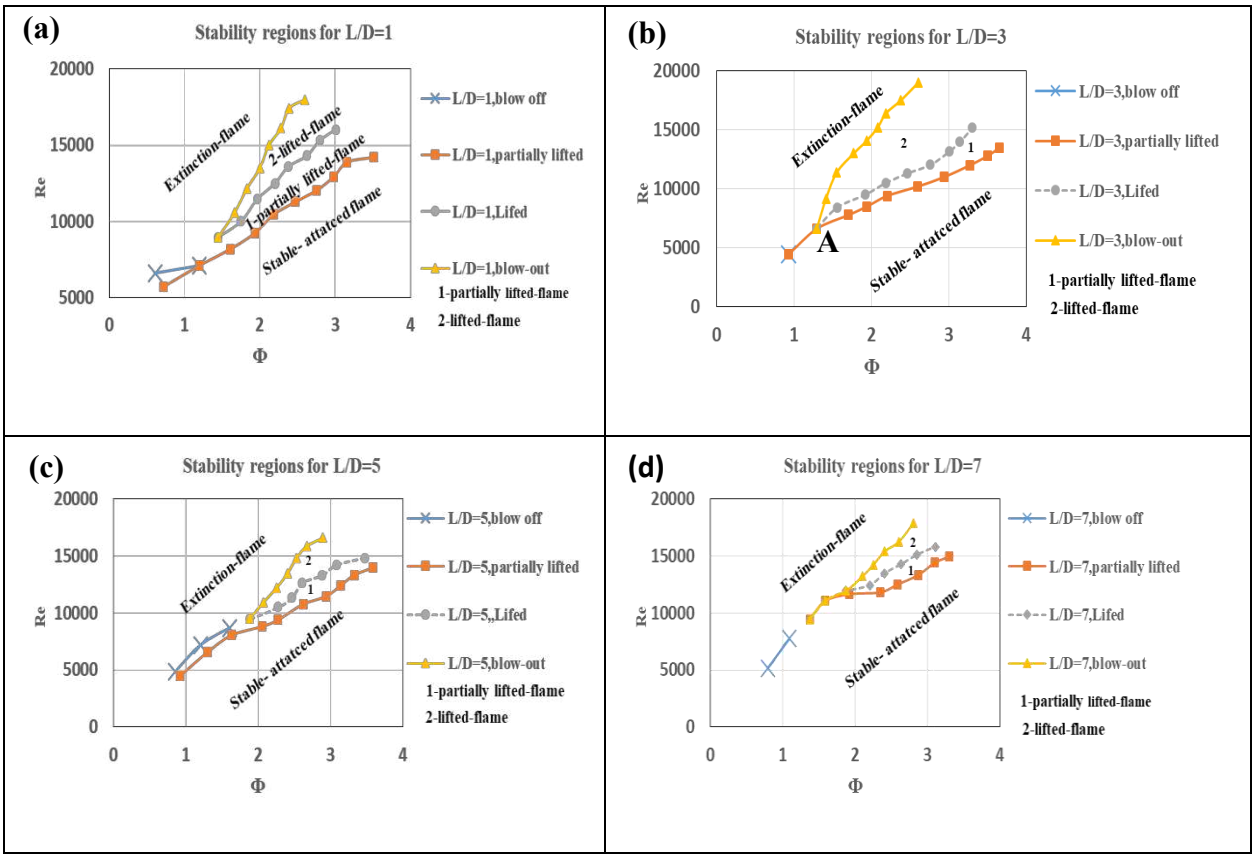


Figure (5):-Sequence of flame blow-out from lifted conditions without the conical nozzle. The flame changes from left to right by increasing the jet velocity at the same equivalence ratio (ϕ = 2): (A) attached, (B-E) lifted and partially lifted, (F) close-to-extinction, and finally blow-out.



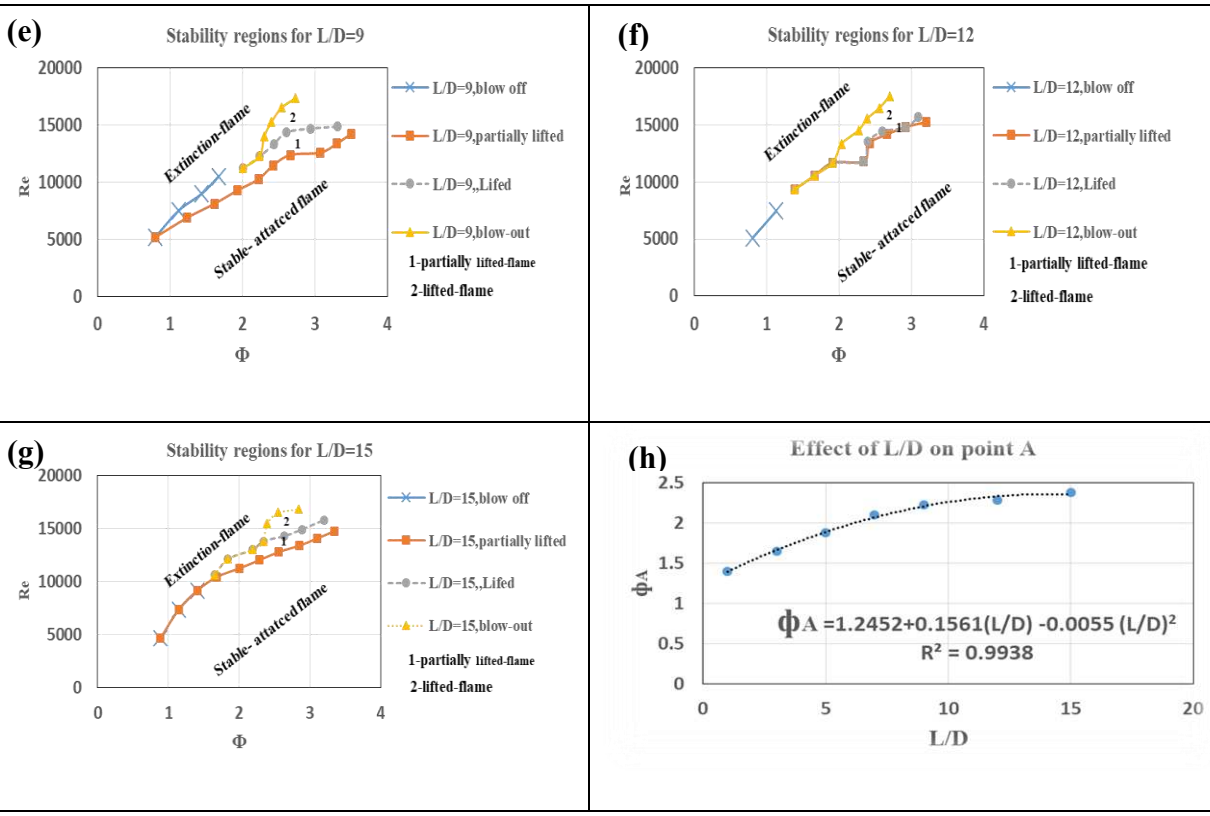
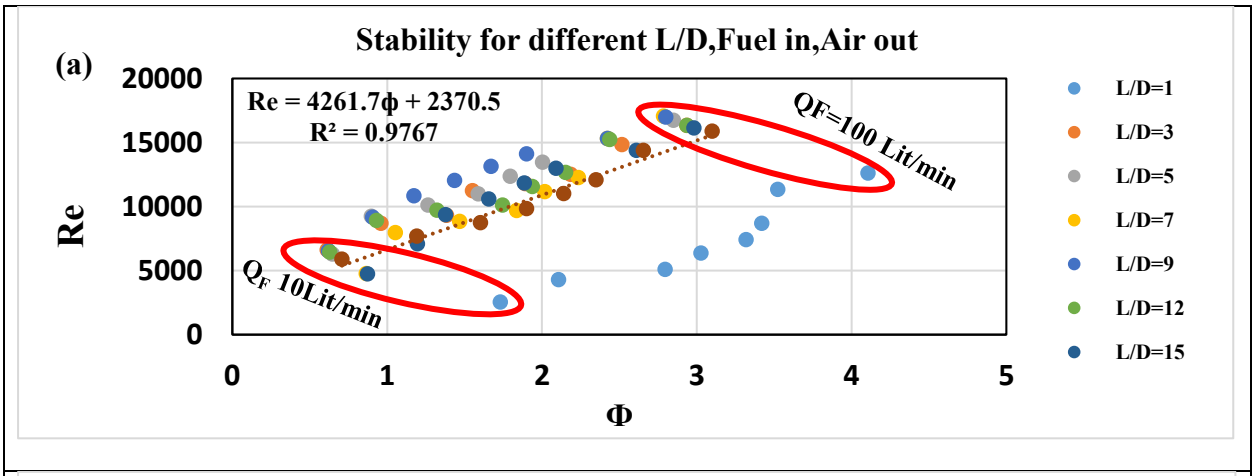


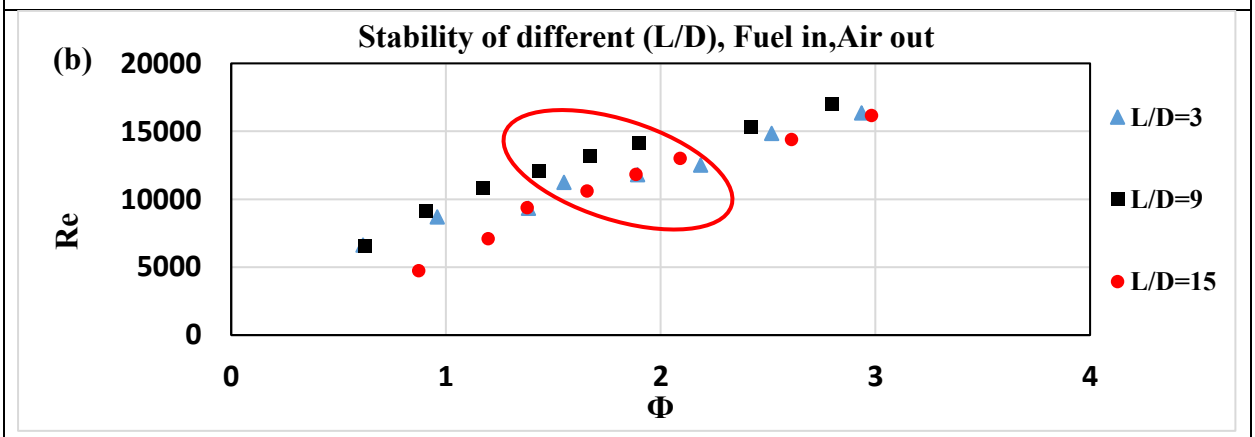
Figure 6..illustrate investigation of point A that represent seperation point for different stability regions for different L/D ((a) to (g)),(h) represent relation between equivalence ratio at (A) and L/D.

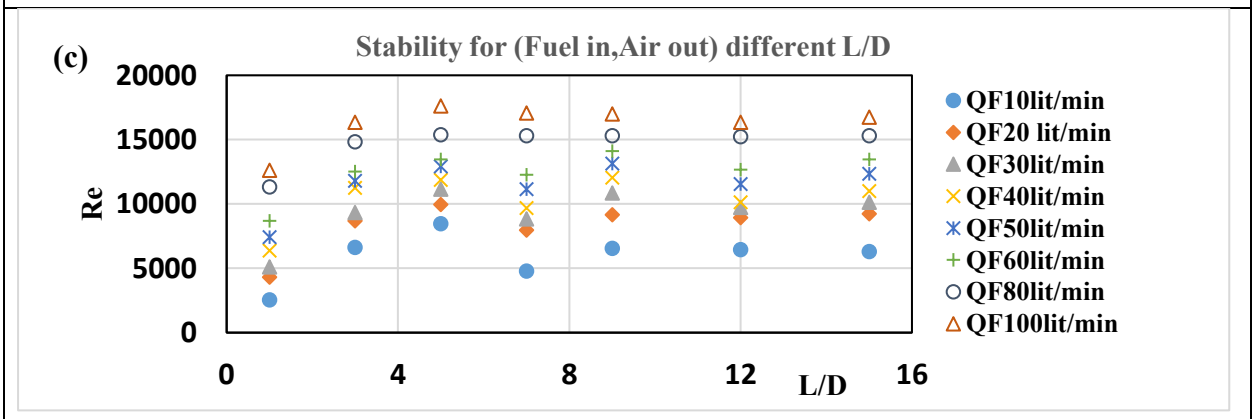
4.2 (Fuel in – Air out) mixing field

In this strategies we will scan stability by increasing fuel from 10 lit/min to 100 lit/min for each fuel quantity we will increase air until flame extinguish. For the burner used in this investigation, the resulting air-to-fuel area ratio is A_R = 1/3, providing the desired flow distribution between the oxidizer and fuel streams.

Relation between Reynolds number (Re) and equivalence ratio is plotted to investigate stability for different level of inhomogeneity (L/D) as shown in figure 7.Applying this method will enhance idea that CFSB can achieve high stability level with different strategy. By analysis stability curves that are obtained from stability measurements refer that also there is optimized stability that can achieve at certain level of homogeneity (L/D) then stability curve became straight and this phenomena will disappear by increasing fuel quantity . Also at lower L/D=1 stability achieve its lower value but there is certain values of inhomogeneity level that can achieve higher stability (L/D=5, L/D=9).


(a)
Stability for different L/D,Fuel in,Air out
Re = 4261.7ϕ + 2370.5
R² = 0.9767
QF=100 Lit/min
QF 10Lit/min
Re
Φ
L/D=1
L/D=3
L/D=5
L/D=7
L/D=9
L/D=12
L/D=15


(b)
Stability of different (L/D), Fuel in,Air out
Re
Φ
L/D=3
L/D=9
L/D=15


(c)
Stability for (Fuel in,Air out) different L/D
Re
L/D
QF10lit/min
QF20 lit/min
QF30lit/min
QF40lit/min
QF50lit/min
QF60lit/min
QF80lit/min
QF100lit/min

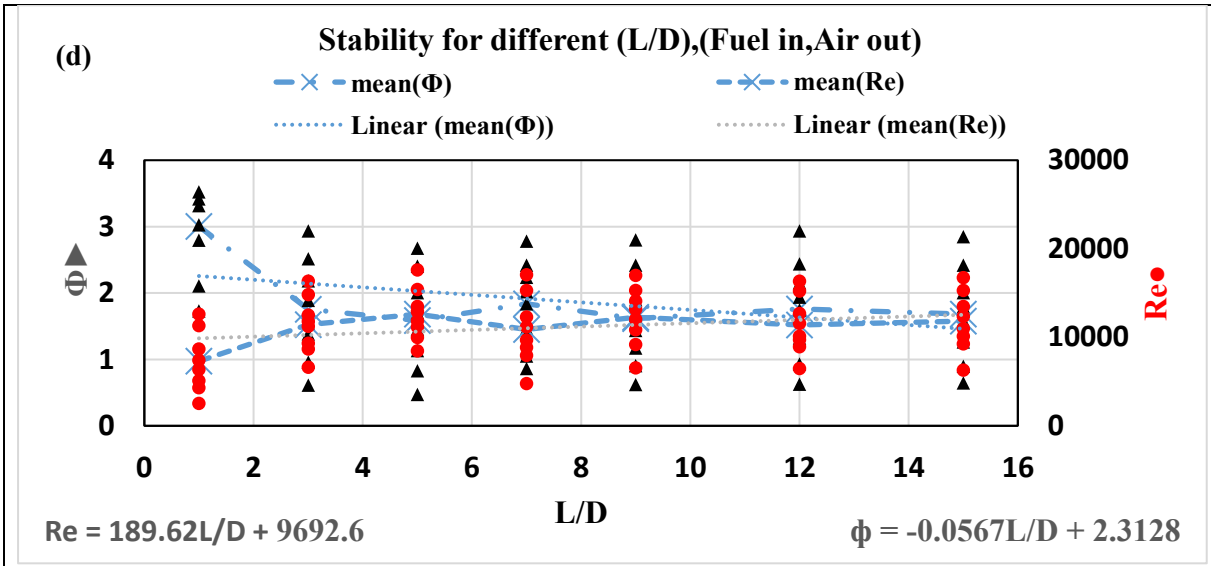
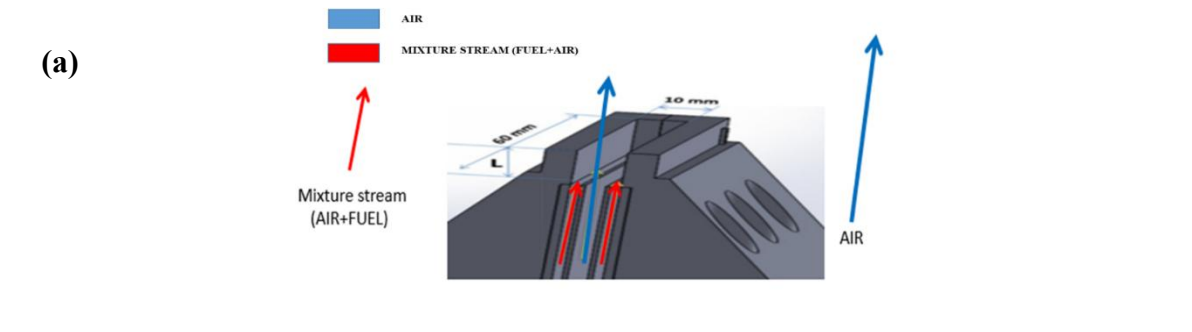
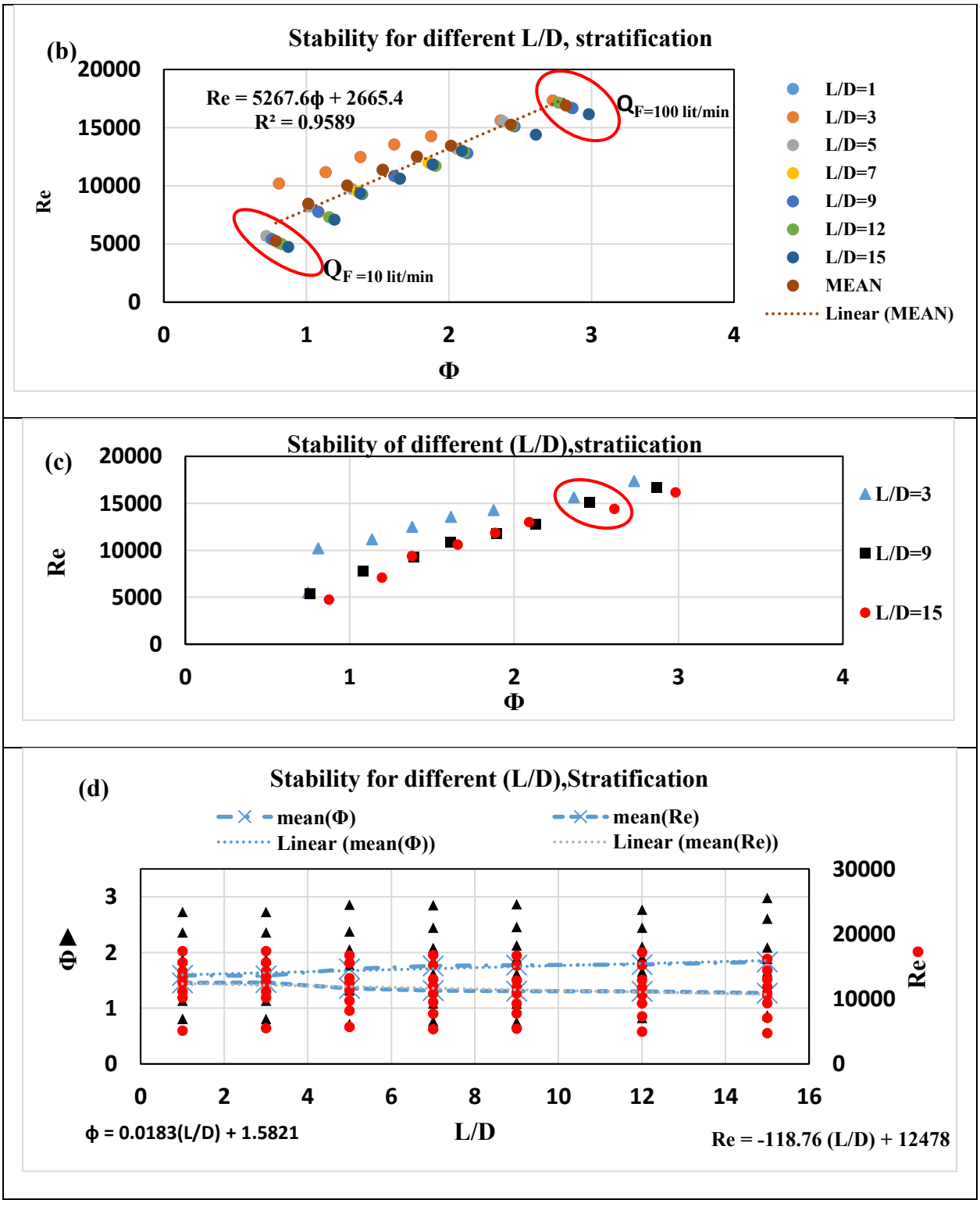


Fig 7 :- illustrate Fuel in-Air out stability strategy (a) all size of L/D with fuel flow (10-100 lit/min) (b) Transform range of fuel and L/D for stability finite with red circle (d) shows trend of Re and Φ for all fuel quantity from 10-100 Lit/min

4.3 ((Mixture out – Air in)-stratification)

Investigation another technique for CFSB in very important to reach best way for stabilizing mixing field, this technique depend on stratification that means mixture will be outside and air inside as shown in figure 8.a. For the burner used in this investigation, the resulting air-to-fuel area ratio is $A_R > 3$, providing the desired flow distribution between the oxidizer and fuel streams. This methodology can achieve different lean and rich environment at same state of stability studying. Stability relation between ϕ and Re shows that there is no peak or optimized level of homogeneity L/D but lower values of L/D achieve higher stability for different quantity of fuel from 10 to 100 lit/min as shown in figure 8.d .In this strategy its founded that there is no quantity of fuel will make transition in stability curve rather than another previous strategies. Comparison between slot and global refer that despite lower stability indexing for slot but global refer to high stability indexing. Effective ness for this strategy appears clearly in figure 8.d as its shown that stability of each slot appears low by comparison it with global stability of burner in this case.




(b)
Stability for different L/D, stratification
Re = 5267.6ϕ + 2665.4
R² = 0.9589
Q F=100 lit/min
Q F =10 lit/min
Re
Φ
L/D=1
L/D=3
L/D=5
L/D=7
L/D=9
L/D=12
L/D=15
MEAN
Linear (MEAN)
(c)
Stability of different (L/D),stratiication
Re
Φ
L/D=3
L/D=9
L/D=15
(d)
Stability for different (L/D),Stratification
mean(Φ)
mean(Re)
Linear (mean(Φ))
Linear (mean(Re))
Φ
Re
L/D
ϕ = 0.0183(L/D) + 1.5821
Re = -118.76 (L/D) + 12478

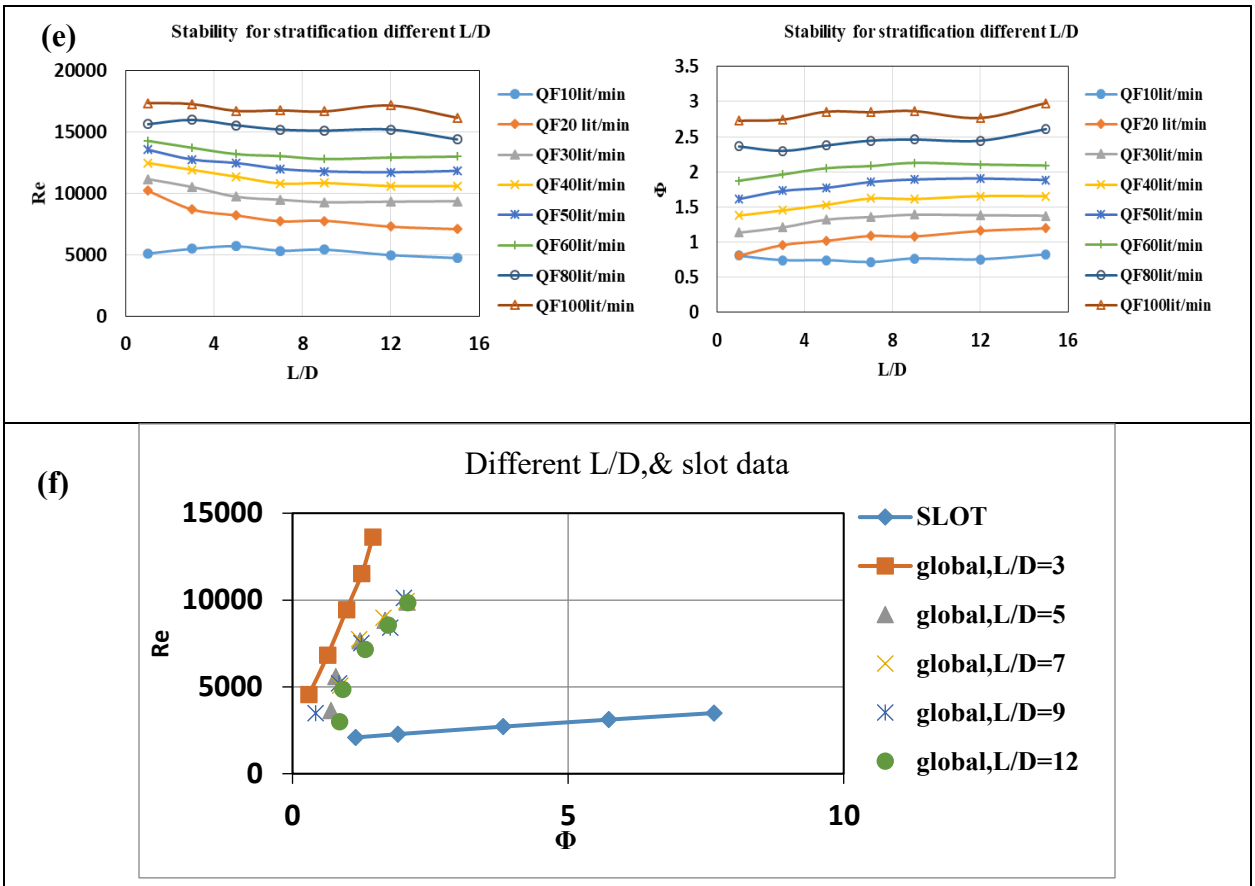


Figure 8. Illustrate stratification stability strategy. (a) Strategy configuration (b), (c) stability for different fuel different L/D. (e) selected L/D for finite transition quantity of fuel finite by red circle (d) Re and Φ for all values of Q_F (10-100 lit/min) ,(f) comparison between slot and global stability

4.4. Finite best strategy of previous mixing field strategies according A_R

In this section best strategy is investigated according different geometry A_R. This ratio can finite arrangement of air and fuel according burner exit nozzle. The ranges of this value are 3 if fuel enters in outer slot, 1/3 if air enters outer slots >3 if mixture (air and fuel) enters outer slot. These strategies are discussed for different L/D that are ranged from (1-20) also for equivalence ratio that are ranged from very lean to rich (0.2-3).Results are showed in figure 9 in this figure it's clear that stratification method is most stable strategy especially from very lean condition start from Φ=0.2 to very rich condition about Φ=2.2 also at stoichiometric condition Φ=1. By changing strategy fuel inner and air out stability is enhanced clearly especially at lean conditions but at rich conditions from Φ=2.2 to Φ=3 stability will enhance by fuel outer and air inner that achieve A_R =3.This results refer that by stratification high stability environment can be achieved as there is high supply of energy from rich pockets to lean pockets. From previous data figures (4-c), (7-d), (8-d) relation

between Re, Φ with L/D are correlated as linear function so in figure 10 these relations are illustrated to obtain ratio that can specify for wide range of L/D (1-20) which of these strategies achieve highest stability according dividing range of Φ and range of Re from eq (2) that illustrate stability factor S_F. larger value of S_F means more stabilize methodology all range of L/D.

$$S_F = \frac{(\Delta Re)}{(\Delta \Phi)} \qquad (2)$$

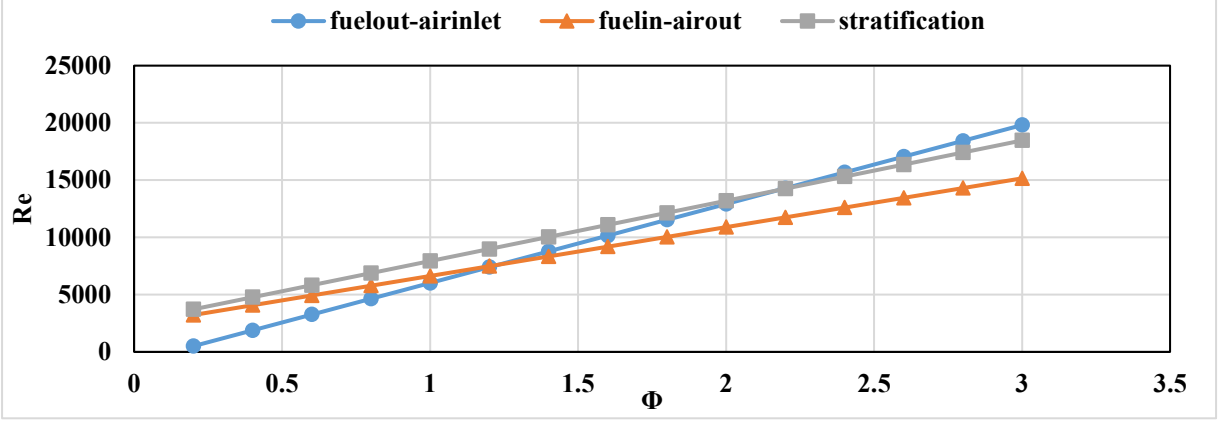
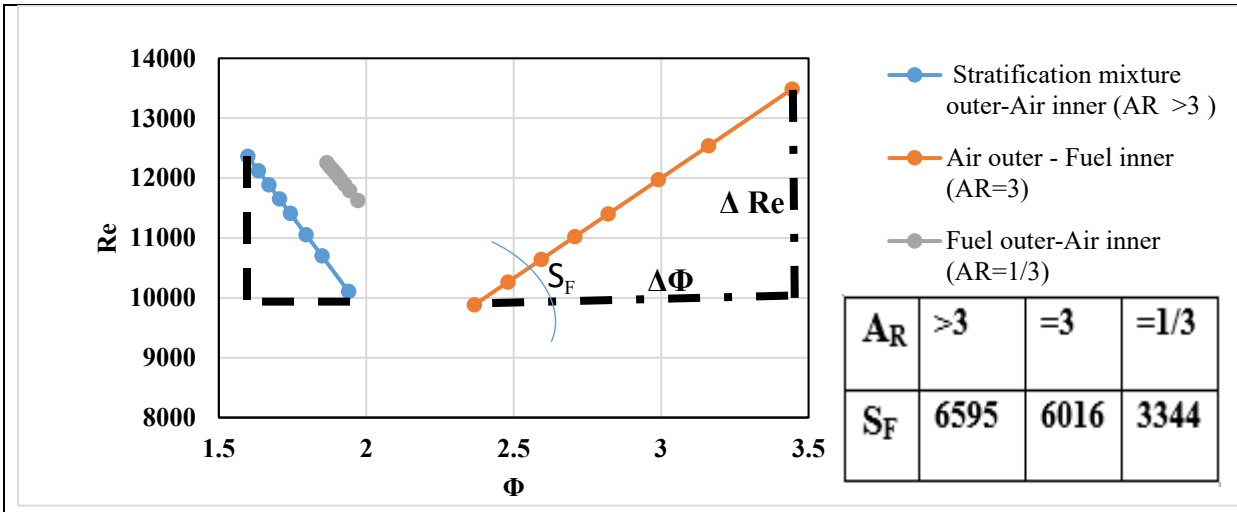


Figure 9.illustrate difference between strategies of arrangement fuel and air of CFSB and controlling with A_R and its effect on stability.

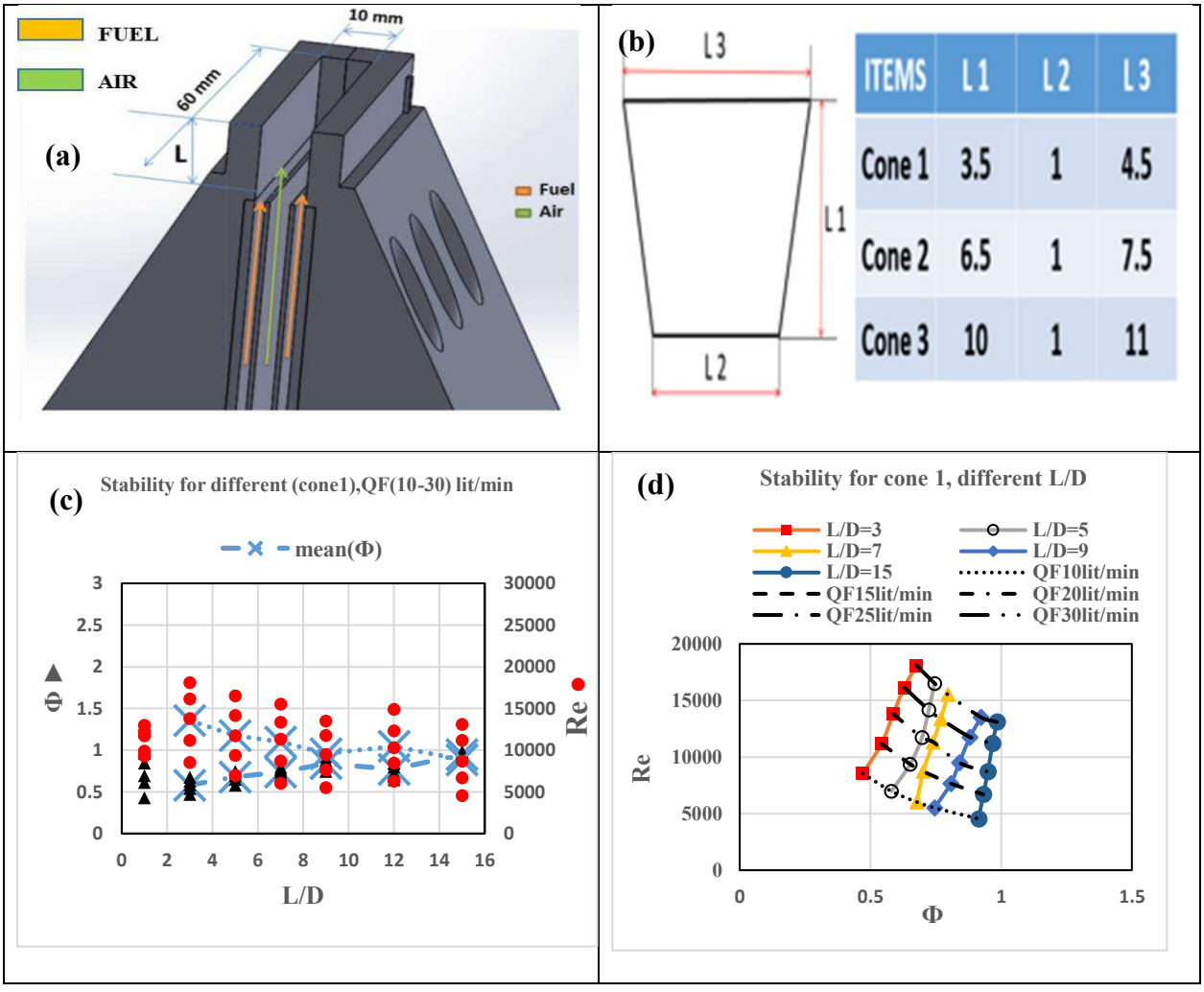


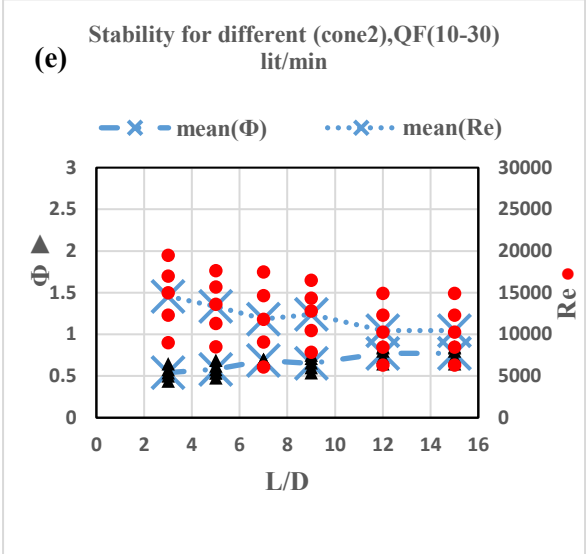
A_R	>3	=3	=1/3
S_F	6595	6016	3344

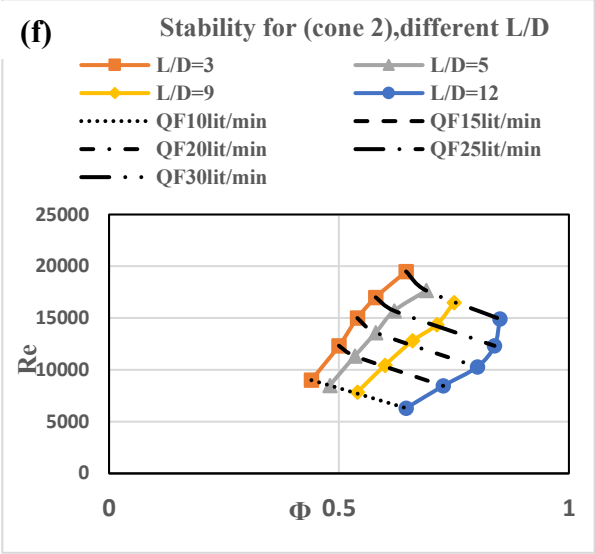
Figure 10. illustrate stability factor for different strategy that represent slope of lines

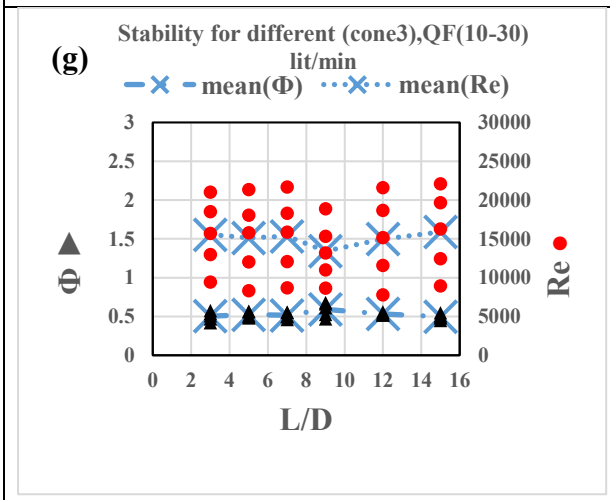
4.5. Cone effect (Strategy depend on Air inner, Fuel outer)

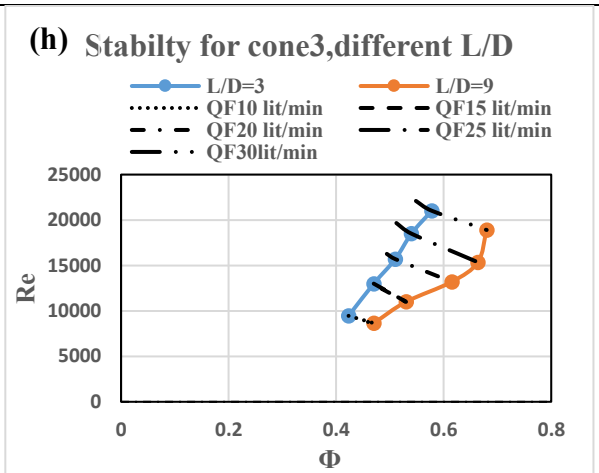
It's founded from previous strategies that Air inner, Fuel outer is the least stability strategy so it's suggested that adding cone to enhance its stability also to study effect of cone on another condition. In this study, three cone sizes were investigated, as illustrated in Figure 11 to evaluate their influence on the aerodynamic characteristics and flame stability of the CFCB burner especially at case of A_R =3 as this technique approved smallest S_F in previous section . Increasing the cone size is expected to strengthen the aerodynamic recirculation zone downstream of the burner, thereby enhancing the interaction between the reactants and the hot combustion products. This improved flow structure promotes more effective flame anchoring and increases resistance to blow-off under high flow conditions. Consequently, larger cone sizes are anticipated to provide superior flame stabilization compared with smaller cones, demonstrating the important role of burner geometry in improving combustion performance.

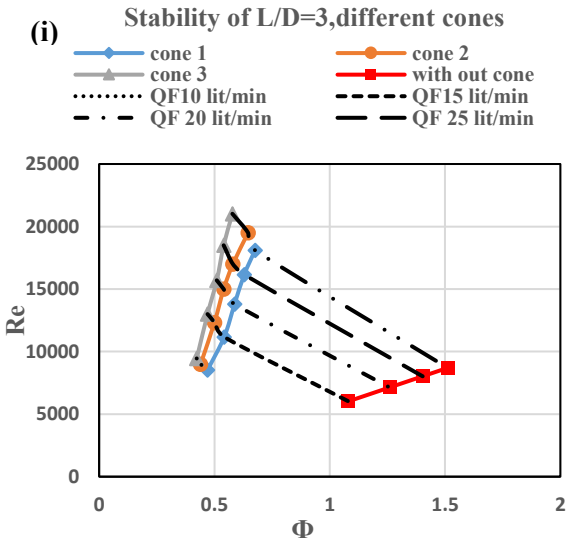


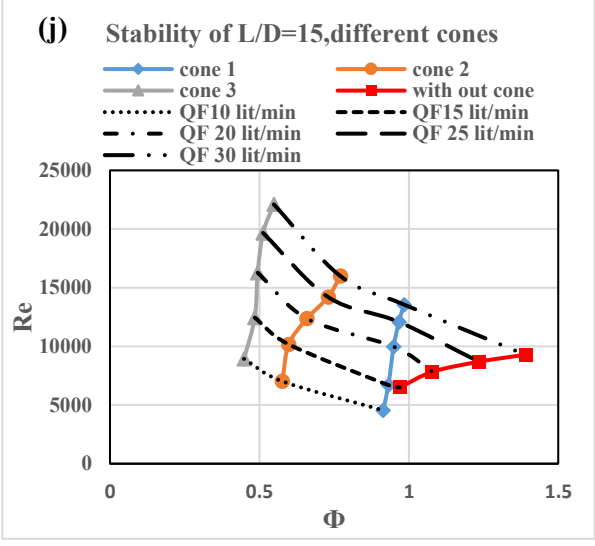

(e)
Stability for different (cone2),QF(10-30) lit/min
mean(Φ)
mean(Re)
Φ
Re
L/D


(f)
Stability for (cone 2),different L/D
L/D=3
L/D=5
L/D=9
L/D=12
QF10lit/min
QF15lit/min
QF20lit/min
QF25lit/min
QF30lit/min
Re
Φ


(g)
Stability for different (cone3),QF(10-30) lit/min
mean(Φ)
mean(Re)
Φ
Re
L/D


(h)
Stabilty for cone3,different L/D
L/D=3
L/D=9
QF10 lit/min
QF15 lit/min
QF20 lit/min
QF25 lit/min
QF30lit/min
Re
Φ


(i)
Stability of L/D=3,different cones
cone 1
cone 2
cone 3
with out cone
QF10 lit/min
QF15 lit/min
QF 20 lit/min
QF 25 lit/min
Re
Φ


(j)
Stability of L/D=15,different cones
cone 1
cone 2
cone 3
with out cone
QF10 lit/min
QF15 lit/min
QF 20 lit/min
QF 25 lit/min
QF 30 lit/min
Re
Φ

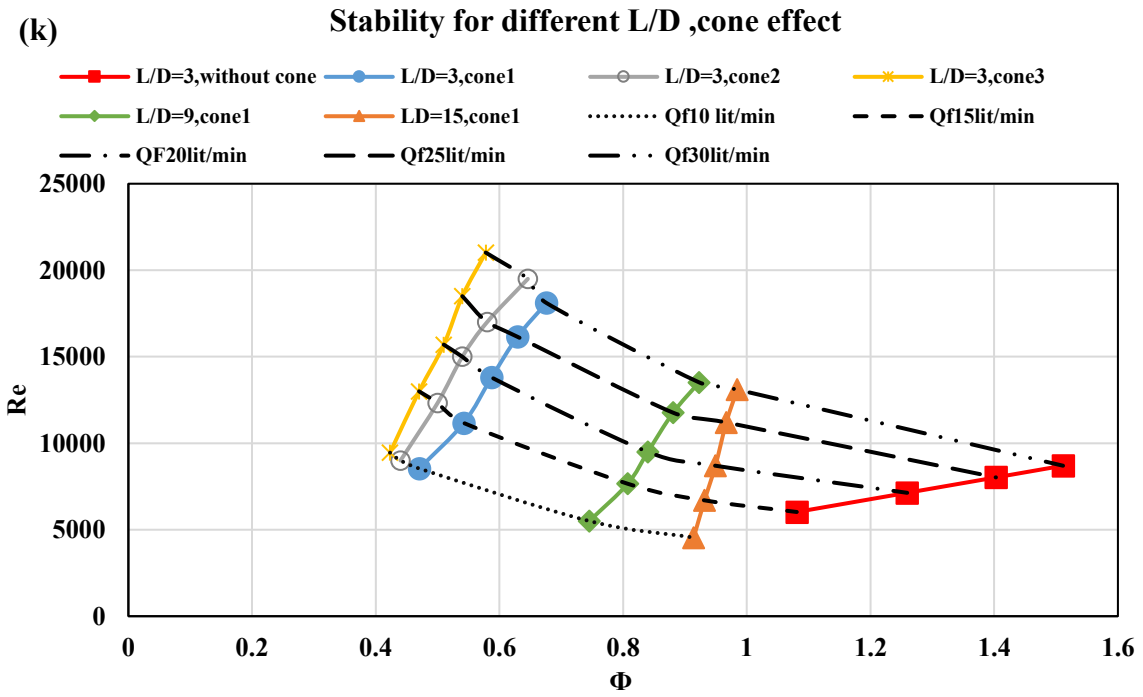


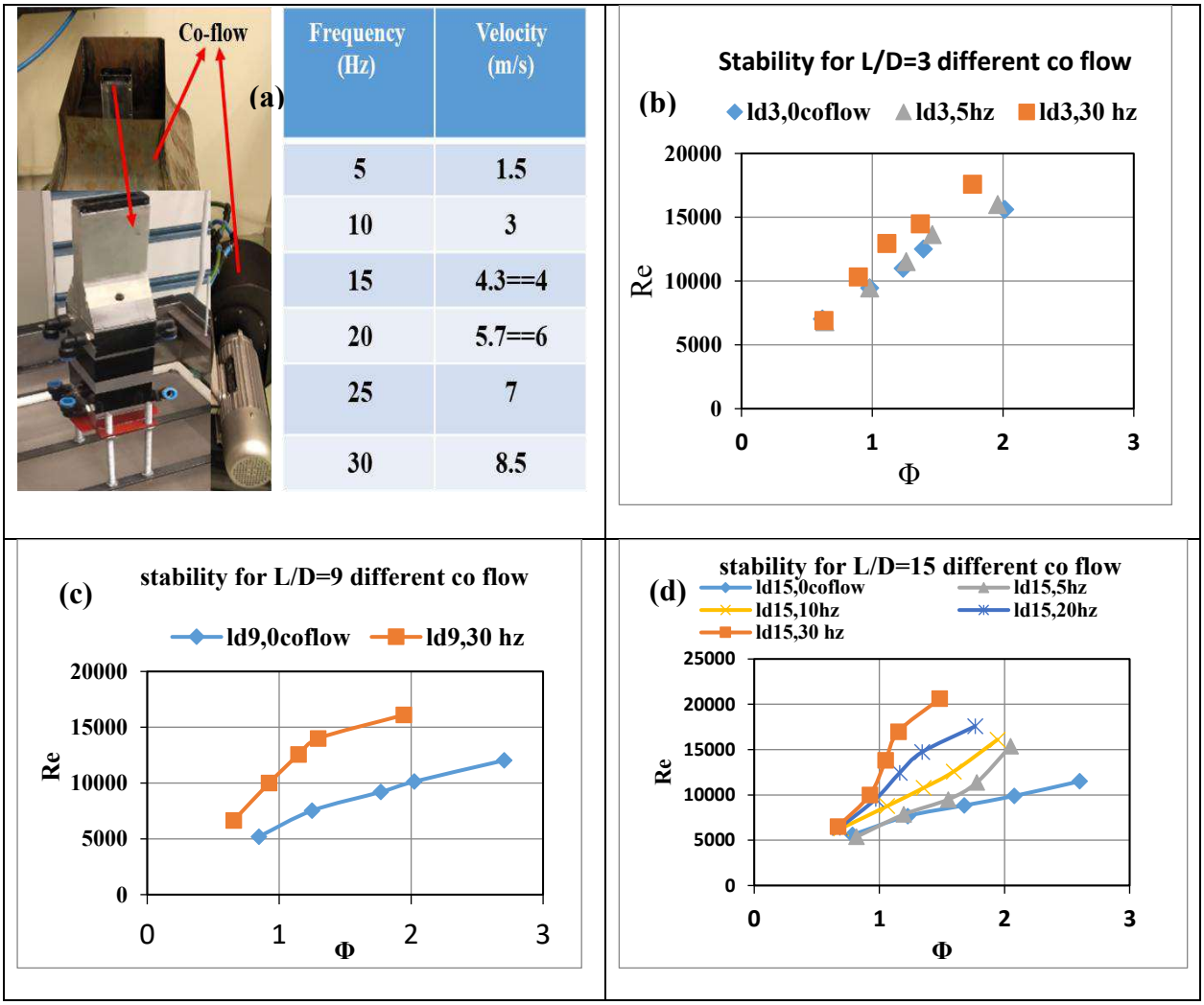
Figure 11 illustrate cone effect on stability (a ,b) configuration of method and cone ,(c ,d) ,(e,f),(g, h) stability of cone size respectively (i, j) effect of cone size and L/D with and without cone ,(h) comparison for different effect strategies with cone and without cone also different L/D for different fuel Q_F .

Figure 11(k) shows that increasing the cone size significantly improves flame stability over the entire range of inhomogeneity levels (L/D) investigated. A larger cone enhances the aerodynamic recirculation zone, allowing better mixing between the incoming reactants and the hot combustion products, which promotes stronger flame anchoring. However, for a given cone size, increasing the inhomogeneity level (L/D) reduces the stability limit because the fuel–air mixture becomes less uniform, leading to weaker combustion. Despite this effect, the addition of a cone consistently extends the stable operating range compared with the burner configuration without a cone. Moreover, the enhanced flow recirculation produced by larger cones enables stable operation under leaner combustion conditions, demonstrating the effectiveness of cone geometry in improving burner performance.

4.6 Co flow effect on stability

The co-flow configuration plays a significant role in improving flame stability for all stabilization strategies investigated in this study. The surrounding air stream modifies the flow field and introduces flame stretching, which enhances the interaction between the reactants and the surrounding gases, resulting in a more stable flame. In addition, the co-flow contributes to reducing

the visible flame length by promoting more efficient mixing and combustion. A carefully designed nozzle was used to produce a uniform velocity profile at the burner exit. Combined with an appropriate mesh arrangement and accurate frequency control, this configuration ensured stable and repeatable operating conditions, enabling a reliable evaluation and comparison of the different stabilization strategies as shown in figure 12.



Frequency (Hz)	Velocity (m/s)
5	1.5
10	3
15	4.3==4
20	5.7==6
25	7
30	8.5

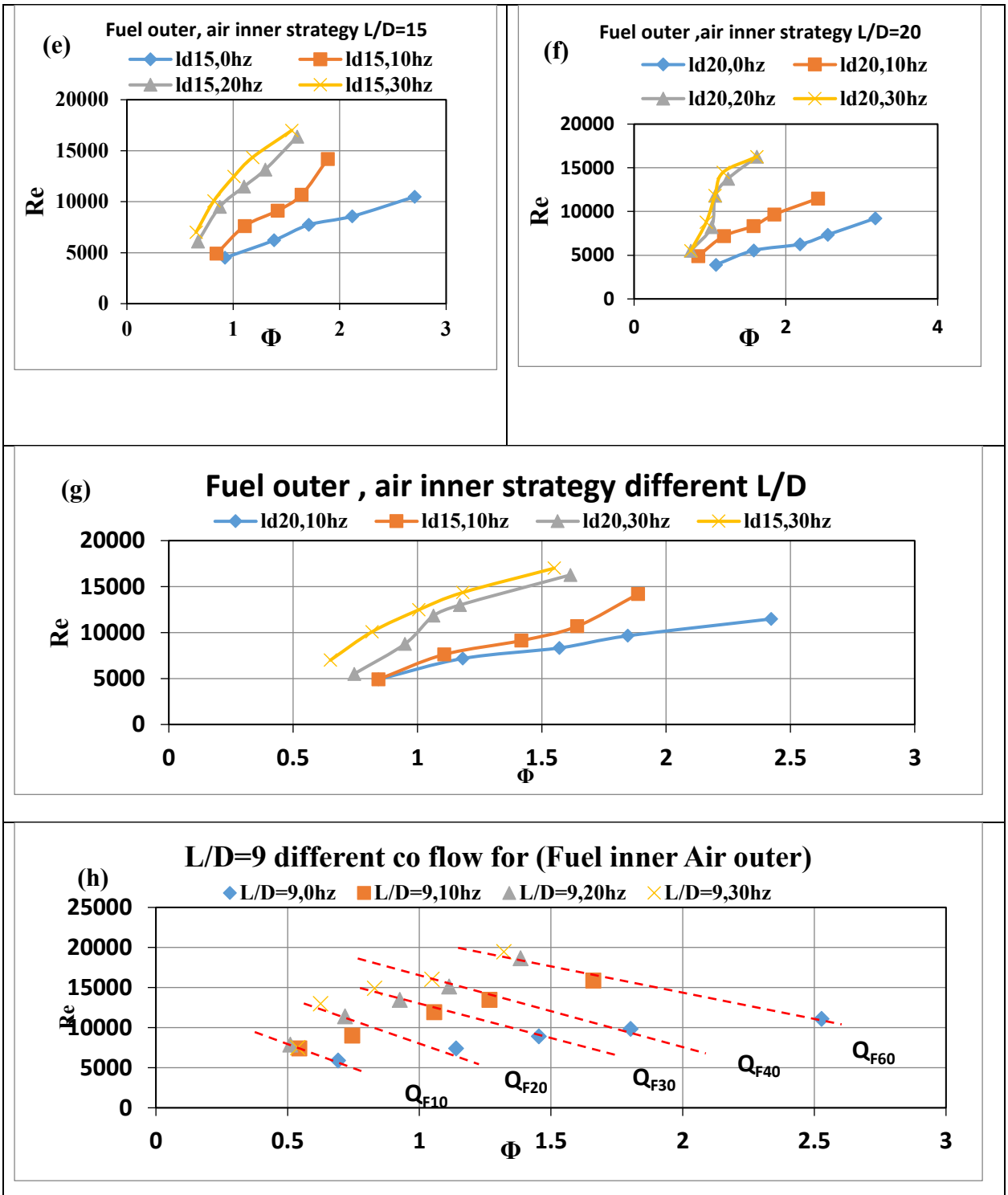
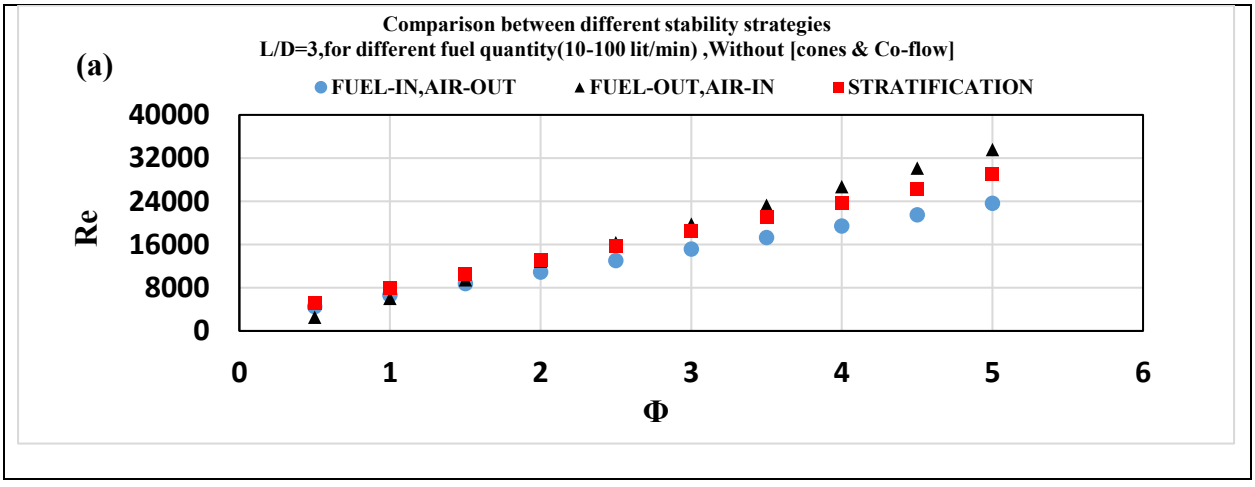


FIG 12:- Co flow effect for different strategies (a) specification for co flow experiment (b) different co flow for L/D=3 and (fuel our –air in) (c, d) different L/D same strategy and same co flow,(e,f) different high L/D and different strategy with all different co flow (g) compare between two different L/D with different co flow (h) Effect of constant Q_F on co flow effect

The results indicate that increasing the co-flow velocity improves flame stability for all investigated stabilization strategies. The additional co-flow promotes flame stretching and enhances the interaction between the flame and the surrounding flow, leading to more stable combustion over a wider operating range. This stabilizing effect becomes more pronounced at higher levels of inhomogeneity, where flame instability is generally more likely to occur. Among the tested configurations, the fuel-outer/air-inner strategy benefits the most from the application of co-flow, exhibiting the greatest improvement in stability under highly inhomogeneous conditions. These findings demonstrate that co-flow is an effective approach for extending the stable operating limits of the burner, particularly when strong mixture inhomogeneity is present.

3.4. Comparison between different strategies

This section presents a detailed evaluation of the influence of each stabilization strategy on the flame stability of the Concentric Flow Slot Burner (CFSB). The performance of the investigated strategies is compared under different operating conditions to identify their effectiveness in extending the stable operating limits. The analysis focuses on the impact of flow arrangement, mixture inhomogeneity, cone geometry, and co-flow on burner stability. As illustrated in Figure 13, the results provide a comprehensive comparison of the proposed strategies, allowing the most effective approach for achieving enhanced flame stability in the CFSB to be identified.



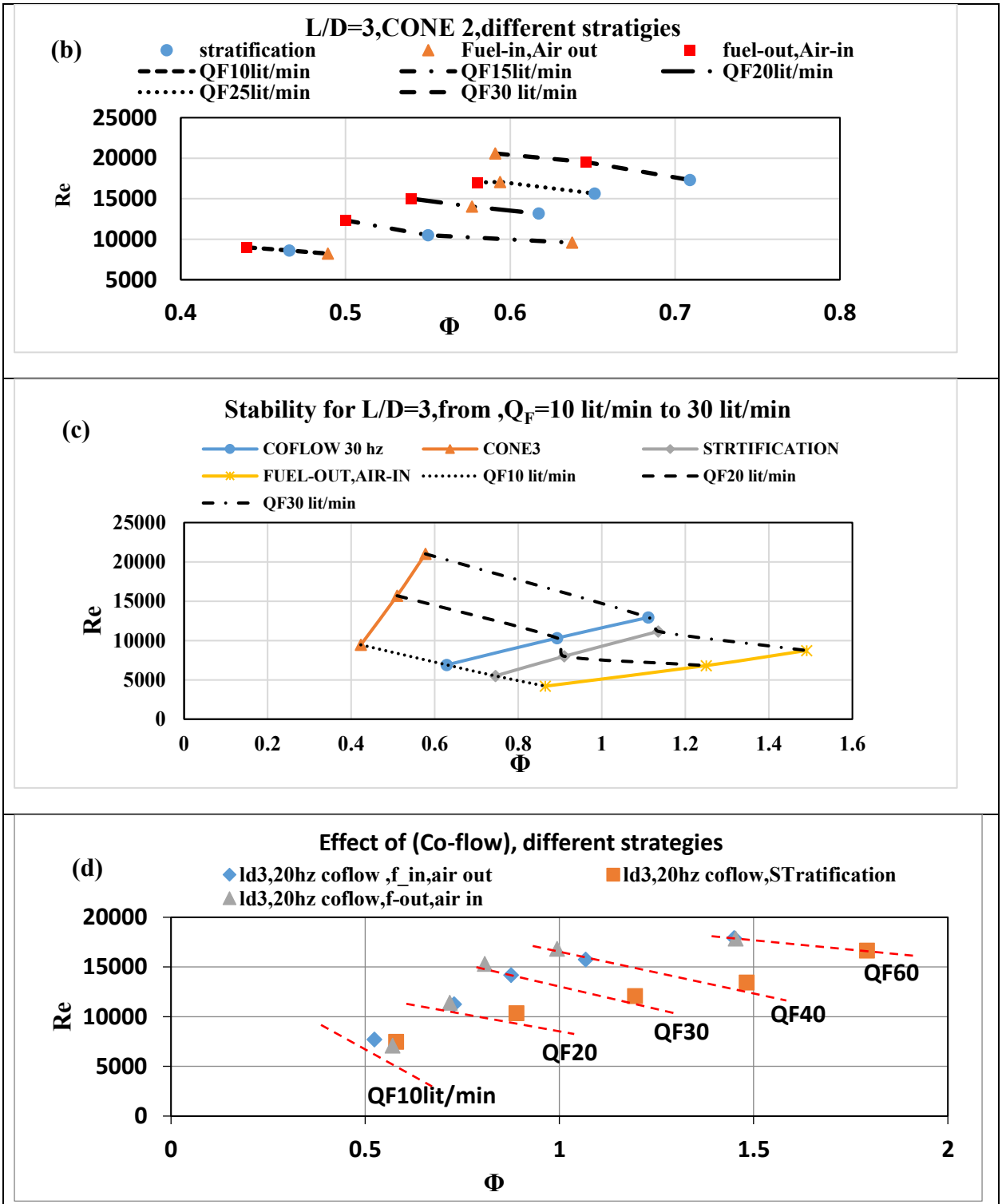


Fig 13.Compare between different strategies and stabilization mechanisms (a) change slots natural to control stability (b) cone effect with different strategy (c) define best mechanism s and stabilization mechanism (d) effect of co flow in different strategies

3.5 conclusion

The results presented in this work demonstrate that the effectiveness of the investigated stabilization techniques depends on both the degree of mixture inhomogeneity (L/D) and the fuel flow rate. Among all the examined strategies, the addition of a cone consistently provided the greatest improvement in flame stability. The cone enhanced the flow structure by creating a stronger recirculation region, which promoted continuous ignition of the incoming reactants and significantly extended the stable operating range. The use of co-flow ranked as the second most effective stabilization technique, as it reduced flame fluctuations and improved flame anchoring through additional aerodynamic support. The influence of fuel stratification was also found to be significant, particularly under operating conditions with low fuel flow rates. In the absence of both a cone and co-flow, stratification produced the highest level of stability by improving the local fuel-air distribution near the reaction zone. Furthermore, the fuel-outer/air-inner configuration showed a substantial improvement in stability when co-flow was introduced, especially at specific values of the inhomogeneity level (L/D). When a cone was incorporated into the burner, the same configuration exhibited superior performance within a limited range of fuel flow rates. However, as the fuel quantity increased, the fuel-inner/air-outer arrangement became more effective, indicating that the optimal stabilization strategy changes with operating conditions. Overall, the experimental results confirm that controlling the mixing field has a direct influence on flame stability. Both the spatial distribution of the fuel-air mixture and the local mixture fraction play essential roles in determining the stability limits of partially premixed flames. These observations suggest that conventional stability analysis based solely on physical parameters is insufficient. Therefore, the next chapter introduces a newly developed stability diagram based on the mixture fraction field, providing a quantitative framework for analyzing flame stability under different mixing conditions and identifying the governing mechanisms responsible for stable combustion.

Symbols:-

D Burner exit diameter

L Mixing length

L/D Degree of mixing

CFSB Concentric Flow Conical Burner

Re Reynolds number

SF Stability factor

A_R Air ratio to Fuel ratio

Greek Symbols:-

Φ Equivalence ratio

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Data availability

Date will be available on request

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