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IMPACT OF THE NOZZLE ANGLE, DISTANCE BETWEEN BURNERS, AND N_2 ON BURNING VELOCITY OF THE DIFFUSOIN COUNTER FLAMES

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Abstract: The achievement of precise measurements on the laminar diffusion flames plays a big role in the process of realizing a wide flames range. Despite most of fuel is likely burnt in the turbulent combustion, there is still data requirement for the data on the velocities of the laminar burning as input to several models of the turbulent combustion. And, in engines with an internal combustion, the first combustion is laminar, thus once more, there is a requirement for the velocity of the laminar burning. The burning velocity of the laminar diffusion flame was measured at three nozzles at different angles (30º, 45º, and 60º) and different distances between the nozzles burners (H = 20, 30, and 40 mm) with and without the N_2, and wide range of equivalence ratios ($0.65 \leq \phi \leq 1.5$). Schlieren photographs were captured to qualitatively assess the effect of angle of nozzles, distance, and N_2 on the burning velocity of the diffusion flame. Burning velocity depends on the stagnation surface of the flame front, which in turn relies on the vertical distance (H) between the burners. Also, it was noticed that the increase in distance between the burners leads to a decrease in the velocity of the reactants since it is affected by the air surrounding.

Keywords: *Diffusion Counter Flame, Distance between Burners, N_2, Burning Velocity.*

1. Introduction

Stion phenomena arise from the interaction of chemical and physical processes. Combustion can be defined as “rapid oxidation generating heat or both heat and light”. This definition emphasizes the intrinsic importance of chemical reactions to Combustion; in general, the flame can be classified depending on four concepts:

1. Stability: If the flame front is moving relative to the function or anything consistent, then it is called unstable flame front, but when it is possible to see the flame front consistently moving inside the system, then it is called stable flame front [1].

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2. Stability: If the flame front is moving relative to the function or anything consistent, then it is called unstable flame front, but when it is possible to see the flame front consistently moving inside the system, then it is called stable flame front [1].
3. The method of mixing and the diffusion of reactions: The flame will be either premixed flame or simultaneously mixing and combustion (diffusion flame).
4. The nature of the flow of gas through the reaction zone: This can be divided into two types, (laminar flame) and (turbulent flame).
5. The physical state of the primary reactants (gas - liquid - solid) [1, 2].

The study of the laminar and turbulent flame diffusion is very important to analyze the uncontrolled combustion phenomenon, such as fire that controlled in the internal combustion engines, rocket engines, gas turbine and furnaces, etc. Despite the ultiplicity of research in the field of diffusion flame, studies are still going on because of the need to accurate practical results that define the factors, which describe the spread of flame, and also the complexity of the theoretical models for the chemical kinetics and the need to apply them practically [3].

The flame front that accompanies the combustion is mainly divided into two types: the first type is the premixed flame, in which the reactants are mixed on a regular basis before combustion, resulting in a uniform flame front shape, while the second type is called the diffusion flame, which occurs as a result of the diffusion and mixing of the reactants with each other during the reaction, and through both types, a stable flame front can be obtained. If the flame front moved through the static primary mixture, then it is described as non-stationary flame front [4, 5]. Flame front consists of two main zones: the first is preheating zone, and the second is reaction zone. There are two main factors responsible for the growth and diffusion of the flame, they are thermal conductivity and the diffusion of the flame zone to the new mixture as described by [6, 3]. To study the stable diffusion flame, one must know the limits of stability and determine the range of reaction with the stay of the burner flame in stable state on the front burner rim. The flame front starting from the reaction zone is divided into three visual areas: the luminous zone, the shadow zone and the Schlieren zone, where the shadow and Schlieren zones cannot be observed by the naked eye but they require special optical techniques. Figure (1) shows visual areas of the flame front [7].

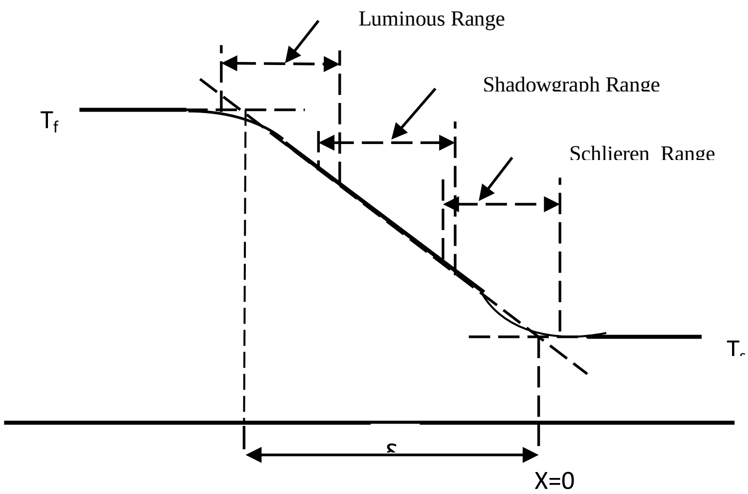


Figure 1. Visual areas of the flame front [7].

The flame front can be exist usually when the mixing ratio of the original components in the combustion zone to be close to the stoichiometric ratio, these hypotheses are the result of the following reasons: When assuming that one of those components enters to the combustion zone with flow exceeded the optimization level, it will penetrate the zone and go to another zone of the reaction, and it is heated to a high temperature, passes through the flame and then it reacts more actively, causing to change the location and direction of the combustion zone. These procedures and processes are continuing and will proceed until the combustion zone takes its final location in reactions at stoichiometric ratio [8]. (In terms of obtaining higher temperatures in the reaction zone), that the thermal diffusivities and mass diffusivities for each of the reactant and the resulting components are almost equal. Flame front is usually formed when achieving the flow of the original components in the combustion zone and mixing with stoichiometric condition. The temperature of heating of exhaust gases reaches to the adiabatic state, see figure (2) [8].

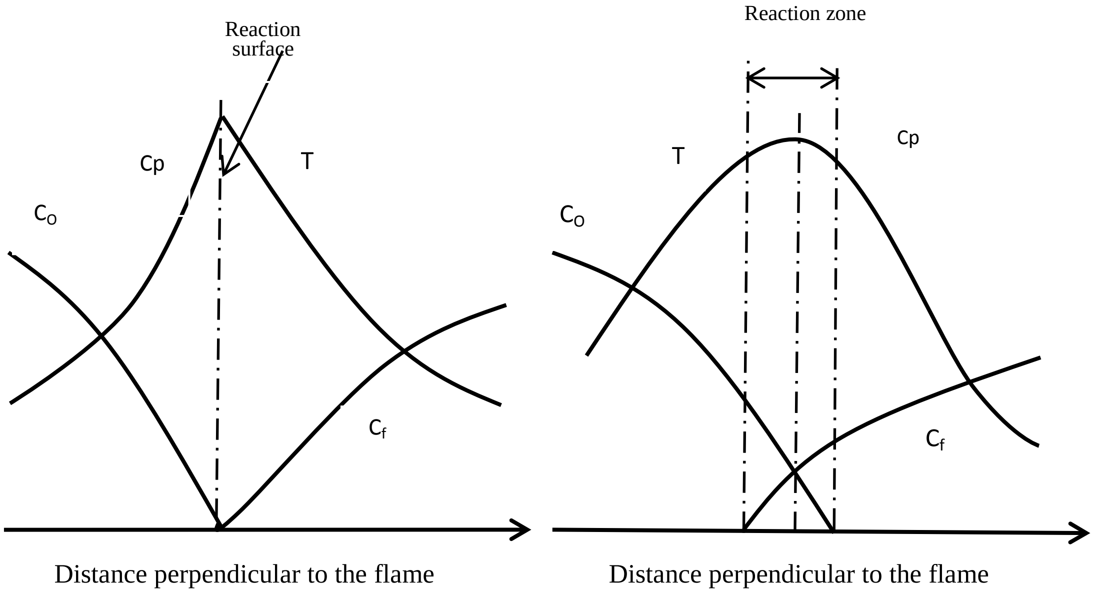


Figure (2: Determinants the distribution of the real and ideal flame diffusion [8]

The mechanism for achieving the diffusion flame stability in the experimental and theoretical sides constitutes a great importance in the design and the work of the combustion systems. It is well known that the diffusion flame stability could be controlled through the edge flame properties. The edge flame is usually formed in partially premixed zone. There is no consensus about the mechanism of edge flame stability, so there are several ways, methods and investigations of predicting to study the basis of the edge flame stability and formation [9, 10].

The researchers [10, 12] are giving a sample of counter flow burner as shown in figure (3), which consists of two round nozzles in opposite sides, with a flat-plate and porous-disc. The air is flowing through the first nozzle and effects on the flat plate, while methane is flowing through the second nozzle through the porous disc, and when the collision occurs between the two flows, the diffusion flame takes place in shape of a round disc. In experiments, a small hard disk with different diameters (0, 3, 5, 10 mm) has been installed and placed over the porous disc to make a gap in the center of the flame disc and to study the limits of the blow-off (with the existence of a gap and without it) in terms of fuel injection velocity.

Where in flame show (which does not use the hard disc), blow-off occurred at a low velocity of fuel injection because of the thermal quenching that was resulting from mixing between the flame and the plate surface.

Many of researchers have used this type of flame [11, 12, 13] and studied the range of flow around the flame disc edge. This type of flame is considered very complicated because of the interference of the medium surrounding the flame and the impact of the edge shape of the burner with a counter flow.

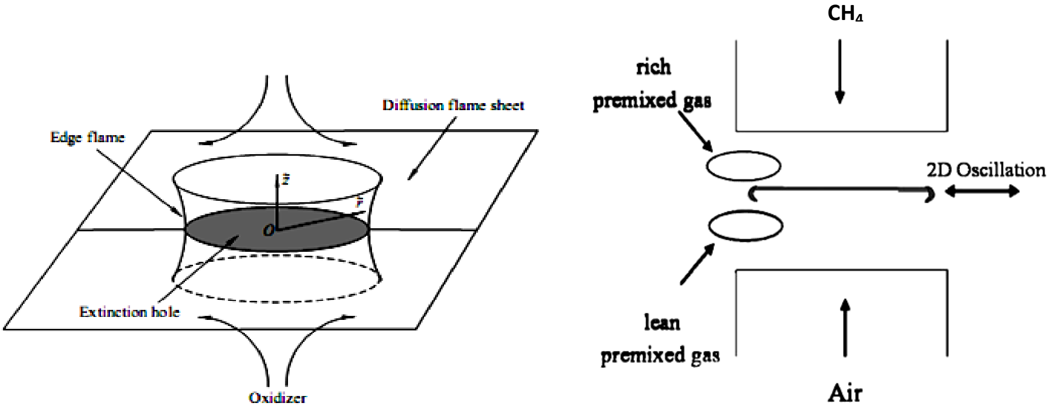


Figure 3. Counter flow burner [11]

Flames that exist in counter flowing axisymmetric streams are, in the mean, planar and circular, the flow is symmetric about the stagnation plane when the mass flow rates are the same from both nozzles, and the flow is independent of the angular coordinate.

This geometry approximates a one dimensional laminar flame subject to stretch. Combustion models for example on laminar flamelet crossing frequencies or fractal properties of the flame surface are well suited to the flat flames produced in counter flowing streams [14, 16].

The supposition of a fully developed parabolic flow region at the exit of the nozzles was initially tested via [16, 17]. Entrance length (EL), shown in figure (4), is the tube length required necessarily to possess a fully-developed parabolic shape. It’s a function of several factors, like Reynolds no., the state of flow at the inlet of the tube, the gradients of temperature, the surface of tube and so on. In reference [18, 19], an almost value is supposed to be:

$$EL = Ld^{-1} = 0.6\ Re \qquad \text{(flow is laminar)}$$

$$EL = Ld^{-1} = 4.4\ Re^{1/6} \qquad \text{(flow is turbulent)}$$

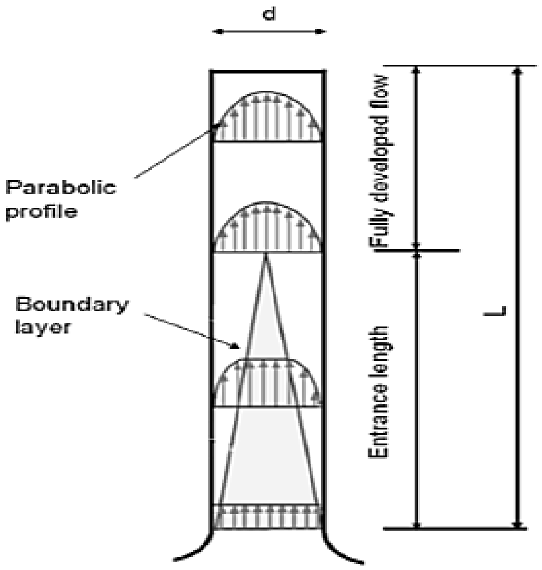


Figure 4. The schematic diagram of the entrance length in a tube [18]

2. Experimental Setup and Procedure

This study was conducted on a counter flow burners system which containing of three units figure (5).

- Combustion unit for counter flame front initialization that includes: -
  1. Valves and regulators to control the flow.
  2. Flowmeters for air and fuel.
  3. Counter Burner.
  4. Flame temperature measuring unit.
  5. Nitrogen supply unit.
- Schlieren optical unite that includes:

1. The light source.
2. Expanding set of the beam.
3. Focusing set of the beam

- Recording and filming unite for combustion phenomenon, in which the Schlieren photos are recorded; these photos are required for the study purpose. Figure (5) depicts the photographs of the practical experiment and its components. Figure (6) manifests the schematic diagram of the experimental test rig.

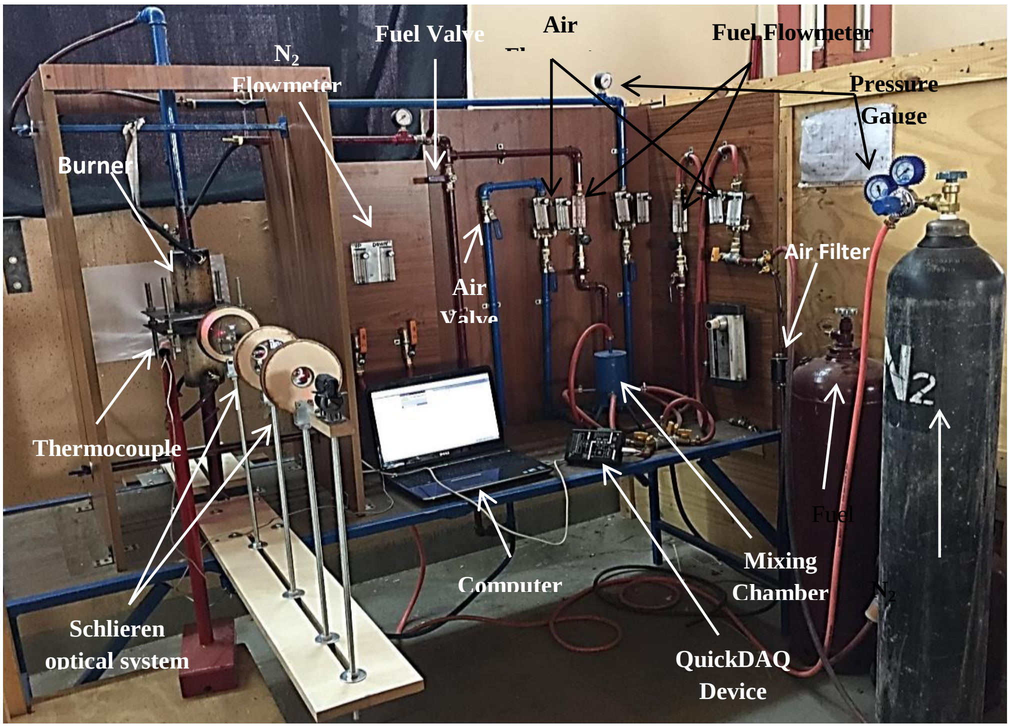
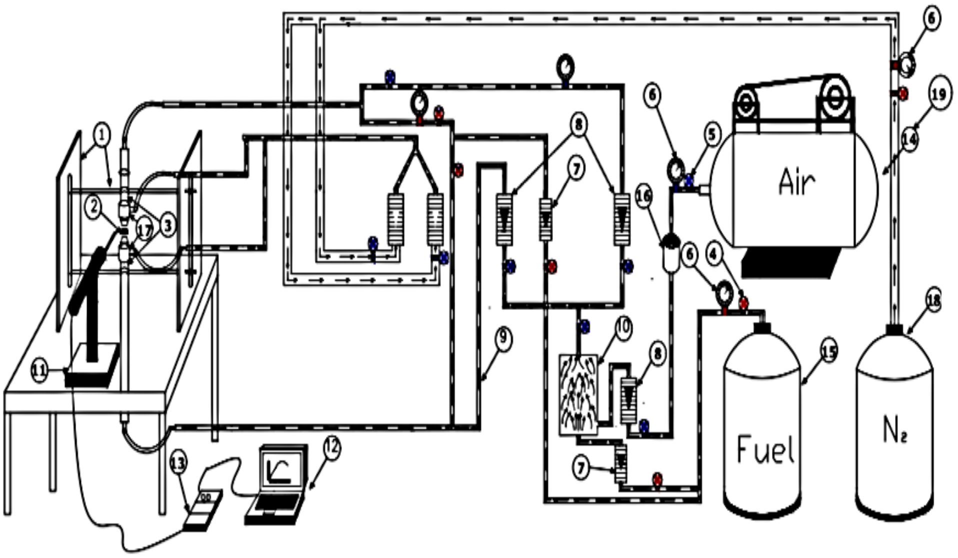


Figure 5. Photograph of the counterflow burner facility.



No.	Name of part	No.	Name of part	No.	Name of part
1	Burner holder	8	Air flow meter	15	Fuel cylinder
2	Flame	9	Pipe	16	Air filter
3	Burners	10	Mixing chamber	17	N_2 jacket
4	Fuel valves	11	Thermocouple holder	18	N_2 cylinder
5	Air valves	12	Computer	19	N_2 valve
6	Pressure gauge	13	Quick DAQ device	20	N_2 flowmeter
7	Fuel flowmeter	14	Compressor	21	Thermocouple
				22	Valve regulator

Figure 6. The schematic diagram of experimental test rig

2.1. Combustion System

In order to get the flow stability of fuel and air, a number of valves (plug valve (4, 5) and spring loaded valve regulators (22) have been used. In experiments the fuel (ILPG) was supplied from a standard gas cylinder with (8 bar), the fuel flow was controlled by ball valve (valve no.4) along with pressure regulator are placed after the standard fuel cylinder. Using the purity of liquefied petroleum gas (LPG) plays a key role in accuracy determining of the equivalent ratios. The air supply unit consists of a reciprocating compressor with maximum pressure (12 bar), valve (valve no.5) and regulator to control flow. To measure volumetric flow rate of fuel and air, flow meters are equipped for both (fuel, air).

The counter burner is one of the main parts of the combustion system which can study the premixed flame properties, it is considered one of the most complex types of burners due to the fact that the components of the combustion mixture (fuel and air) enter into the two burners separately and then unite at the burner rim in the nozzles, and the diffusion and the reaction of the flame front make this type called diffusion flame.

The second type, when mixing the reactors before entering the burner, is called the premixed flame. The basic principle of raising the efficiency of diffusivity burners is to increase the aerodynamic and to create vorticity at the surface of the stagnation zone.

The counter flow device composed of a pair of convergent nozzle burners having (12 mm) external diameters that are vertically placed in opposition to tubes made from brass and with a spacing of (20, 30, and 40 mm) separately. Three angles of nozzle (30, 45, and 60 deg.), distances (20, 30, 40 cm), and fuel LPG were used in other researches. In this research have been used same distances, angles, and fuel for comparing the experimental data with N_2 and without N_2, the schematic of the counter flow nozzle burner is revealed in figure (7).

The LPG as fuel and air streams as oxidizer respectively composed of various equivalence ratios (ϕ = 0.65 to 1.5). Additionally, the average velocities of exit at the nozzles were fixed similar. The type of fuel was (LPG) with a composition almost (40% C_3H_8, 60 % C_4H_{10}), it was taken from the chief supply using a compressor at (1 bars) (gauge) pressure and then filtered for removing the oil, the particles of dust and the droplets of water having diameters > 2 μm.

Flow meters calibrated were used to measure the rates of flow by and organized so as every burner can be provided with (0-6) L/min of gas and (0-16) L/min of air for the diffusion flames. The two jets moment was fixed similar so as the non-oscillating flow stagnation plane was placed at the mid distance (H/2) between the pair of adverse assemblies.

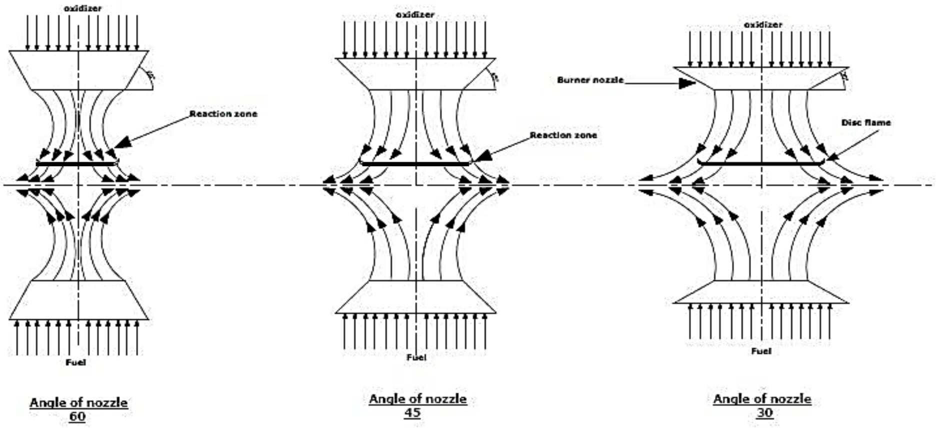
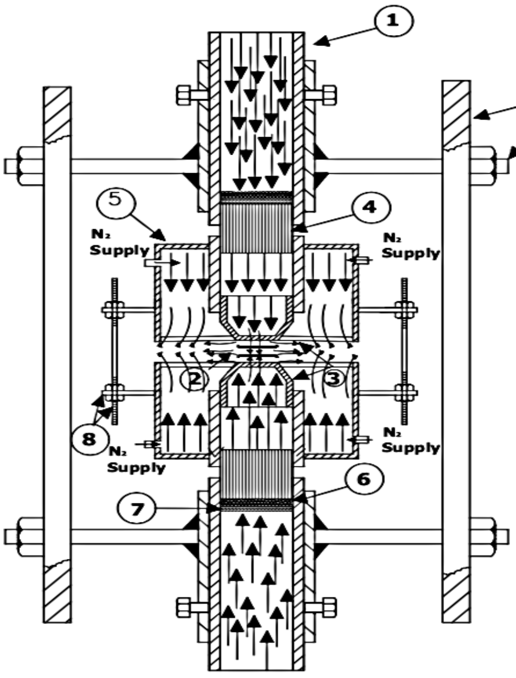


Figure 7. The schematic illustration of counter flow nozzle burner

3. Characterization of Burner

Profiles of the blend composition, which received between the pair of injections, were utilized for defining the layer thickness of injection, the strength of blend and the influential boundary conditions. The flow nozzle contoured design, associated with the honeycombs having (1/25)th cell size, guarantees the profile of an exit velocity with a proper consistency. Containing many tiny wire mesh screens close the exits of nozzle, a standard method causes the laminar flow [9, 10, 11, 20].

The same burner can be utilized under the premixed and the incomplete premixed circumstances. For this state, the two same premixed streams are supplied to bottom and top burner, and the twin flames are set in a symmetrical way relevant to the stagnation plane of gas. The circumstances of exit were standard atmospheric pressure and temperature. Figure (8) displays the burners' details.



No.	Name of parts
1	Tube burner
2	Double flame
3	Nozzles
4	Honeycomb
5	N_2 jacket
6	Balls
7	Screen
8	Adjust burners
9	Burner hangs

Figure 8. The schematic of counter burners

4. Results and Discussion

4.1. Burning Velocity

The basic principle of the current study is to find the best mixing and diffusion process for streams of the air and jet fuel, and it was done by changing the geometrical shape of the nozzle. This is one of the most important affecting determinants to get a highly efficient mixing of the reactants in the counter flame.

The burning velocity was measured for three nozzles at different angles (30º, 45º, and 60º) and different distances between the nozzles burners (H = 20, 30, and 40 mm) with and without the use of nitrogen. Through figures (9 to 14), it was noted that the burning velocity depends on the stagnation surface of the flame front, which in turn relies on the vertical distance (H) between the burners. Also, it was noticed that the increase in distance between the burners led to a decrease in the velocity of the reactants since it was affected by the surrounding air, leading to that the outside air participated in the interaction and thus affected on the equivalence ratio of the chemical mixture and reduced the burning velocity.

This effect can be recognized through the analysis of the Schlieren and visible optical images as shown in figures (16), which took over the experimental measurements to extract the geometrical dimensions of the flame front for all nozzles that were studied. It was found that the nozzle (60º) is giving the highest value of the burning velocity, while the nozzle (30º) is giving the lowest value of the burning velocity. Which were adopted mainly on the counter-streams and the vorticity zone resulting from the effects of the aerodynamic flow, to obtain a high efficiency for the mixing of the reactants. Schlieren optical system gives a high accuracy in the measurement because of depending on the refractive indexes of lasers beam through the reaction zone, and also there are no negative factors and side effects on the accuracy of the measurement, as is the case in the use of other techniques such as the particle velocimetry technique. When the initial aeration accrues, both the volume of flow and the velocity of burning during the flame ports raise. Nevertheless, the former increases more than the latter, and therefore the lift of flame may take place. Also, when velocity is more raised, a certain point will be attained, at which the flames will be quenched.

A wide range of equivalence ratios ($0.65 \leq \phi \leq 1.5$) has been utilized in various experiments. Directly, such ratio influences the tendency of sooting and the dissociation level in the product of combustion. Flames at almost stoichiometric states generate the utmost burning velocity owing to the thorough combustion. Flames with rich fuel ($\phi > 1$) creates both non-luminous and luminous thermal radiation, where the flames close the state of stoichiometric ($\phi = 1$) generate only the non-luminous radiation, due to no soot production.

Additionally, it was observed through figures (9 to 14) that there was an increase in the deflection nozzle angle with the horizontal axis that leads to the faster of the reactants and reduces the vortices near the burner nozzle rim, due to decrease of friction force between the tube wall jet and reactant molecules. And, at the same time, it helps to the faster exit of reactants toward the stagnation surface and flame front consistency.

Where, the area of the disc flame changes with the jet angle for the same equivalence ratio, according to the following results at the nozzle angles (30º - Df = 55 mm), (45º - Df = 51 mm), and (60º - Df = 48 mm). Comparing the results obtained with previous studies, it was noted that there is a consensus between them with an increase in the burning velocity of a jet (60º), especially at the equivalence ratio ($\phi = 1$).

In addition, the observation of the use of nitrogen refers to an increase in the burning velocity due to obtaining an equivalent mixing between the reactors and not allowing the outside air to participate.

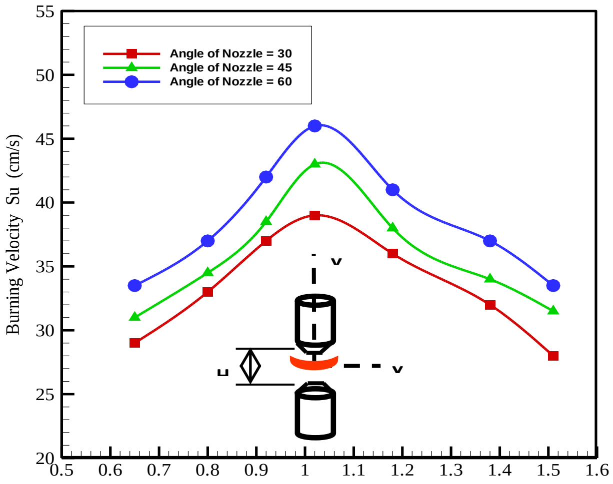


Figure 9. Effect of Types of Nozzle on the Diffusion Burning Velocity without N_2 at (H = 20 mm).

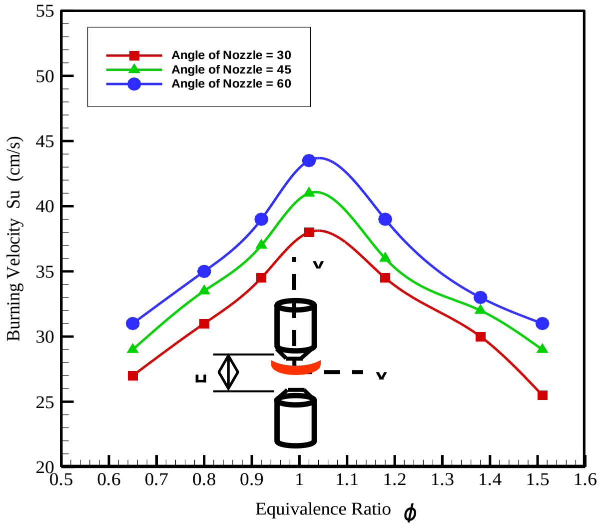


Figure10. Effect of Types of Nozzle on the Diffusion Burning Velocity without N_2 at (H = 30 mm).

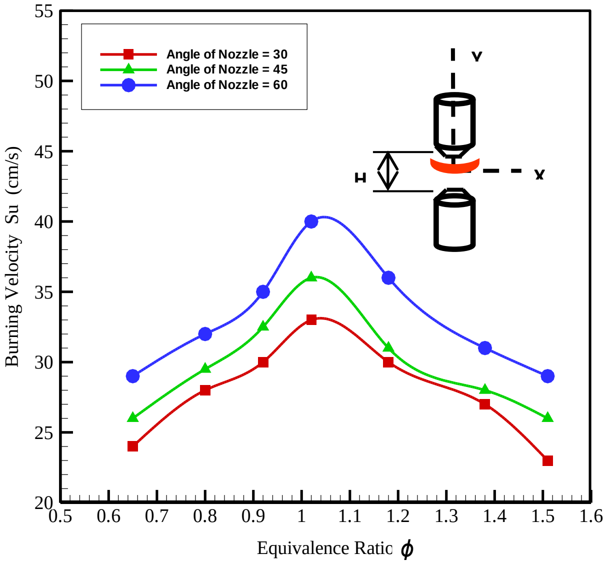


Figure 11. Effect Types of Nozzle on the Diffusion Burning Velocity without N_2 at (H= 40mm).

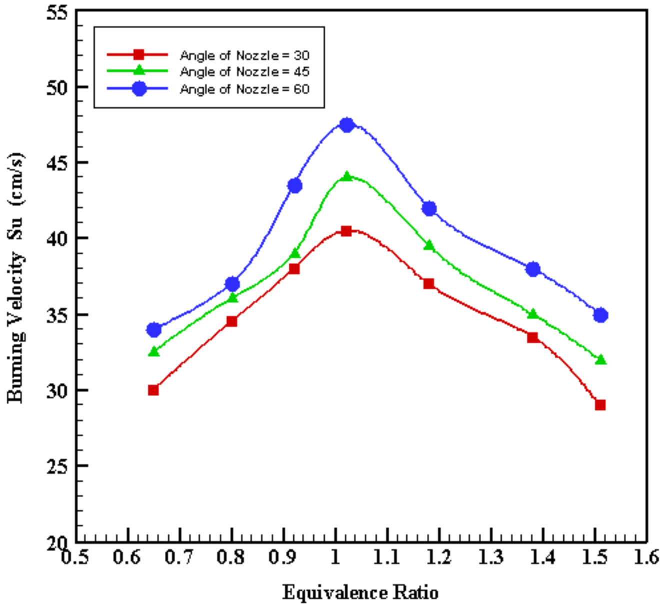


Figure 12. Effect of Types of Nozzle on the Diffusion Burning Velocity with N_2 at (H= 20 mm).

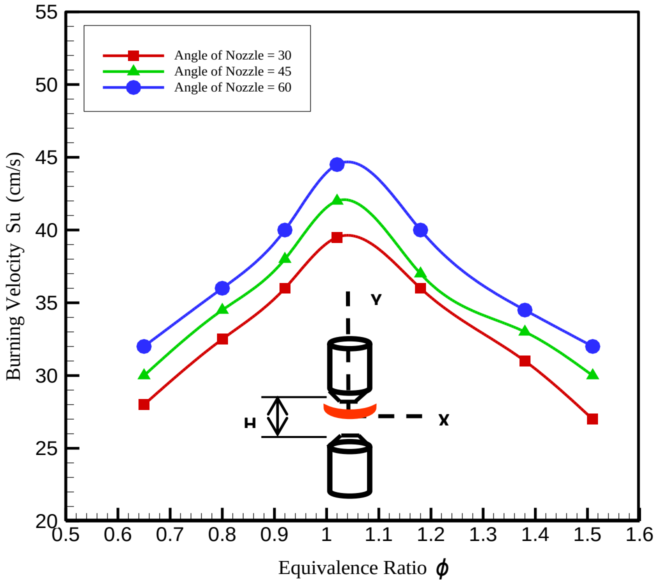


Figure 13. Effect of Types of Nozzle on the Diffusion Burning Velocity with N_2 at (H = 30 mm).

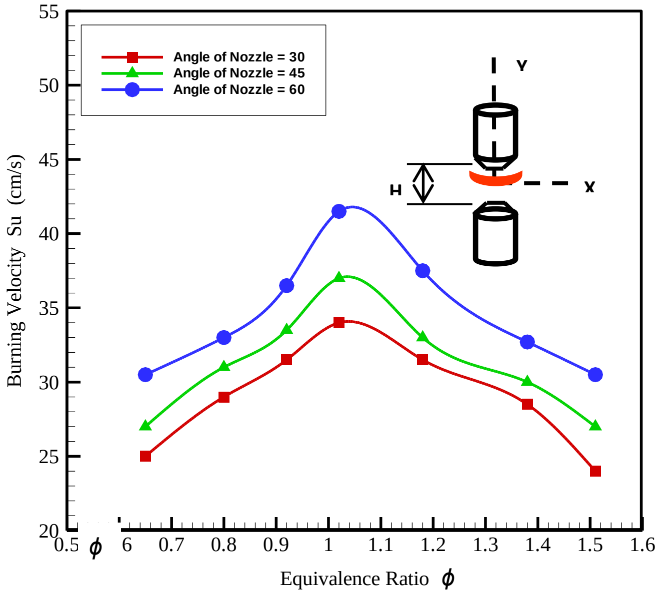


Figure 14. Effect of Types of Nozzle on the Diffusion Burning Velocity with N_2 at (H= 40 mm).

4.2 *Stability Limits*

The increasing of the diffusion burner operation area is an importance to get a wider range of flame front stability as well as increase the thermal energy generated from combustion of fuel and air. Figure (15) depicts the stability boundaries of the front of diffusion flame, where the blue region indistinctly indicates the ‘lean diffusion flame disc’ in order to raise the permissible boundary air ratio, shown by the red region that depicts the ‘rich flame disc’. This is owing to the increment in the ratio of fuel, whereas the blue dark line that divides the two areas describes the region of the diffusion flame at the ratio of the stoichiometric air to fuel. And, each region out of those regions reveals the flames instability and extinguishing owing to disproportion level of blending air and fuel and the blending difficulty between them, which leads to incomplete the perfect combustion and flame instability and its extinguishment. This effect can be recognized through the analysis of the Schlieren and visible optical images, as shown in figure (16).

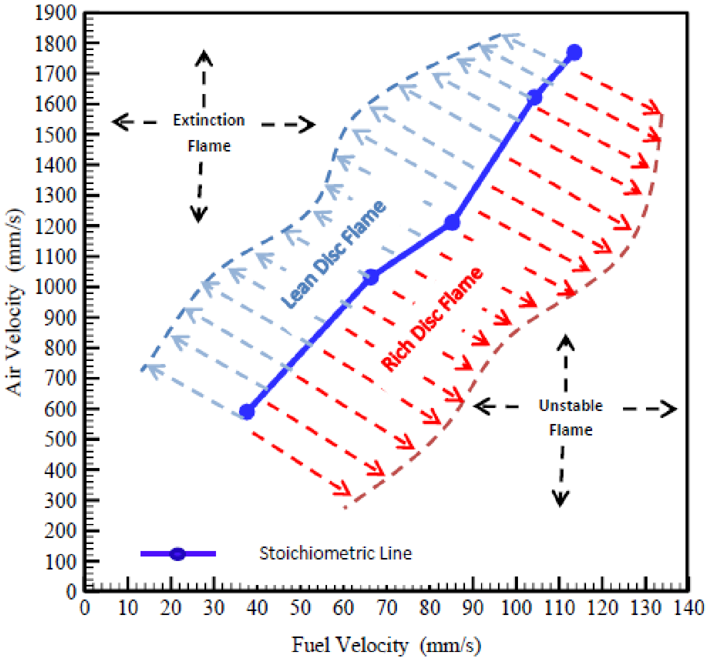
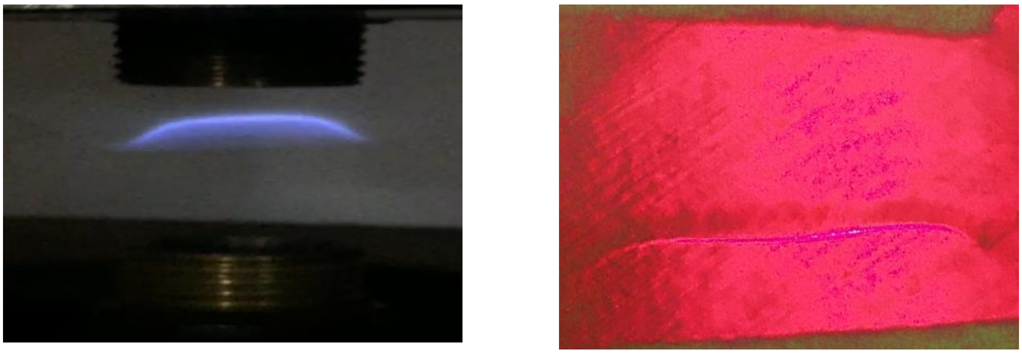


Figure 15. Limits of Operation Diffusion Flame Angle of Nozzle 30° at (H =20 mm)



Visible Disc flame **Schlieren Disc Flame**

Figure 16. Photo of diffusion flame in counter burner.

5. Conclusions

The conclusions derived from this experimental study are summarized as follows:

1- The use of Schlieren optical system technique makes it possible to provide high accuracy in the flame front analysis, because of its dependence on the reference surface for flame incandescence without causing any turbulent to the reactants flow.

2- The geometric shape of the nozzle burner is playing a key role in the mechanism of flame stability.

3- In diffusion counter combustion it was found that nozzle (60°) is giving a highest value of the burning velocity, while nozzle (30°) is giving a lowest value. Which were adopted mainly on the counter- streams and the vorticity zone.

4- Burning velocity depends on the stagnation surface of the flame front, which in turn relies on the vertical distance between the burners (H).

5- Increasing the angles of nozzle lead to increases the burning velocity.

6- Use of nitrogen leads to an increase in the burning velocity due to obtaining an equivalent mixing between the reactors and not allowing the outside air to participate.

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