IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 08, Issue 4 (April. 2018), ||VIII|| PP 39-51

Liquid Fuel Double Swirled Combustion with Gaseous Fuel Injection

A.Ezzat[1], A.M.T.A El-Dein Hussin[2], M. M, Kamal[3]
Department of Mechanical Power Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt
Corresponding Authors: A.Ezzat

Abstract:-The effects of the cross flow using opposing jets as gaseous fuel in addition to the effects of the double swirling on the performance of the diffusion flame was investigated experimentally . The cross flow in terms of opposing jetswas premixed mixture of gaseous fuel and air). And the influence of the double swirler on the flames characteristics was investigated with two swirling modes;CO-swirl and Counter-swirl. The combustion chamber was provided with dual fuel, such that liquid fuel was burnt in a cross flow of gaseous fuel. Meanwhile, the air was co-axially introduced in a double swirl flow field. ٍThe effects of varying the swirl number, mode, and air to fuel ratio on the emissions and flame length were investigated. The results illustrated that more flame stability, reduction in the concentration of the unburned hydrocarbon as well as the carbon monoxide could be achieved by the opposing jets, however an increase in NOx concentration occurred.

Keywords: -Combustion, Opposing Jet, Swirl Number, Duel Fuel

Date of Submission: 12-04-2018 Date of acceptance: 30-04-2018

I. INTRODUCTION

The main requirements from the combustion chamber of a gas turbine are to achieve low exhaust emission, high stability limits, good mixing between the fuel and the introduced air, and high combustion efficiency over different operating conditions. One of the best ways for ensuring a good mixing between the fuel and the combustion air is to generate a swirl motion for the incoming combustion air stream. This method supplied better control than that normally gained from the other means like air stream tangential entrance into the combustor. The swirl motion influences substantially at the size of flame, flame stabilization, the efficiency of combustion, and the concentration of the exhaust., Subsequently, the motion of the swirl needed for getting less pollutants, more combustion efficiency, and more flame stabilization at wide range of the air to fuel ratios. The impact of swirl on the pollutants is a function of numerous parameters, such as the type of fuel, the location of the injection swirl mode and swirl strength. By increasing the swirl motion, the rate of the entrainment of the introduced air increased in the confined configuration which leads toreduction of the flame temperature, hence reduction of NOx concentration.

Several experiments showed that at near the combustor outlet the CO concentration is much higher than on the flame tube axis for swirler of large hub . For large axial distance, the concentration of CO becames much higher near the flame tube for all types of swirlers The local equivalence ratio distribution became a rich mixture at the flame tube axis with uniform local equivalence ratio distribution by the double swirler which clarify the good mixing of the air and fuel, [1].

The analysis of the exhaust gas concentrations of many combustion chambers clarify that the concentration of oxygenis low at center line but large concentration of products CO and CO_2 at the combustor center line and the CO concentration at the combustor center line reached to 1500 ppm. But by moving toward the combustor wall, the oxygen concentration increases. The combination of combustion air as double swirler (CO and Counter) swirlers types with the liquid fuel injection axially at the combustor center line and the concentration of CO_2 have a maximum values at the furnace center line with the decreasing gradually towards the combustor walls. Also, used combination of (counter and CO) swirlers with the inner swirlers 60° but the outer swirler 45° which found that the CO concentration across the combustor center lines was a minimum values which was reached to 100 ppm ,[2].

The effect of swirl on the stability of the diffusion flames of the hydrogen jets by using combustor had double swirler showed that the flame stability is improved by addition the swirl of the fuel jet and if the direction of the swirl of the fuel jet and air stream is the same, get the most favorable effect of swirl of the fuel,[3].

Furthermore,the diffusion flames have been considered to characterize the heat re-circulation from the exhaust gases into the zone of the reactions. While, in the system of combustion, the hot gases are frequently re-circulate to upgrade the stability of the flame. The cross flow i.e. opposing jets is used for acting as obstructing the main stream which making a stagnation points which result a re-circulation zone to support and concentrate the flame. The advantage of the cross flow is to generate much turbulence to support quite enough oxygen content in the flame area. In this situation, the incoming air into the fuel core through the diffusion flame becomes roughly enriched by the mixing where the flow characteristics effect to the flame structure. It may be reduced the pollutant like by controlling the mixing rate between the air and the fuel, [4].

The aerodynamically of the dominated flames which the re-circulation around the combustor exhaust and shear layer made vortices made the gas jet and cross flow at perfect mixing. To occur the enhancement of the flame stability and combustion efficiency, a control technique of passive or active are used,[5].

II. TEST RIG

The basic configuration of the test rig allows separating the combustor from test rig for easy changes of liquid fuel nozzle, gaseous fuel nozzles and swirlers. The test rig assembly , see Fig. 1, consists of combustor with four main systems;Liquid fuel system, gaseous fuel system and liquid fuel supply air system and gaseous fuel supply air system. The primary supply air system is supplying air for liquid fuel burning where a centrifugal blower (1). The air supply reaches a cylindrical combustion chamber (7) and is varied by the butterfly valves (2); while the pressure differences across the orifice plates (3) indicate the flow rates and measured by a set of manometers (4) connected to the tapings. The air is entering the combustion chamber after crossing a double vanned type swirler (10). This swirler splitsthe combustion air into two streams; inner stream which is close to the liquid fuel nozzle, and an outer stream which is surrounding the inner stream. The secondary supply air system is supplying air for gaseous fuel burning where a centrifugal blower (11).The air supply reaches a cylindrical combustion chamber (7) that are varied by the butterfly valves (12); while the pressure differences across the orifice plates (13) indicate the flow rates and measured by a set of manometers (14) connected to the tapings. The air is entering the combustion chamber after premixing with the gaseous fuel at the mixing manifold then the premixed gaseous fuel line was split into six lines downstream of premixing chamber, then each line is split into two lines of two opposing jet (9) with shutoff valve (8) for each one producing twelve opposing jets inside the combustion chamber. On the liquid fuel side, the fuel is supplied from a liquid fuel reservoir through a fuel filter before entering a gear pump. The fuel pressure can be adjusted by a built in pressure regulating valve inside the fuel pump and monitored via a pressure gauge. Once the liquid fuel has been regulated, it is directed to a fuel nozzle (5) having a pattern spray cone of 60°. Gaseous fuel supply system, consists of Liquefied Petroleum Gas, LPG, cylinder, where the flow rates are separately regulated and measured via the rotameter flow meter before entering a manifold (6).

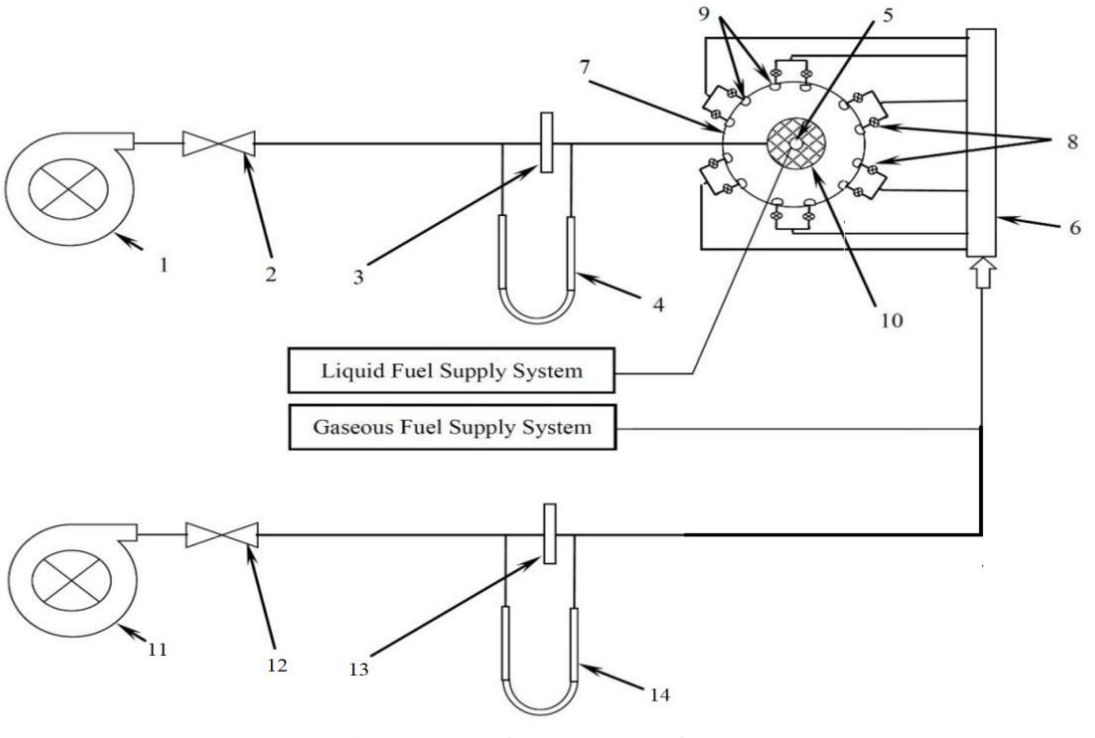
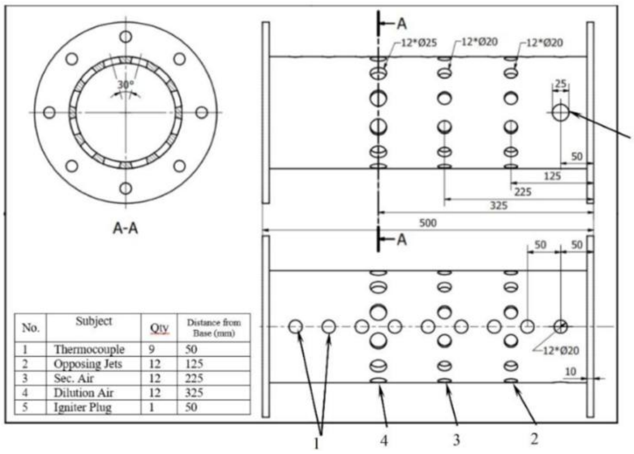


Fig.1: Air Supplying System Schematic.
1- Primary Blower. 2- Butterfly Valve. 3- Orifice Meter. 4- Manometer. 5-Liquid Fuel Nozzle 6- Gaseous Fuel Manifold. 7- Combustion Chamber. 8- Shutoff Valve (12). 9- Opposing Jet Nozzle (12). 10– Swirler. 11- Secondary blower. 12- Butterfly Valve. 13- Orifice Meter. 14- Manometer.

Figure 2 shows the Combustor which is a cylindrical shape with 500 mm of length and 147 mm of diameter. To ensure efficient combustion, part of the air flow was admitted into the 12 secondary and 12 dilution, see ports (3) and (4), in Fig.2. Air was delivered symmetrically into the combustor Also, the 12 ports (2) have been provided to deliver the gaseous fuel jets into the combustor by 12 removable 3 mm hole nozzles, Fig. 3.



No.	Subject	Qty	Distance from Base (mm)
1	Thermocouple	9	50
2	Opposing Jets	12	125
3	Sec. Air	12	225
4	Dilution Air	12	325
5	Igniter Plug	1	50

Fig. 2: Combustion Chamber ports distribution.

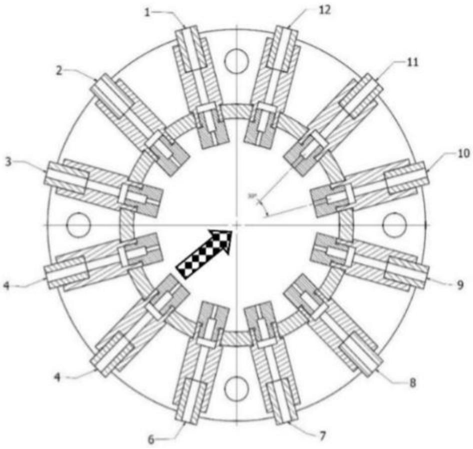


Fig. 3: Gaseous Fuel Opposing Jets section in the Combustion Chamber (Air Flow Inside View).

Swirler Manufacturing

The body of each swirler was made from four parts;inner ring, intermediate ring, outer ring and vanes.The whole body was manufactured by welding the vanes between the inner and intermediate rings also vanes were welded between intermediate and outer rings.

Table 1 shows the specifications of the swirlers, i.e. inner, intermediate and outer diameter, inner and outer swirl angle, number of vanes at each stage and swirler direction or type.

Table 1: Swirlers specifications.

Swirler identification	Inner Diameter (cm)	Intermediate Diameter (cm)	Outer Diameter (cm)	Inner swirl angle	Outer Swirl Angle	Number of inner Vanes	Number of outer Vanes	Swirl Direction
Swirler 45°x45°	**2**	**5.1**	**7.5**	**45°**	**45°**	**8**	**8**	**co**
Swirler 45°x45°	**2**	**5.1**	**7.5**	**45°**	**45°**	**8**	**8**	**counter**
relriwS °45x°60	**2**	**5.1**	**7.5**	**60°**	**45°**	**8**	**8**	**co**
relriwS °45x°60	**2**	**5.1**	**7.5**	**60°**	**45°**	**8**	**8**	**counter**

relriwS °60x°60	**2**	**5.1**	**7.5**	**60°**	**60°**	**8**	**8**	**co**

Measurements

The flow rate of the supplied air was measured by a standard orifice plate between blower exit and combustion chamber. The orifice plate was designed and manufactured in according with British Standard, [6]. The flow rate of Diesel fuelwas measured by counting the time lapsed to consume a specific quantity of the Diesel fuel while the flow rate of gaseous fuel was measured by a rotameter, [6].

The local flame temperature was measured by an unshielded thermocouple type S (90% Platinum/10% Radium–Platinum, by weight), able to measure temperatures up to 1600 °C. This thermocouple was used to measure a local temperature of as a mesh of 30 points distributed inside the combustion chamber along five axial stations with six radial points. The six radial reading positions were in equal distance of 1 cm from its center axis tothe wall. The five axial reading positions were in equal distance of 5 cm starting from just downstream of liquid fuel nozzle. Concentrations of Carbon Monoxide (CO), Nitrogen Monoxide (NO) and UHC (unburned hydrocarbon) were measured radially at last station in the combustion chamber by a portable gas analyzer LANCOM III .

Setup and Constraints:

Regarding the liquid fuel, an injection pressure of 17 bar was kept constant during the experiments, such that the flow rate was 2.4 kg/hr. While, the flow rate of gaseous fuel was kept constant at 0.36 kg/hr. The mass flow rate of the primary air required for the combustion was 44 kg/hr and the mass flow rate of the secondary air was 11.1 kg\hr.

The air to fuel ratio of the liquid fuel was 18 while it was was 40 for the gaseous fuel.

III. RESULTS AND DISCUSSION

By increasing the injected fuel at the opposing jets, the A\F ratio for liquid fuel was increased also this test for zero swirl and the following table shows the increasing the flammability limit by increasing gaseous fuel flow rate

Table 2: The relation between the opposing jets and liquid fuel flammability limit

GASEOUS FUEL A\F RATIO	LIQUID FUEL A\F RATIO FLAMMABILITY LIMIT
N\A	10
25	20
17	39
12	55

By testing the flammability limit of the gaseous fuel ,it was found that the A\F ratio equal to 40. The figure 4 shows the combustion by using the opposing jets only.

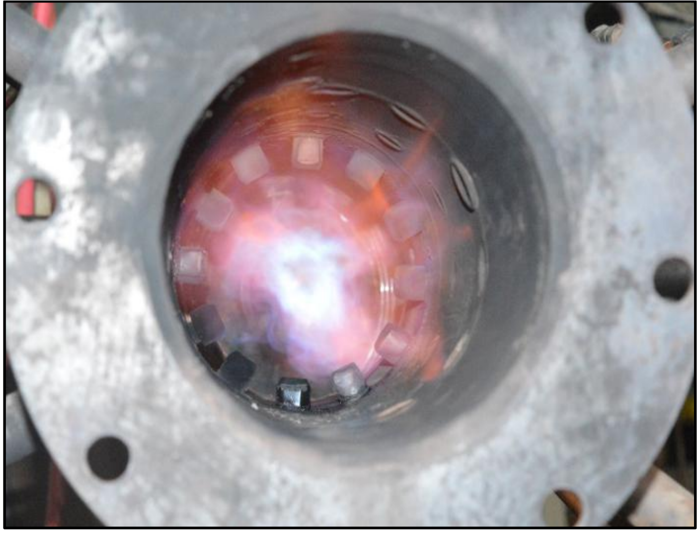
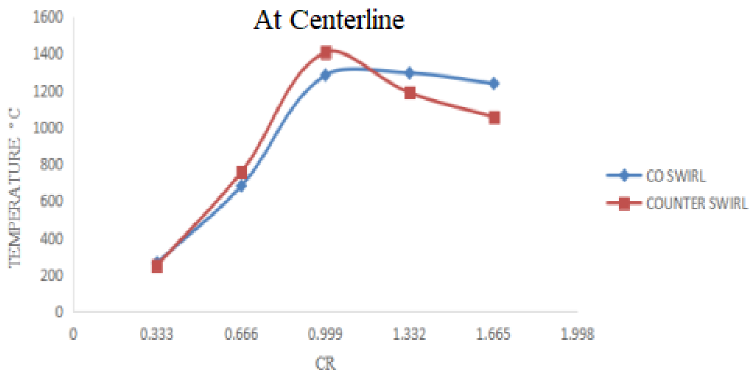


Fig.4: The flame shape for using opposing jets only.

Comparative Study between the CO-Swirl and Counter-Swirl:

Figure 5 shows the difference at the local flame temperature between the CO-Swirl and Counter-Swirl for the same inner and outer swirl angles which inner swirl angle 60°and the outer swirl angle 45°


At Centerline
TEMPERATURE °C
1600
1400
1200
1000
800
600
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0
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0.333
0.666
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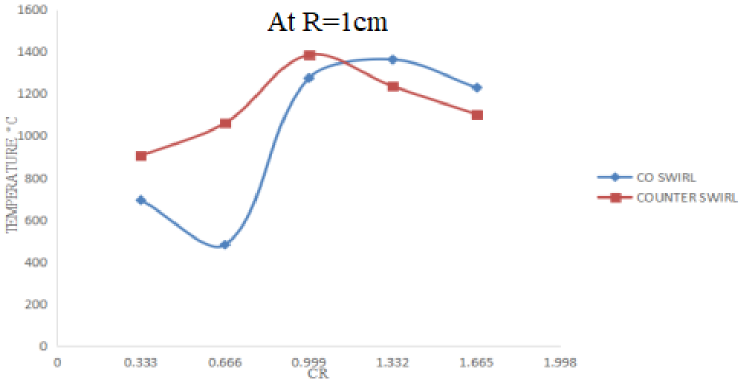
1.332
1.665
1.998
CR
CO SWIRL
COUNTER SWIRL


At R=1cm
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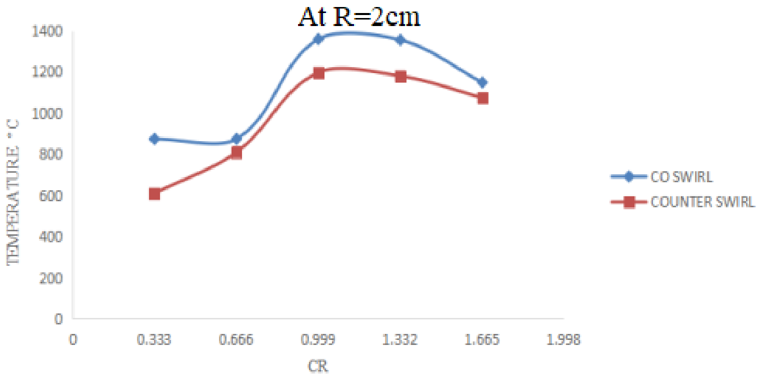
1.665
1.998
CR
CO SWIRL
COUNTER SWIRL


At R=2cm
TEMPERATURE °C
1400
1200
1000
800
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200
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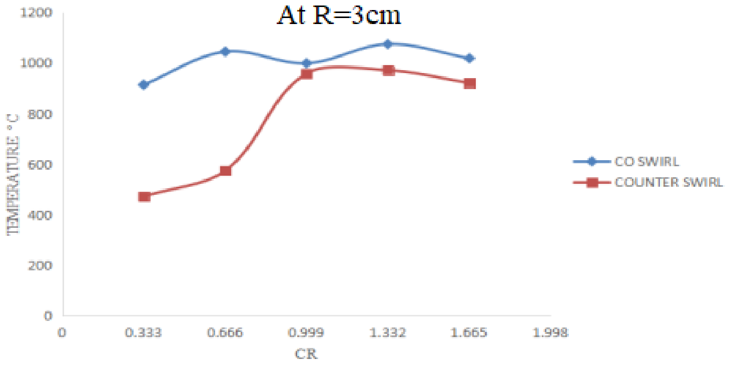
0.999
1.332
1.665
1.998
CR
CO SWIRL
COUNTER SWIRL


At R=3cm
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CR
CO SWIRL
COUNTER SWIRL

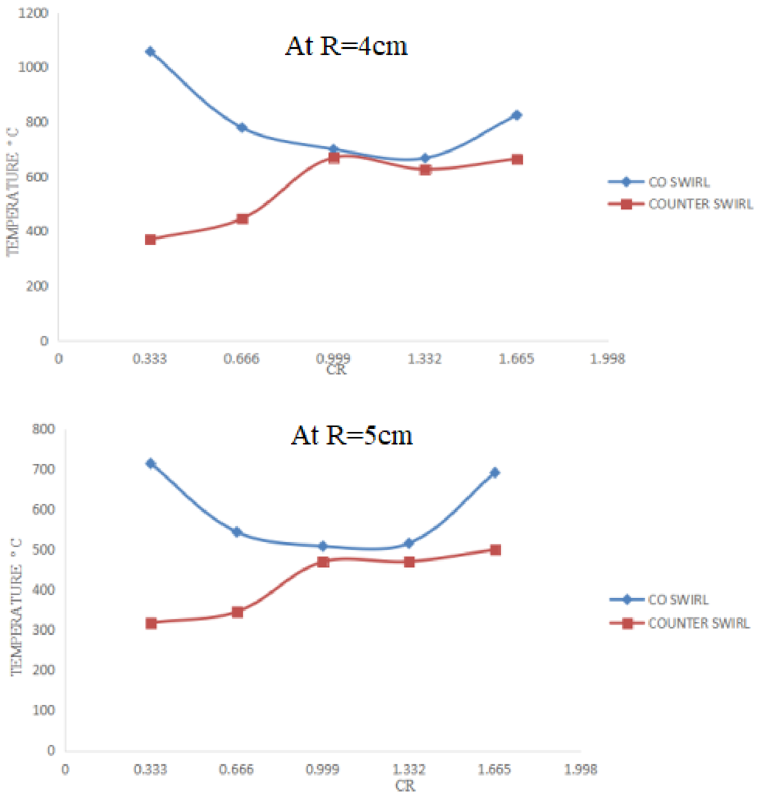


Fig. 5: Flame temperature contours comparison between co-swirl and counter-swirl at the same combustor radius.

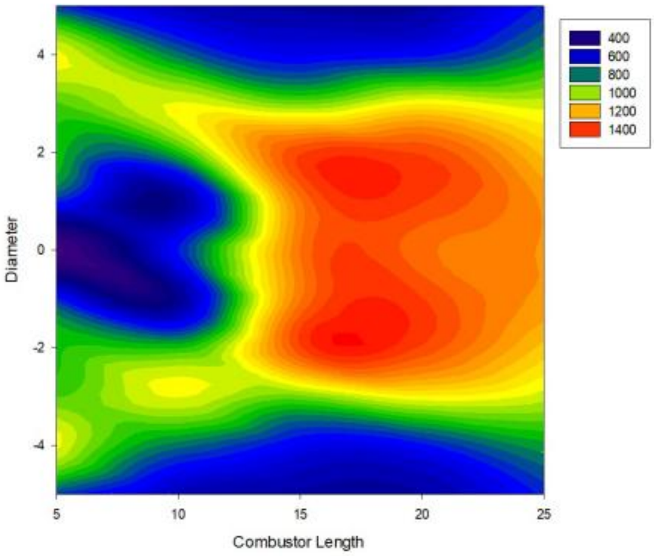
At the center line, almost no difference of the local flame temperature between CR (Confinement Ratio: the ratio between the furnace diameter to the furnace length ratio) 0.333 and 0.666, due to the swirling motion, which had a turbulent zone. At CR=1, the local flame temperature for CO-swirl became higher than that of counter-swirl, due to the steady state stream of the exhaust gases.

At R=1cm,the local flame temperature for the counter swirler became higher than that of the CO-swirler, due to swirling motion for the counter made flame cone angle higher than the CO-swirler. At CR=1, the local flame temperature at CO-swirler was increased, due to the flame length for CO larger than the Counter-swirler, so the heat transfer across the CO-swirler higher than the Counter-swirler .

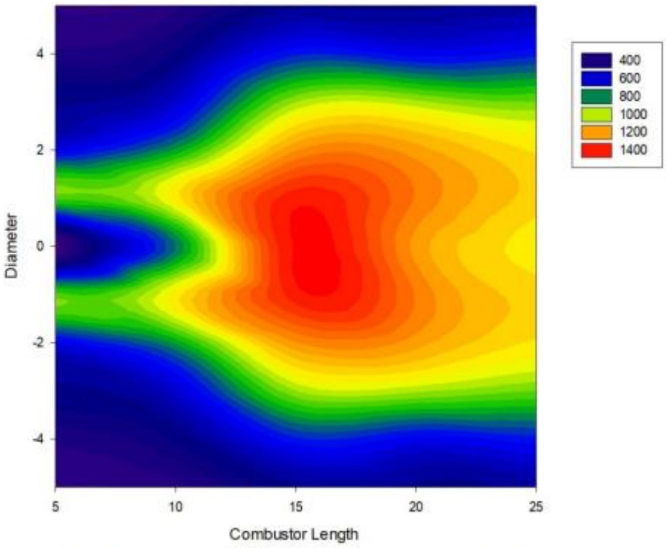
At R=2cm, the local flame temperature at CO-swirler was higher than Counter-swirler, due to the flame core diameter at CO-swirler larger than Counter-swirlerand the flame length for CO-swirler larger than Counter-swirler .

The same same for R=3cm , R=4cm and R=5cm, which the temperature for CO-swirler was higher than Counter along the combustor length, due to having the larger flame length than the Counter-swirler.

The following figures show the local flame temperature contour across the combustor and the difference between the CO-swirler swirl and the Counter-swirler. The shape of local flame contours across combustor represented that the flame cone angle for the CO-swirler is larger than the Counter-swirler and the flame length also shorter at the Counter-swirler, due to the swirling intensity at the CO-swirler higher than the Counter-swirler.



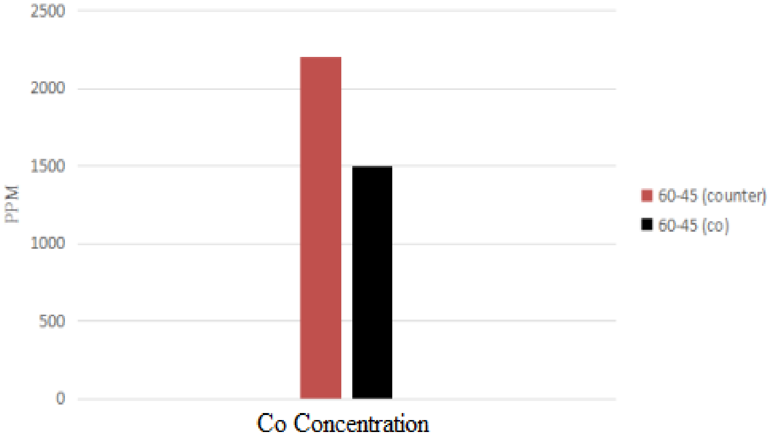
Swirl Mode: CO Inner Angle:60° Outer Angle=45°



Swirl Mode: Counter Inner Angle: 60° Outer Angle: 45°

Fig. 6: Flame temperature contours comparison between CO-swirlerand Counter-swirl across the combustor.

Figure 7 shows the variation of the exhaust concentration by using different types of the swirling mode.



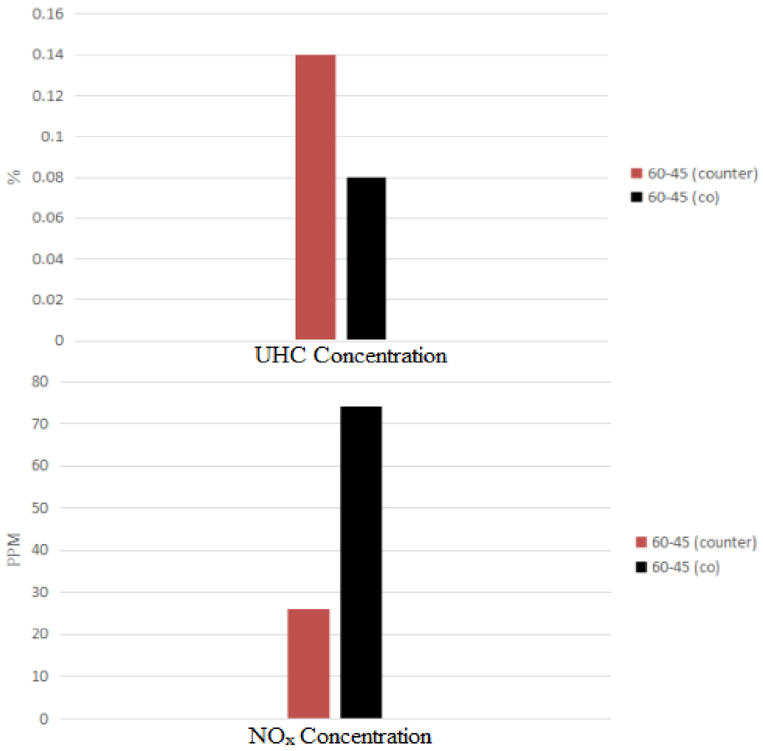


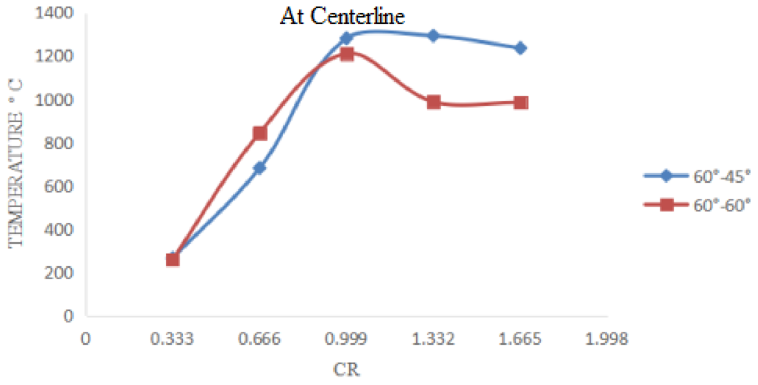
Fig. 7: Exhaust concentration comparison between CO-swirlerand Counter swirl across the combustor.

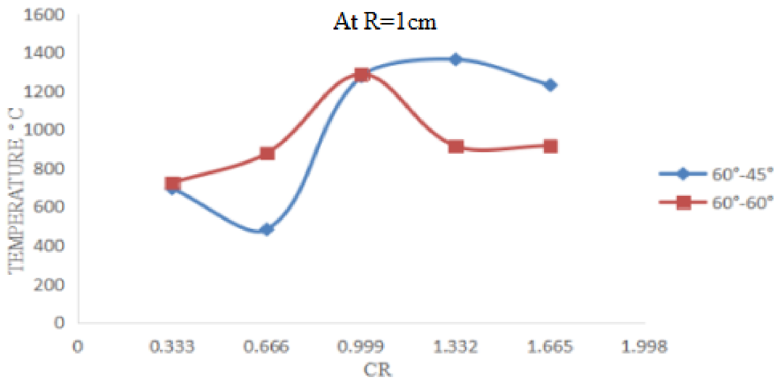
In this work , it could be concluded that, the CO-swirlers had flame stability than Counter-swirlers, and the concentration for CO-swirlersand UHC was higher at Counter-swirlers, due to higher local flame temperature, the concentration of NO_x at CO-swirlers higher than Counter -swirler. By compariing the swirler modes of CO-swirlers and Counter-swirlers , it was found that the CO-swirlers had more flame stability than that of the Counter-swirlers, and the concentration difference of the carbon monoxide and unburned hydrocarbon between the swirlers was 35% and 40% respectively. Due to higher local flame temperature the concentration of NO_x at CO-swirler was higher than Counter-swirler by 55% .

These results was agreed with Bach and Gouldin,[8], who noticed that, the mixing in the inter-jet shear layer under the counter swirl conditions was rapid so it will quench the chemical reaction, which got the efficiency became low and got high concentration of Co and unburned hydrocarbon compared to the CO-swirlers .The previous conclusion was agreed with Kamal, M, M.,[2], who concluded that the counter-swirler cases associated with flame instability, while CO-swirlers cases has more flame stability and also matches with results Durbin and Ballal,[7], who noticed that CO-swirlers produced a larger range of the stability.

Comparative Study for different swirl number for the same swirling mode:

Figure 8 shows the local flame temperature across the combustor by varied the swirl number of the swirler which is altered by changing the outer angle but the inner swirl angle kept constant as 60° and the outer once time equal 60° and the other time equal 45°




At R=1cm
TEMPERATURE ° C
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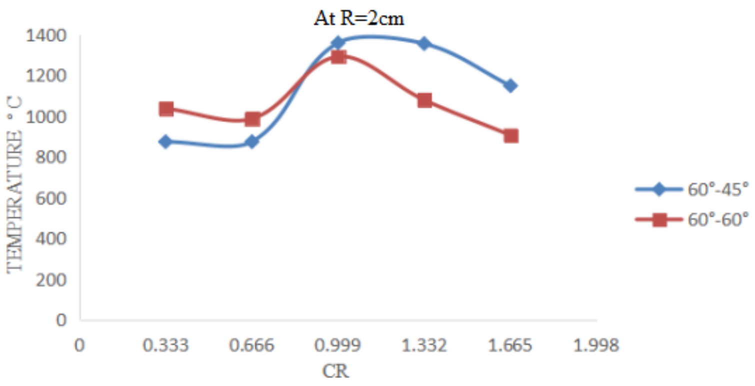
CR
60°-45°
60°-60°


At R=2cm
TEMPERATURE ° C
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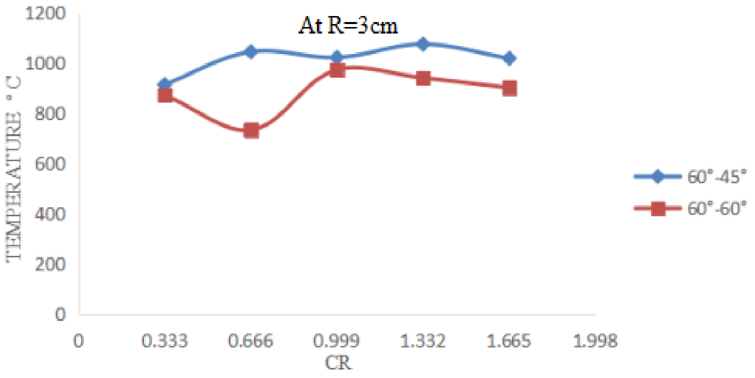
CR
60°-45°
60°-60°


At R=3cm
TEMPERATURE ° C
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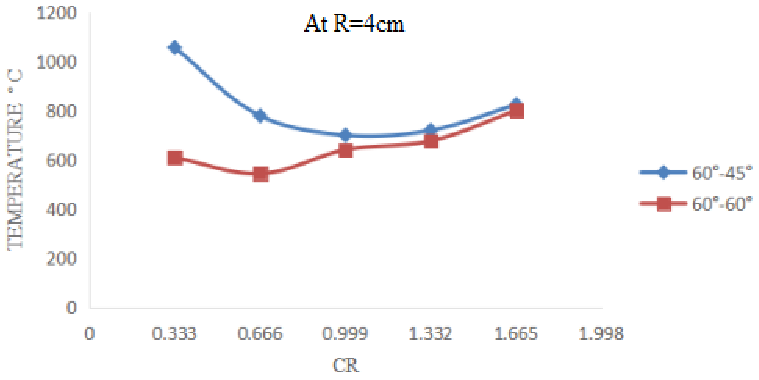
CR
60°-45°
60°-60°


At R=4cm
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CR
60°-45°
60°-60°

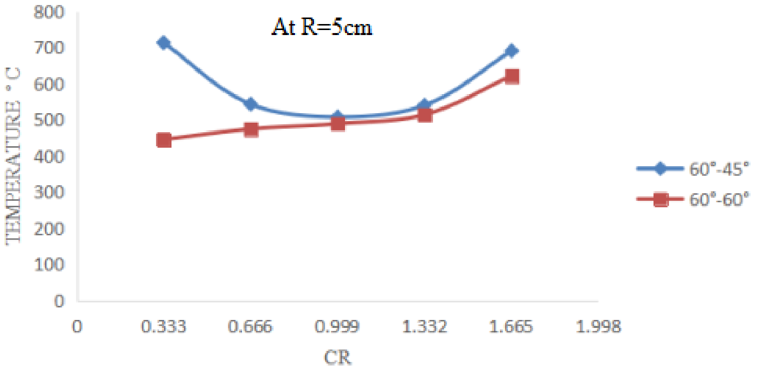
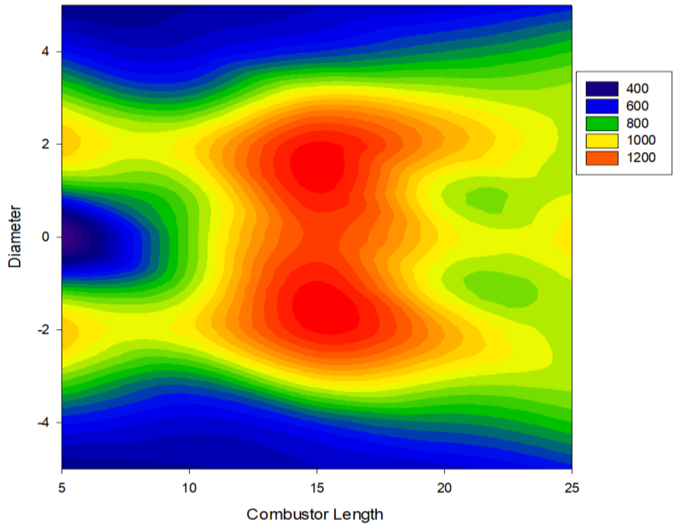
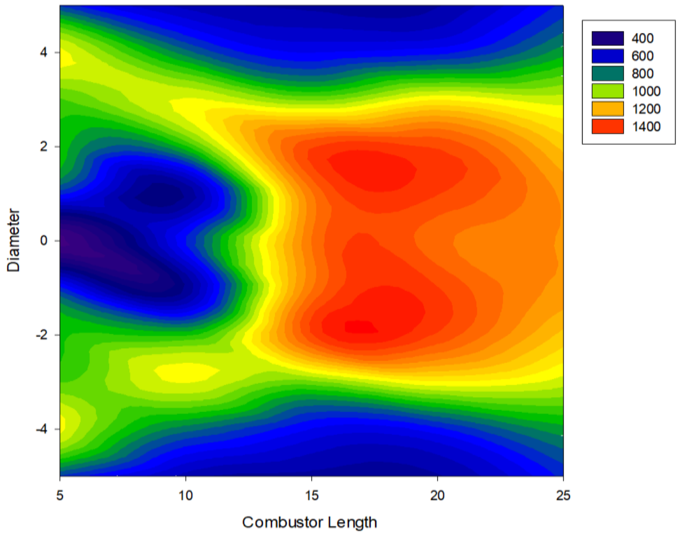


Fig. 8: Flame temperature comparison by variation the swirl number the same combustor radius.

Figure 9 present the flame contour across the combustor by varied the swirl number which shows that swirl number at outer swirl angle =45° was 0.94 and at outer swirl angle =60° was 1.22 for the same outer angle. The local flame temperature decreased, and at the same section the maximum local flame temperature at swirl number 0.94 was higher than swirl number 1.22 and the flame length at swirl number 0.94 was higher than swirl number 1.22.



S_N=1.22, Inner Angle= 60°, Outer Angle= 60°



S_N=0.94, Inner Angle= 45°, Outer Angle= 60°

Fig. 9: Flame temperature contours comparison by variation the swirl number the same combustor radius.

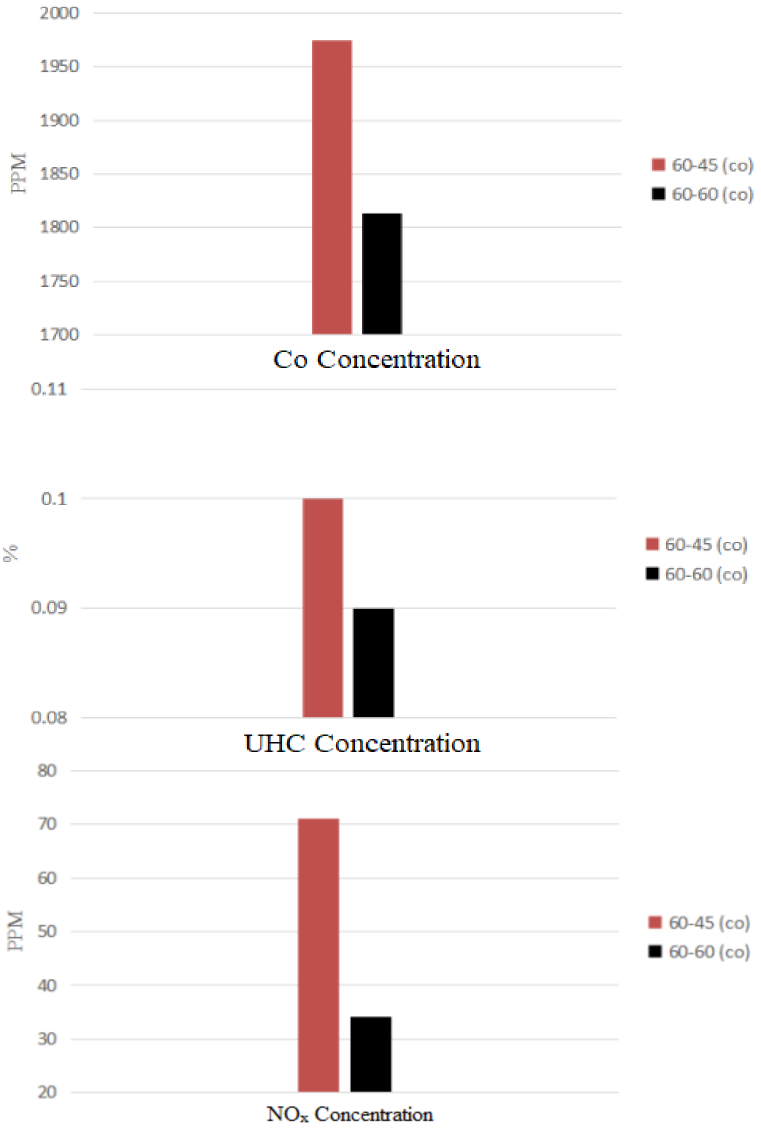


Fig. 10: Exhaust concentration comparison by variation the swirl number the same combustor radius.

The previous conclusion had an agreement with Kamal, M, M.,[2], who concluded that, by increasing swirl number from 0.7 which (45°o-45°i) increasing the maximum flame temperature to a maximum at swirl number 0.99 (45°o-60°i). After that the decreasing in the maximum flame temperature again at swirl number 1.22 (60°o-60°i).

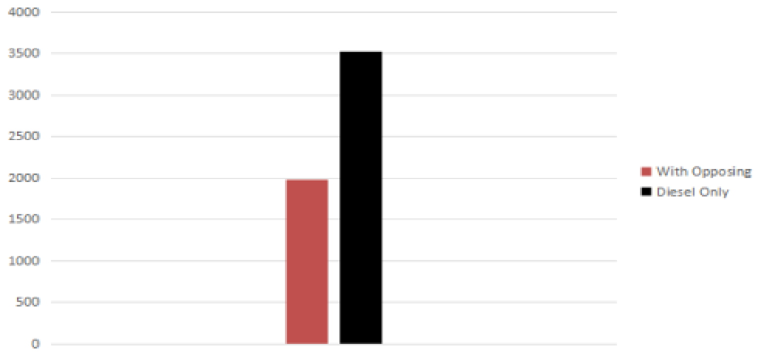
Also an agreement was achieved with Ginn Yaun,[9], who concluded that, the penetration length of the fuel spray is reduced with increasing in the swirl level resulting in shorter and wider flames with lower values of CO and the maximum temperature region shifts to the upstream part of the burner and spread more uniform and wider at the case of the high swirl motion.

Moreover, this work is in agreement with Fricker,[10], who concluded that at high values swirl number. The flame jet spread was occurred, which produced an intense blue flame with S 0.93 and for the flame with S 0.84 had a short reaction zone.

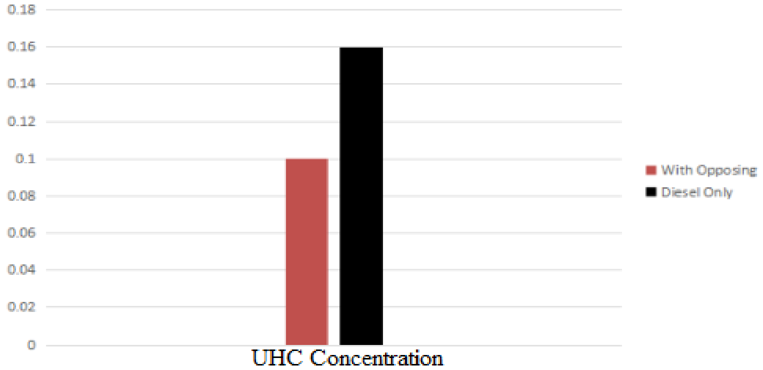
The survey from Nasr Eldine,[11], who had noticed that, the increasing swirl degree causes improvement at fuel spray evaporation. And fuel and air turbulent mixing that was add to high rate chemical reaction.

Fig. 10 shows the exhaust concentration and the effect of the changing the swirl number which concluded that by changing the swirl number from 0.94 at swirler (60°i-45°o) to 1.22 at swirler(60°i-60°o) with the same swirler mode as CO-swirler type. The local flame temperature decreased and the flame length decreased by 18%, which the concentration of the carbon monoxide and unburned hydrocarbon at swirl number 1.22 more than swirl number 0.94 by 15% and 20% respectively. But the concentration of the NO_x decreased by 55%.

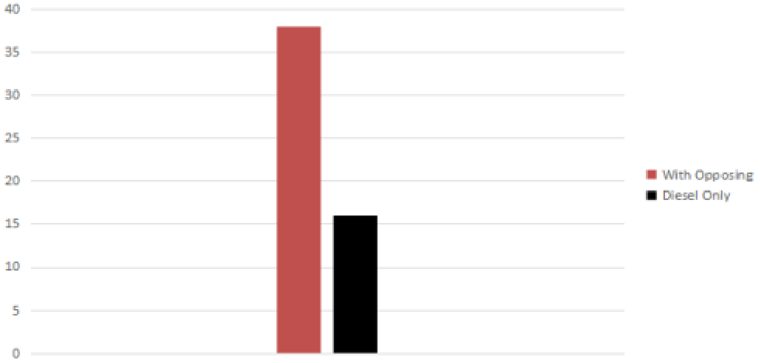
Comparative Study Between using Diesel Only and Diesel with Opposing Jets for Exhaust analysis:
Figure.11 show the comparison between using diesel fuel only and using diesel fuel with gaseous fuel for the same swirler which using swirler with outer swirl angle 45° and inner swirl angle 60° with swirling mode CO-swirl.



Co Concentration



UHC Concentration



NO_x concentration

Fig. 11: Exhaust concentration comparison by using opposing jets with diesel fuel.

by using the gaseous fuel as opposing jets for the liquid fuel, the concentration of CO is reduced by more than 50% , due to higher temperature for the exhaust gases, because the large flame length, due to using the opposing.

On the other hand, the percentage of UHC is reduced more than 50% ,due to also for more combustion produced by using the opposing jets. But the concentration of NO_x increased also, due to the formation of thermal NO_x, because higher flame temperature. this result is an agreement with Koyama.M and Fujiwara.H.,[12], who concluded that, by using gaseous fuel with kerosene the smoke emission reduced and high combustion efficiency maintained.

Also in agreement with Azimov. U.,[13],who concluded that, the using of hydrogen as opposing jets with another fuel lead to increase at maximum pressure and increasing in flame temperature with increasing combustion efficiency, but the concentration of NO_x had been raised.

IV. CONCLUSION

The present work examined the influence of the variation of the inner and outer swirl angle and variation of the swirl mode and using premixed gaseous fuel as cross flow (opposing jets) on the characteristics of the combustion of the liquid fuel as diffusion flame. The conclusions form the results are listed as follows.

1. The flammability limit using Diesel fuel only with swirler which had zero swirl angle was at A\F ratio 9.5 and the flammability limit for the cross flow (opposing jets) only was at A\F ratio 40.
2. By changing the A\F ratio for the opposing jets for the same swirler and same A\F ratio for the liquid fuel the local flame temperature increased and the concentration of the carbon monoxide and unburned hydrocarbon decreased but the NOx formation increased also.
3. By compariing the swirler modes of CO-swirler and Counter-swirler, it was found that the CO-swirlers had more flame stability than that of the Counter-swirlers, and the concentration difference of the carbon monoxide and unburned hydrocarbon between the swirlers was 35% and 40% respectively. Due to higher local flame temperature the concentration of NO_x at CO -swirler was higher than Counter-swirler by 55% .
4. By changing the swirl number from 0.94 at swirler (60°i-45°o) to 1.22 at swirler(60°i-60°o) with the same swirler mode as CO type. The local flame temperature decreased and the flame length decreased by 18%, which the concentration of the carbon monoxide and unburned hydrocarbon at swirl number 1.22 more than swirl number 0.94 by 15% and 20% respectively. But the concentration of the NO_x decreased by 55%.
5. By using the opposing jets the local flame temperature and flame length increased so the concentration of the monoxide and unburned hydrocarbon decreased by 40% and 40% respectively, but the concentration of the NO_x increased by 55% due to the more fuel injected and the turbulence induced in the combustor.

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