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# Combustion performance of triple flames issuing from elliptical Swirlers

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**Abstract:** An experimental work has carried out to characterize the combustion performance in terms of flame length, temperatures and emissions for a triple flame structure of concentric fuel rich mixture surrounded by fuel lean mixture premixed flame combined with the cross flow stream. A set of elliptical double swirlers of different angles and aspect ratios were compared to a circular double Swirler was used to investigate the effect of swirling direction modes (co- versus counter swirl), the effects of swirl angles, and ellipticity. It was found, for counter and co-swirl, that counter swirler leads to higher enhancement of combustion process than co-swirler, due to higher levels of premixing, slight differences in the flame length were found. The counter swirl induces higher levels of turbulence than co-swirl with the consequent enhancement in the mixing of the mixtures and reducing the flame peak temperatures thus decreasing $NO_X$ , by 36%, and CO, by 29%, emissions comparison to that of the co-swirl. In addition, increasing the inner swirling angle shortens the flame length. Increasing the inner swirl favorably produces flames of higher average temperatures and lower emissions of CO and $NO_X$ emissions. In this scene, it was found that the elliptic swirl of ($45^o$i, $30^o$o) produces higher flame temperatures and lower emissions concentrations of $NO_X$ , by 38%, and CO, by 10%, than that for the elliptic swirl of ($30^o$i, $45^o$o). Furthermore, it was found that the elliptic swirl shows shorter flame length than circular swirler, while the elliptic swirl of AR=1.25 produces the shortest flame length relative to other Swirlers of different aspect ratios. The effect of the ellipticity was noticeable, since it was found that the elliptic swirl of AR=1.25 produces flame of higher temperatures and lower $NO_X$ emission than any other Swirlers of different aspect ratios. Increasing the aspect ratio leads to decrease the concentrations of CO emission. Finally, it was concluded that double circular swirl produces higher CO and $NO_X$ than double elliptic swirl.

**Nomenclature and Greek letters:**

| | | |
|---|---|---|
| AR | : | aspect ratio |
| CO- | : | Coaxial |
| CN | : | Counter |
| i | : | inner |
| o | : | outer |
| $\varphi_i$ | : | Inner equivalent ratio |
| $\varphi_o$ | : | outer equivalent ratio |

## I. INTRODUCTION

Large scale coherent structures play an important role in combustion and heat-release processes by controlling the mixing between fuel and air in diffusion-flame configurations and the mixing between the fresh fuel/air mixture, hot combustion products, and fresh air in premixed combustors [1]. Recently, increased demand on clean fuel and clean combustion process as long as clean exhaust gases has become a challenge for combustion engineers to develop a new approach for introducing new combustions control techniques to enhance mixing between air and fuel to increase combustion efficiency and reduce pollutant emissions concentrations like CO, $CO_2$, $SO_X$, $NO_X$ through optimized use of aerodynamics and nozzle design features. There is always a direct couple between turbulence and combustion enhancement which can be favorably modulated to increase the combustion efficiency, minimize pollutants and establish firing technique as well as extending the flame stability limits.

In this sense, there are multiple interactive scenarios available by incorporating elliptical jets with other favorable mixing techniques to enhance the combustion performance [2]. From previous investigations, it could be noticed that coupling between elliptic jets , swirling flows and triple flame structure could be a new promise discipline for numerical and experimental researches.

The flow dynamics and combustion characteristics of elliptical jets have continuously been highlighted for quantifying their associated jet shearing, fluid entrainment and induced flow perturbation for stable and efficient combustion [3]. Noncircular jets have been the topic of extensive research in the last 15 years, as reviewed by Gutmark and Grinstein [4]. These jets were identified as an efficient technique of passive flow control that allows significant improvements of performance in various practical systems at a relatively low cost, because noncircular jets rely solely on changes in the geometry of the nozzle. The applications of noncircular jets include improved large- and small-scale mixing in low- and high-speed flows and enhanced combustor performance by improving combustion efficiency [5]. Another non-circular nozzle configuration that has received attention early is the small aspect ratio elliptic nozzle [6] which shows increased entrainment due to the phenomenon of axis switching associated with them. It was shown by Winant and Browand [7] that in two dimension flows, entrainment is dominated by vortex merging alone, However, in three dimension elliptical jets, entrainment is due to vortex merging and azimuthal deformation of vortices at the same time [6]. Hussain and Husain[8] carried out a comparative study of aspect ratio effect in the range of 2:1- 8:1. It was observed that for a given equivalent dia, the aspect ratio is an important parameter controlling the deformation and typological changes, that is, bifurcation of large scale vortical structures in elliptic jets, and that the dynamics of low aspect ratio elliptic jets are basically different from that of moderate high aspect ratios. In addition, the axis switching location was found to be a linear function of aspect ratio for the entire range of aspect ratios studied. It is accepted that there is a differential spreading rate and relative jet expansion for the vortex element to move outward along the minor axis and inward along the major one to drive axis switching [9, 10] which tends to remove the jet initial instability by becoming symmetric downstream. Elliptical ports thus act as pumping devices to mix ambient and core fluids where the jet spreading rate increases with the aspect ratio up to the limit of 5 at which the entrainment rate is decelerated due to enlarging the azimuthal distance between the two axes[11]. In the light of these features and in order to enhance the heat/mass transport rates so as to improve the mixing and reaction rates, it is worthy to maximize the entrainment rates between the reactive streams by optimizing the relevant concentric flow parameters [6],[12]. Potential benefits arising from the application of elliptic shaped nozzles include, improved combustion efficiency, the alleviation of combustion in stability, subsonic and supersonic exhaust noise reduction, vectored thrust for increased aircraft agility, thrust augmentation ejector for vertical/short takeoff or landing aircraft and turbofan engine infrared signature reduction contribution towards stealth[13].

Regarding another prospect, it is well-known that double-swirl is a mechanism that produces flexible aerodynamic flow control via straining the two shearing streams at variable angles as well as by creating a central reverse flow [14]. Swirl combustion is widely found in various thermal power engineering devices, including furnaces, boilers, kilns, and gas turbine engines [15, 16]. Swirling flows have been studied for decades, with detailed descriptions in the work of [17, 18]. It was found recently that swirl might influence not onlycombustion characteristics but also NOx formation [19]. Swirl is an implement for steady flame and heat transfer control and increased combustion efficiency[20, 21]. To meet these requirements, many types of swirl burners were developed, which employ complicated swirl gas/particle flow to ensure their performance[22]. Swirl stabilized burners stabilize the combustion process by creating an aerodynamically generated recirculation zone. As the swirling flow propagates downstream, centrifugal force creates a low pressure region in its centre which causes the flow to collapse inwards creating a recirculation zone known as a vortex breakdown bubble. The vortex breakdown process is highly dependent on the swirl number and the low pressure region in the centre of the flow. Pressure pulsations in the combustion chamber can cause oscillation of the vortex breakdown bubble which can also lead to amplified combustion instabilities if the Rayleigh criterion is met [23]. Swirl stabilization is used in combustion systems such as gas turbines, which also exhibit combustion instabilities. Rational modification of large-scale vortices is important to control swirl induced instability and to increase combustion efficiency [1].

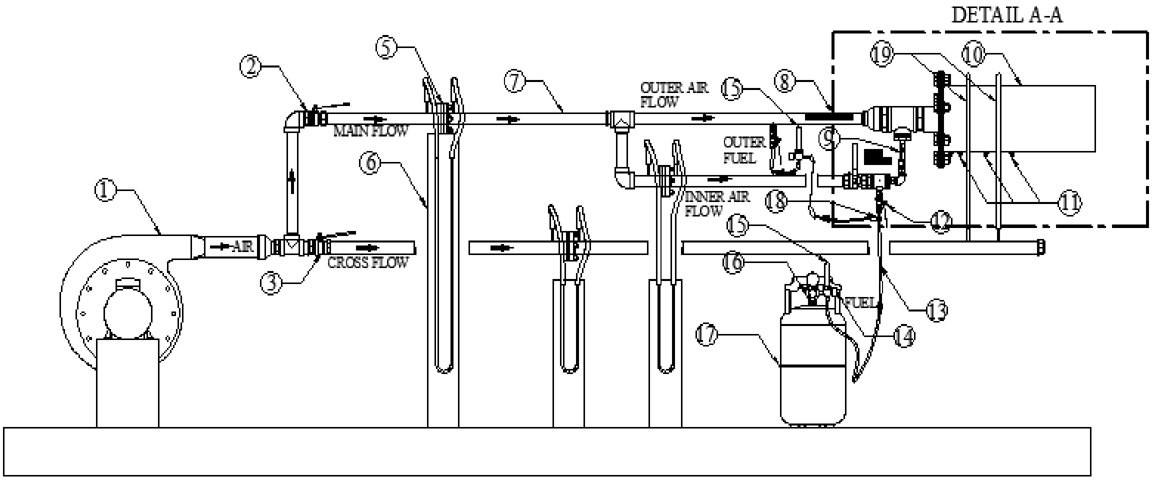
In addition, the triple flame, which is A triple flame is a partially premixed flame consisting of two premixed reaction zones (one fuel-rich and the other fuel-lean) and a non-premixed reaction zone. The two premixed reaction zones form exterior “wings” of the flame. The non-premixed reaction zone that is established in the region where excess fuel and oxidizer from the respective rich and lean premixed reaction zones mix in stoichiometric proportion is enclosed in between these two wings[24]. The behavior of triple flames is of fundamental importance for several reasons. First, triple flames may play an important role in the stabilization of laminar non-premixed flames [25]. Secondly, triple flames play an important role during re ignition in turbulent flows when, after a local extinction due to excessive strain, the turbulence intensity decreases so that re ignition can occur[26].

The combination of an elliptical jet and double-swirl introduces favorable features, where it elongates the swirling flow path (along an ellipse instead of a circle). Along such swirling elliptical path, the reactive streams periodically travel from the minor to the major axis tip (at which the flow shearing is maximized) thus providing a fluctuating strain effect that magnifies the production rates of turbulent kinetic energy. Furthermore, more differential shearing effects are introduced at the major/minor axis tips, where an interaction is stimulated between the axial flow velocity shearing and the tangential swirl flow disturbance [2]. Such combination of two perpendicular strain rates has not been encountered in conventional studies on elliptical nozzles.

## II. EXPERIMENTAL SETUP

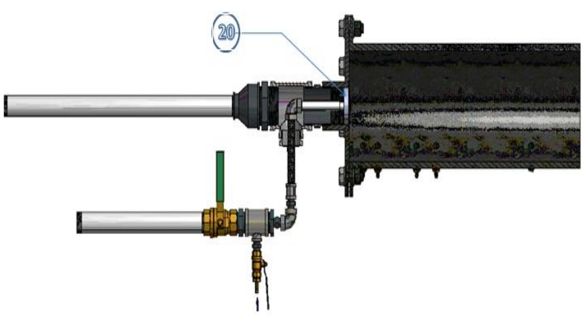
### 4.1 Test Rig:

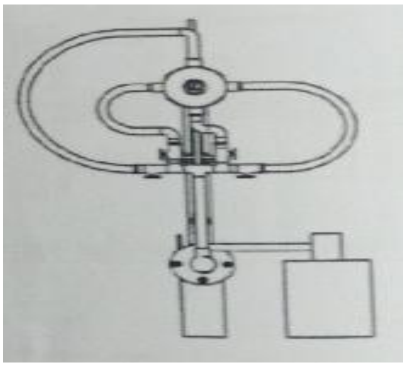
As shown in figure. 1, the current test rig is composed of a co-flow line, cross flow line, and fuel line. The cross flow line is connected to co-flow line and air compressor via three way elbow connection. The Co-flow line is branched to two lines, inner line and outer line, to achieve different air flow rates divisions. The inner line is concentric with the outer line, while, both are concentric with the combustor. The combustor has three successive taps at certain distances from the swirler face for inserting the thermocouple for the radial measuring of flame temperatures at three axial distances. The fuel used in the current research is a mixture of commercial butane and commercial propane having both saturated and unsaturated hydrocarbons which is commercially known as LPG. The fuel line is starting at LPG cylinder, then, it is branched to two flexible hoses, one of them is connected to the inner line, while, the other is connected to the outer line to achieve different air/fuel mixtures in both inner and outer lines. Cross flow air is injected through two stage injection ports, each stage has four injection ports distributed 90 degrees along the circumferences of the flame tube and such injectors are connected to the cross flow line pipe through flexible pipe connectors. A set of five double elliptic swirlers was tested against one circular swirler. The swirler body is made entirely as a whole part on a 3- axis CNC machine, each swirler consists of 3 concentric rings, a central circular ring with internal diameter of 2cm and two outer rings at various dimensions as shown in Table -1, a set of set straight inner vanes and 8 straight outer vanes were machined between the rings, the number of vanes was chosen to facilitate the manufacturing process and to reduce the pressure drop. In addition Figures. 2a, 2b, 2c, 2d, 2e and 2f show photos of the manufactured swirlers.Table-1: Main dimensions of swielers used in the current investigation.




ELEVATION OF TEST RIG SHOWING THE MAIN PARTS

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | CENTRIFUGAL BLOWER | 6 | U TUBE MANOMETER | 11 | THERMOCOUPLE ENTRY PORTS | 16 | GAS REGULATOR | | |
| 2 | MAIN AIR FLOW RATE ADJUSTMENT VALVE | 7 | 1.5" CO-AIR PIPE | 12 | FUEL ISOLATION VALVE | 17 | LPG GAS CYLINDER | | |
| 3 | CROSS FLOW RATE ADJUSTMENT VALVE | 8 | 1.5" OUTER- PIPE | 13 | CONNECTION HOSE | 18 | THREE WAY CONNECTION | | |
| 4 | ELECTRIC MOTOR | 9 | 1.5" INNER- PIPE | 14 | GAS FLOW ADJUSTMENT VALVE | 19 | CROSS FLOW FLEXIBLE CONNECTIONS | | |
| 5 | AIR ORIFICE | 10 | CYLINDRICAL FURNACE | 15 | GAS ROTAMETER | 20 | SWIRLER BODY | | |





**DETAIL A-A** **SIDE VIEW**

**Figure 1 Test rig facility**

Table-1: Main dimensions of swielers used in the current investigation.

| Swirler | Aspect Ratio | Inner Diameter ,(dii), cm | Intermediate Major Axis,(ai), cm | Outer Major Axis,(ao), cm | Intermediate Minor Axis,(bi), cm | Outer Minor Axis,(bo), cm | Inner Swirl Angle | Outer Swirl Angle | Direction |
|---|---|---|---|---|---|---|---|---|---|
| 30-45-Circular | 1 | 2 | 6 | 8 | 6 | 8 | 30 | 45 | CO |
| 30-45-1.25-CO | 1.25 | 2 | 6 | 8 | 4.8 | 6.4 | 30 | 45 | CO |
| 30-45-1.4-CO | 1.4 | 2 | 6 | 8 | 4.4 | 5.8 | 30 | 45 | CO |
| 30-45-1.4-CN | 1.4 | 2 | 6 | 8 | 4.4 | 5.8 | 30 | 45 | COUNTER |
| 30-45-1.5-CO | 1.5 | 2 | 6 | 8 | 4 | 5.4 | 30 | 45 | CO |
| 45-30-1.4-CO | 1.4 | 2 | 6 | 8 | 4.4 | 5.8 | 45 | 30 | CO |

**Fig. 2a**
**30-45-Circular**

**Fig. 2b**
**30-45-1.25-CO**

**Fig. 2c**
**30-45-1.4-CO**

**Fig. 2d**
**30-45-1.4-CN**

| | |
|---|---|
|  |  |
| **Fig. 2e**<br>**30-45-1.5-CO** | **Fig. 2f**<br>**45-30-1.4-CO** |

**4.2 Measuring Instruments**

The test rig used in the study is composed of a centrifugal blower and delivery pipes. Three orifice meter assemblies with their respective manometers tapings are connected to separate indicating tubes for the requirement of measuring the flow rate of both co- and cross-flow air streams. A platinum-13% rhodium/platinum thermocouple with 0.5 mm wire diameter was utilized for measuring the time-averaged flame temperatures (having been corrected for thermal radiation from the thermocouple bead). Time-averaged NOx and CO concentrations in the exhaust gas streams are measured across the exit section of the flame by an electrochemical gas analyzer (EUROTRON, GREENLINE- MK2). The exhaust gas sample was aspirated at a flow rate of 1550 cm3/min. The analyzer was equipped with a water-cooled stainless steel probe having a machined tapered end of 3.0 mm diameter to minimize disturbances onto the flame. A Nikon digital camera with 2560 X 1920 pixels and a shutter speed of 1/4000 s was used to indicate the flame qualitative features. Table 2 shows the uncertainty values corresponding to both systematic and fluctuation errors of the respective measured quantities.

Table-2: Uncertainty analysis.

| Variable | Uncertainty (%) |
|---|---|
| Fuel flow rate | 1.4 |
| Air flow rate | 1.1 |
| Gas temperature | 2.2 |
| NOx concentrations | 0.9 |
| CO concentrations | 1.0 |

## III. RESULTS AND DISCUSSION

All Swirlers were tested under the same conditions of cross flow rate amount, inner and outer equivalence ratios of $\varphi_i$=3.6 and $\varphi_o$=0.86.

**5.1 Flame length:**

Figure 3 (images a, b, c, d, e and f) shows the flame length corresponding to each swirler used in the current investigation. Concerning the aspect ratio effect (images a, b, e and f), it can be noticed that the circular swirler shows the longest flame length while (30$^o$i, 45$^o$o-co-AR=1.25) produces the shortest flame length relative to other Swirlers of different aspect ratios, which indicates that the swirler of (AR=1.25) shows better mixing and enhancing the combustion process. Increasing the inner swirling angle, images b and c, leads to decrease the flame length as found by Kamal [27], these agrees with enhanced rates of heat and mass transfer as highlighted by Gupta et.al. [28]. Regarding the swirling direction mode (co- versus counter swirl), images b and d, it can be noticed that counter and co-swirl that due to higher levels of premixing, slight differences in the flame length were found, it agrees with D. Durbin [29], who concluded that the flame was very short and no noticeable difference in flame length between co- and counter swirl conditions.

**Image a-(30°i-45°o-CO-AR=1)**

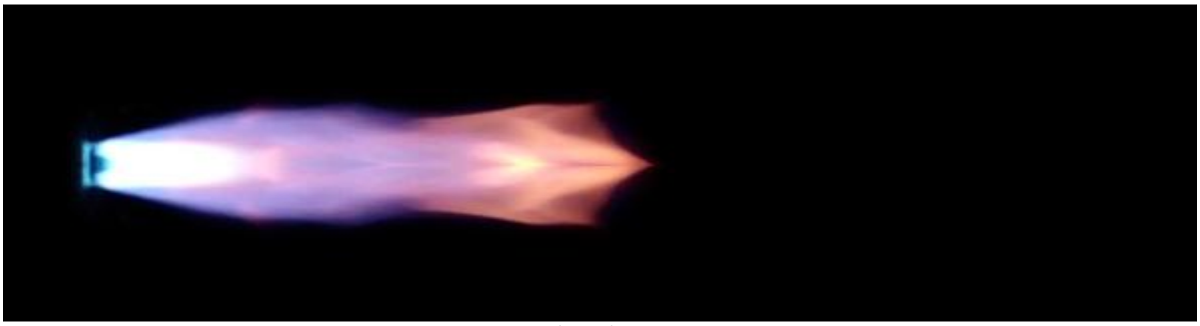


**Image b- (30°i-45°o-CO-AR=1.4)**

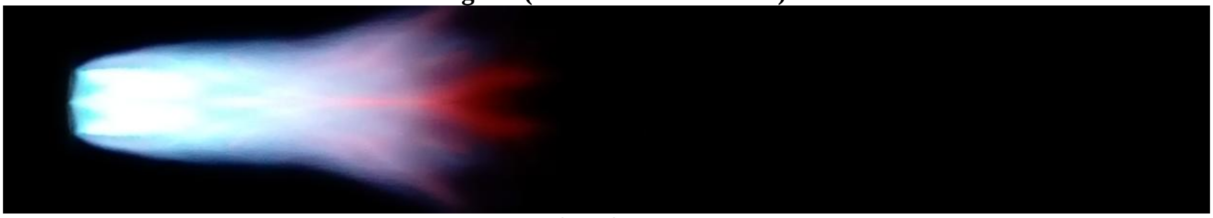


**Image c- (45°i-30°o-CO-AR=1.4)**

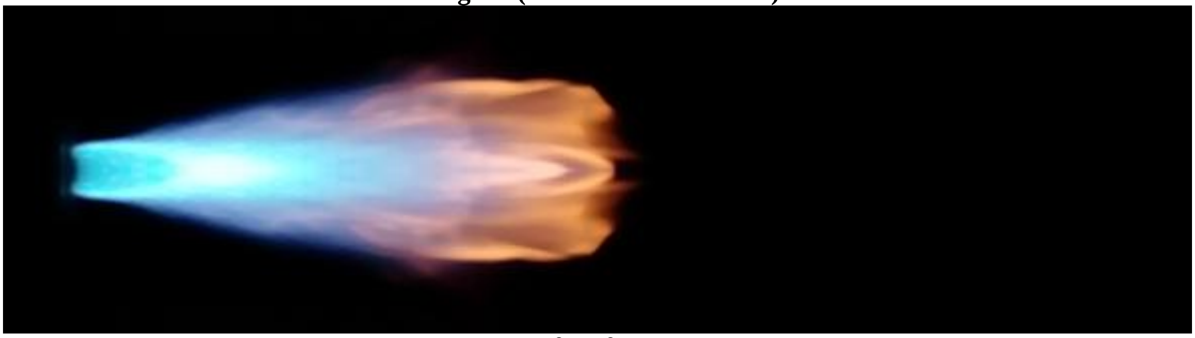


**Image d- (30°i-45°o-CN-AR=1.4)**

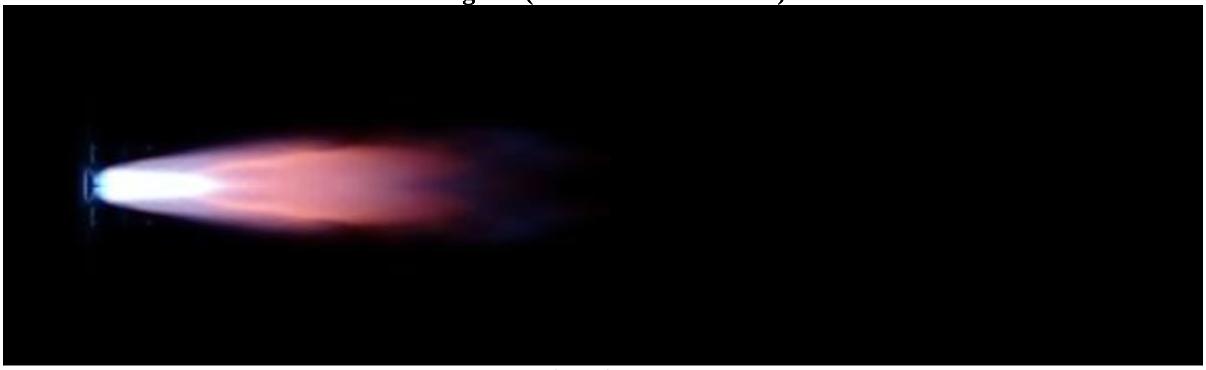


**Image e- (30°i-45°o-CO-AR=1.25)**

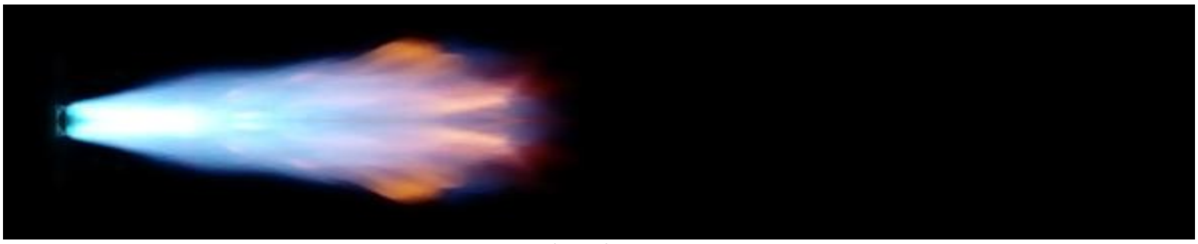


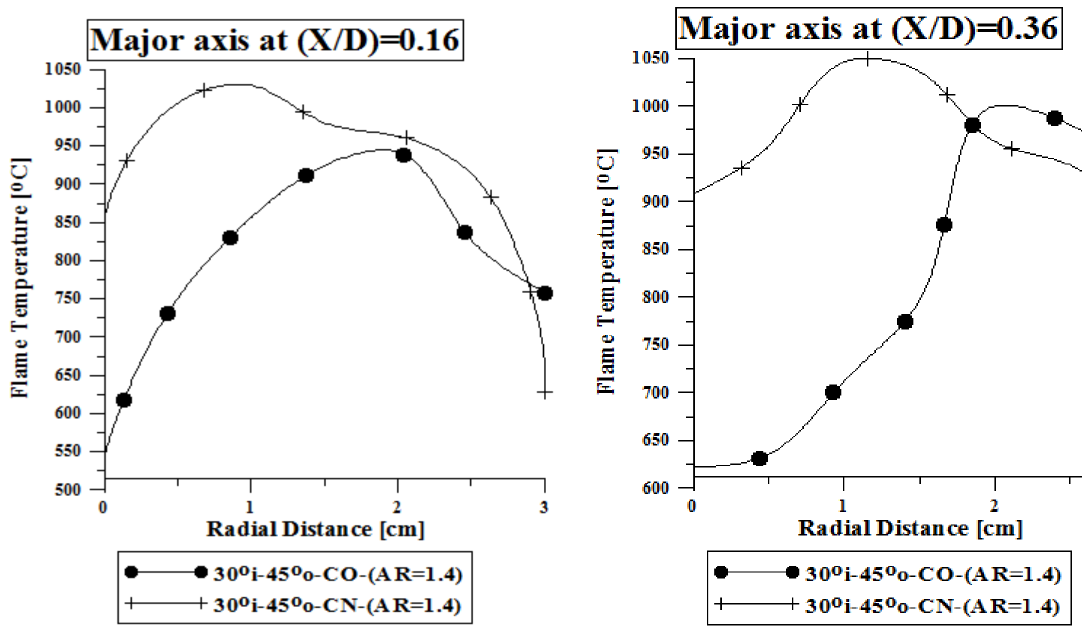
**Image f- (30°i-45°o-CO-AR=1.5)**

**5.2 Temperatures:**

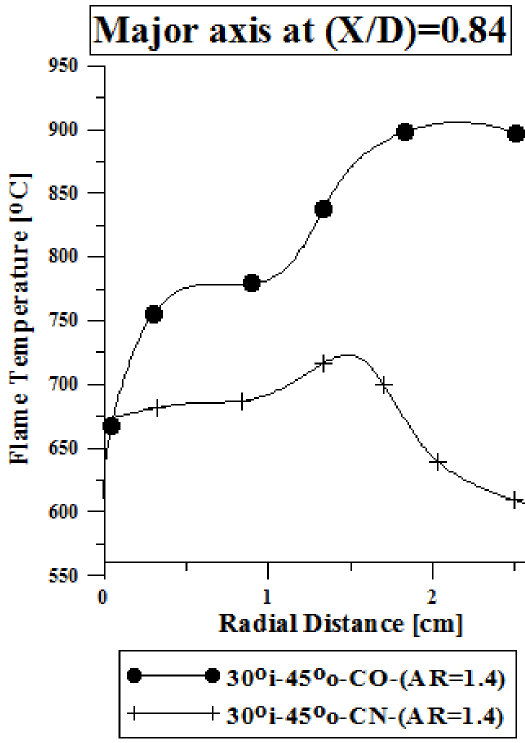
The axial and radial temperatures are summarized in the following figures. While Temperatures are measured in °C, the value R is expressed in cms and X/D is dimensionless value. Where R is a distance measured from the combustor centerline and X/D is the ratio between the distance from the swirler face (X) to the combustor diameter (D).

**5.2.1 The effect of the swirl direction mode (co versus counter swirl):**

The radial and axial survey of the flame temperatures for co-swirler (30°i, 45°o) and counter swirler (30°i, 45 °o) on the major axis figure 4. As shown in these figures, it can be observed that counter swirl attained higher flame temperatures than co-swirl through the first two ports in both major and minor axis, but the opposite occurs at the third port that the co-swirl shows higher flame temperatures than the counter swirl. Since, the counter swirl induces higher turbulences at the exit of the swirler than the co-swirl, so it could reach its maximum temperature through the first two ports. Unlike the co-swirl that induces less turbulence at the beginning of the combustor and needs more length to reach its maximum flame temperature, so it reaches its maximum flame temperatures at the end of the combustor. In general, it can be concluded that the counter swirl shows higher flame temperature than the co-swirl through the major part of the combustor burner, it agrees with Bach and Gouldin [30] , who reported that as the swirl changes from co-swirl to counter, increasing diffusion and dissipation of the inner swirl, the axial pressure gradient becomes more adverse, leading to a larger recirculation bubble and a large back flow velocity. It can be also found that flow expansion at the inlet further increases the adverse pressure gradient. Under the co - swirl, where inter jet shear is small and the flow is nearly cylindrical, turbulences energy production and outward radial diffusion are not significant. Further agreement with D. Durbin [29], who concluded that counter swirl may generate a strong shear layer. On the other hand, co-swirl generates a high tangential momentum but produce a weaker shear layer. It also agree with all cold swirl investigations that concluded counter swirl produces higher shear stress than co-swirl. In addition, it was noticed that the range of the flame temperatures on the major and minor axis are roughly the same, since the combined effect of cross flow and the turbulences induced by the swirler overcomes the effect of ellipticity and produces a homogeneous temperature distribution inside the combustor.




(a) (b)




**(c)**

**Figure 4 Radial flame temperatures distribution on the major axis at different axial distances for co and counter Swirlers**

**5.2.2 The effect of the relative swirl angle:**

Figure 5 represents the variations of radial and axial temperatures for both (30°i, 45°o-co-AR=1.4) and (45°i, 30°o-co-AR=1.4) Swirlers on the major axis. It can be noticed that (45°i, 30°o) produces higher flame temperatures in the major and minor axis than that for (30°i, 45°o). In other words, increasing the inner swirling angle leads to a progressive enhancement of flame behavior. It agrees with Inas [31], who reported that for the only outer swirling, the air stream lines are straight and parallel, no strong evidence of mixing enhancement. . In addition, the axial velocity profile was hardly affected compared to the no swirl case, i.e. negligible enhancement in translational mixing. For the inner swirling only, swirler creates a strong swirling pattern. The axial and radial views showed that the swirling flow is very clear at the chamber centerline at section very close to the injector tip. The parallel streams diminish to be just close to the chamber wall. The same phenomena was observed with increasing the inner swirling angle except that the swirl is stronger and the path followed by the air is longer. A further agreement was achieved with Emad [14], who found that increasing the outer swirl angle with no inner swirl is not effective in altering the axial velocity component. He also found that the formation of a recirculation zone is dependent on the presence of inner swirl. Variation in the inner vane angle from 30° to 45° revealed that the recirculation is strengthened with the increase in the vane angle. Furthermore an agreement was achieved with Durbin et.al [32], who have shown that increasing the inner vane angle increases turbulent mixing and strengthens the inner recirculation zone. The same conclusion was made by Chen and Discoll (1988) who concluded that increasing the inner vane angle widen flame shape. This occurs because increase in vane angle increases the size and strength of the inner recirculation zone. Furthermore, it can be noticed that (45°i, 30°o) swirl records higher flame temperatures than (30°i, 45°o) swirl through the first two ports, but at third port (30°i, 45°o) swirl attained higher temperature than (45°i, 30°o) swirl. It agrees with Beltagui and Maccallum (1988) who reported that increasing swirl angle leads to accelerate the combustion process, so the peak flame temperatures occur closer to the swirler exit.

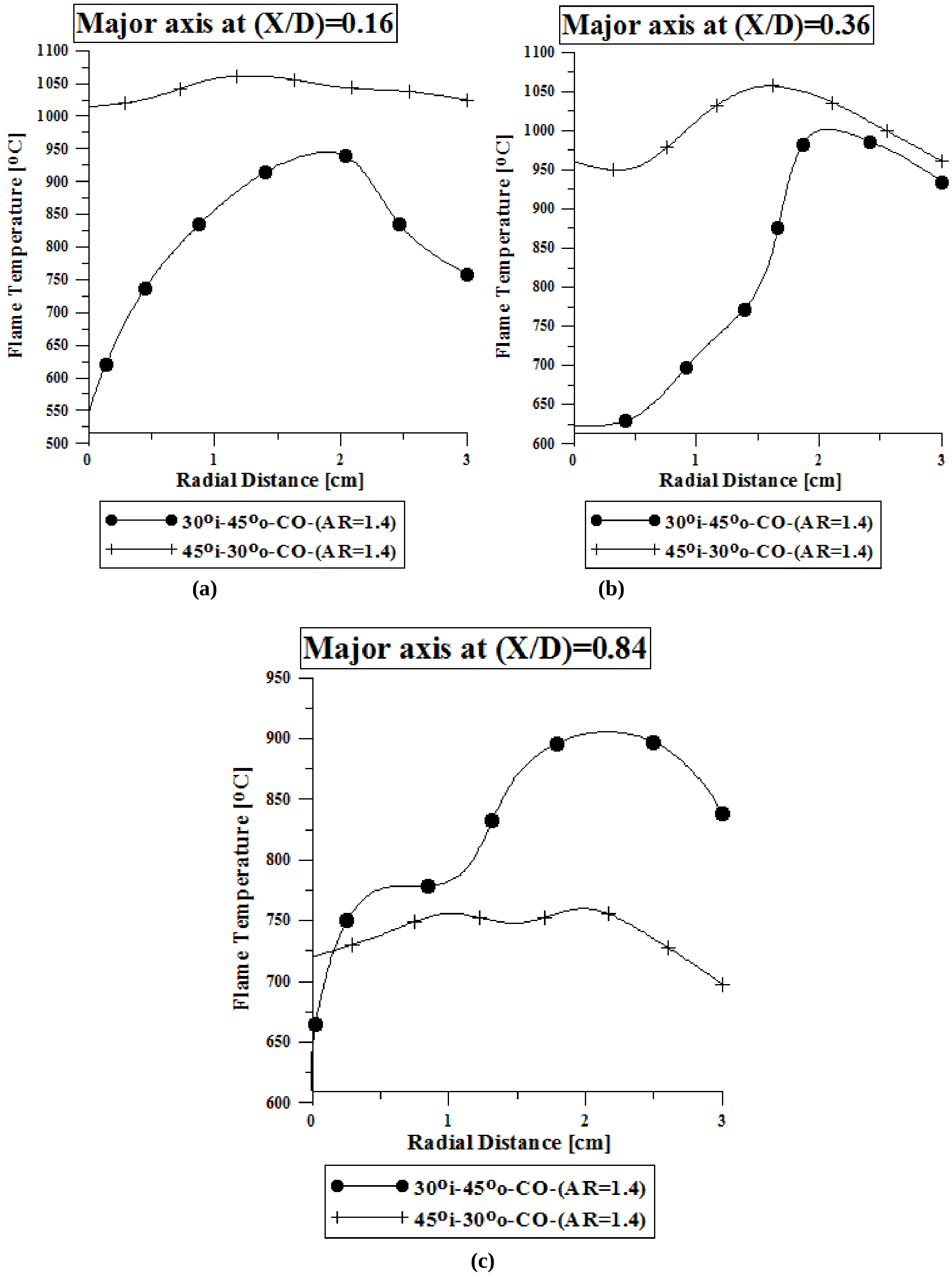
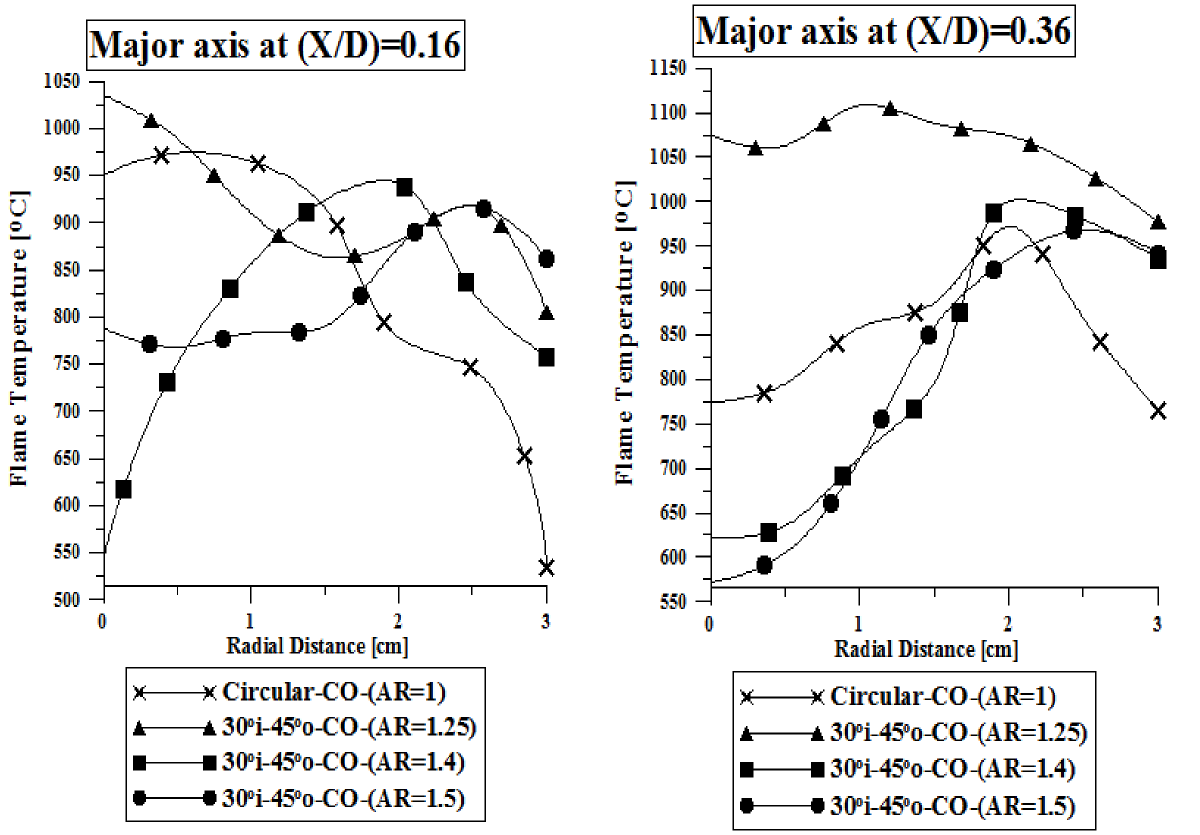


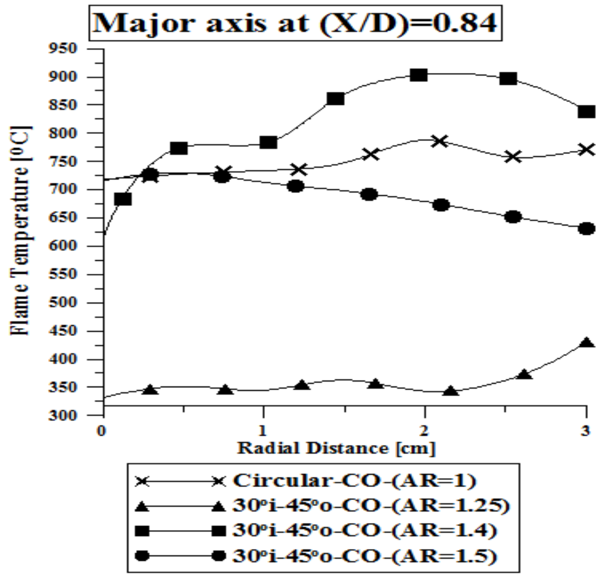

**Figure 5 Radial flame temperatures distribution on the major axis at different axial distances for (30$^o$i, 45$^o$o-co-AR=1.4) and (45$^o$i, 30$^o$o-co-AR=1.4) Swirlers**

**5.2.3 The effect of Elipticity (effect of aspect ratio):**

The axial and radial temperatures of Swirlers with respect to their aspect ratios in the major axis is plotted in figure 6. It can be noticed that there are many fluctuations of the flame temperatures in the first port. The second port, it can be noticed that the (45$^o$i, 30$^o$o-co-AR=1.25) swirl attained the highest flame temperatures compared to the other Swirlers, while in the third port its flame temperatures drop steeply. Since, as mentioned before that the swirler of AR=1. 25 produces a flame with shorter length compared to other Swirlers, so the thermocouple probe cannot reach any flame in this port. Overall, it can be concluded from figure 6 that the best aspect ratio is 1.25 that attained the highest flame temperatures in the major and minor axis through the major part of the combustor. On the other hand, the lowest flame temperatures are given by the swirler of aspect ratio 1.5. It can be concluded that using elliptic swirler leads to many desirable features of increasing the flame temperature and decreasing the flame length. But there is a limitation for the value of the aspect ratio and there is an optimum value that gives higher flame temperatures and more stable flame. In the current investigation the optimum aspect ratio is 1.25 which produces higher flame temperatures and shorter flame length relative to other swirler. Increasing the aspect ratio beyond this value, AR=1.4, leads to decrease flame temperatures, but still higher than that of circular swirl. Excessive increasing on the value of aspect ratio, AR=1. 5, leads to decrease flame temperatures lower than that of circular swirl. It agrees with Ho and Gutmark [6], who reported that there is an optimum value for aspect ratio beyond which (when the distortion becomes appreciable), the vorticity diffusion is already too fast to support significant local entrainment. Such conclusion was clarified by Clement et al.[33], who stated that the azimuthal distance between the minor and major axes (defined as the angular distance along the ellipse circumference) for aspect ratio of 3.0 is larger than that for aspect ratio of 2.0. In consequence, the interaction between the mass entraining large structure and mass distributing small structure is delayed such that the aspect ratio of 2.0 has the highest mixing rate.




(a) (b)




**(c)**

**Figure 6 Radial flame temperatures distribution on the major axis at different axial distances for Swirlers with different aspect ratios**

**5.3 Emissions:**

$NO_X$ and CO species through the circular and different elliptic Swirlers were measured for complete investigation of combustion features of elliptic Swirlers and their effects on emissions and, of course, the environment. The radial survey of $NO_X$ and CO emissions at the exit of the combustor is plotted in the following figures, where $NO_X$ and CO emissions are measured in PPM (Particle Per Million) and (r/D) is dimensionless value, where (D) is the diameter of the combustor and (r) is the radial distance from the combustor wall.

**5.3.1 The effect of the swirl direction mode (co versus counter swirl):**

For co- and counter Swirlers, the average values for CO and $NO_X$ concentrations are plotted in figures 7 & 8, respectively. As it shown in these figures that the counter swirler produces lower CO concentration by 230 ppm (29%) and lower $NO_X$ concentration by 1.13 ppm (36%) than the co-swirler, which improves that counter swirler enhanced the combustion performance than the co-swirler. These figures give a further evidence, with figure 4, that the counter mode enhances the mixing of two streams which leads to increase of the flame temperatures and decrease the emissions.

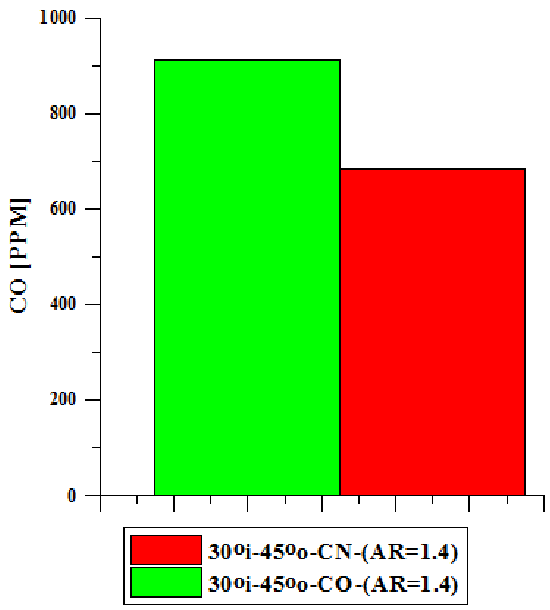



**Figure 7 Average CO Concentration**

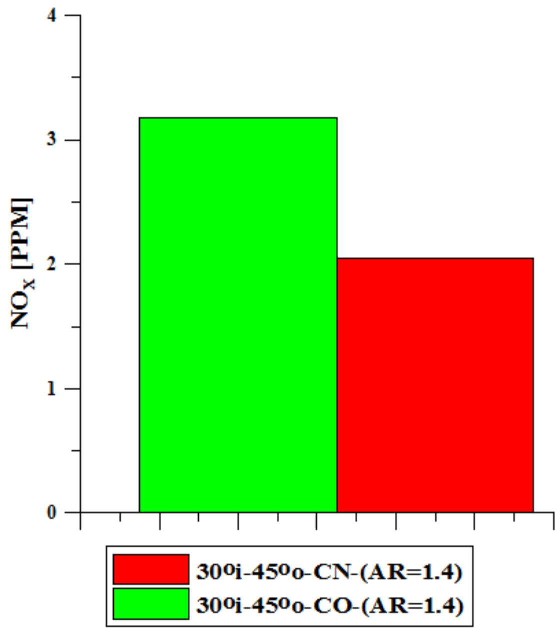



**Figure 8 Average $NO_X$ Concentration**

**5.3.2 The effect of the relative swirl angle:**

Figures9 and 10, respectively, represent the variations of the average values of CO and $NO_X$ concentrations for both (30°i, 45°o-co-AR=1.4) and (45°i, 30°o-co-AR=1.4) Swirlers. As it has been mentioned before that increasing the inner angle leads to improve the combustion performance and increase the flame temperature through the major and minor axis together. Figures 9 and 10 give a further agreement with the previous conclusions that increasing the inner angle leads to enhance the mixing inside the combustor and to reduce the emissions, that increasing the inner swirl angle reduces the average CO concentration by 88 ppm (10%) and the average $NO_X$ concentration by 1.22 ppm (38%). Furthermore, figure 10 shows that CO concentrations for (30°i, 45°o) and (45°i, 30°o) Swirlers are very similar to each other and the variations in CO values are barely significant, but in general, it could be concluded that increasing the inner angle leads to decrease the CO concentration.

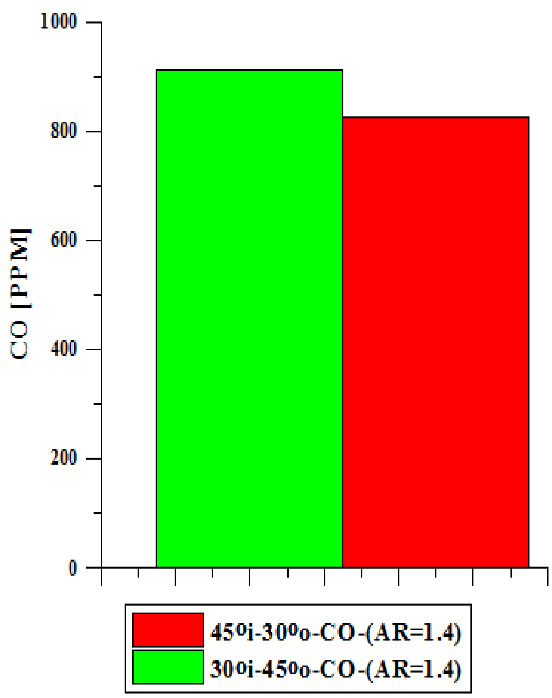



**Figure 9 Average CO Concentration**

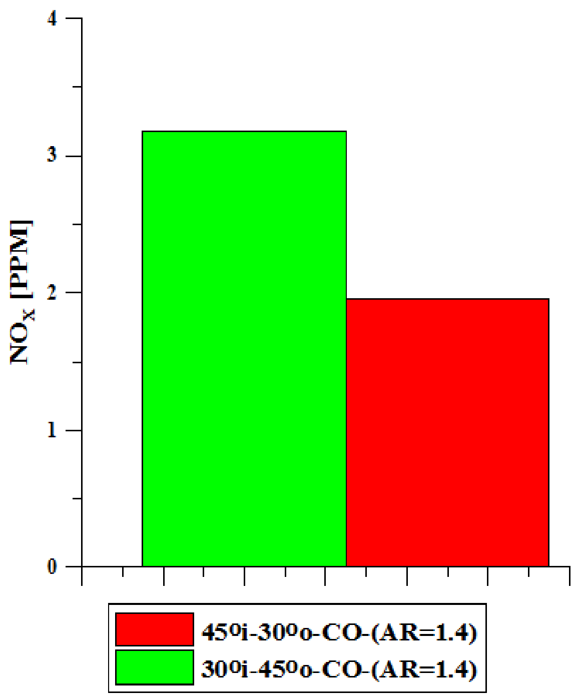



**Figure 10 Average $NO_X$ Concentration**

**5.3.3 The effect of Elipticity (effect of aspect ratio):**

From figure 11, it could be concluded that the increasing aspect ratio leads to decrease the CO emission. This agrees with OA Kashkosha et.al.[2], who reported that increasing the aspect ratio the path elongation of the swirling flow effectively enlarges the heat and mass transfer across the central burning zone thus resulting in less emission of CO. Figure 12 shows that (30°i, 45°o-co-AR=1.25) swirl produces lower $NO_X$ than any other Swirlers of different aspect ratios, 1.4 ppm, that gives a further approve that swirled with AR=1.25 enhances the combustion performance with high flame temperatures and low $NO_X$ concentrations. On the other hand, circular swirler produces higher CO and $NO_X$ emissions relative to elliptic Swirlers, this agree with Gutmark et.al. [1], who concluded that the elliptic swirl decreases the $NO_X$ by a factor of more than four, and the CO by 30-40 % of the circular swirl.

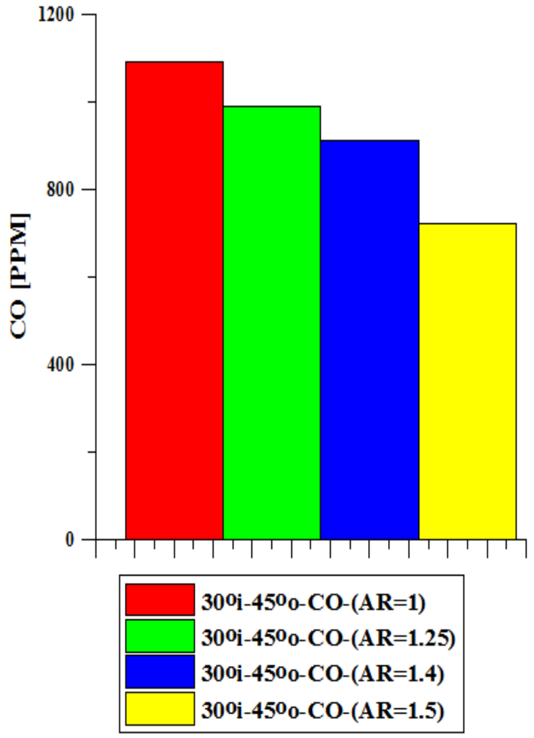



**Figure 11 Average CO Concentration**

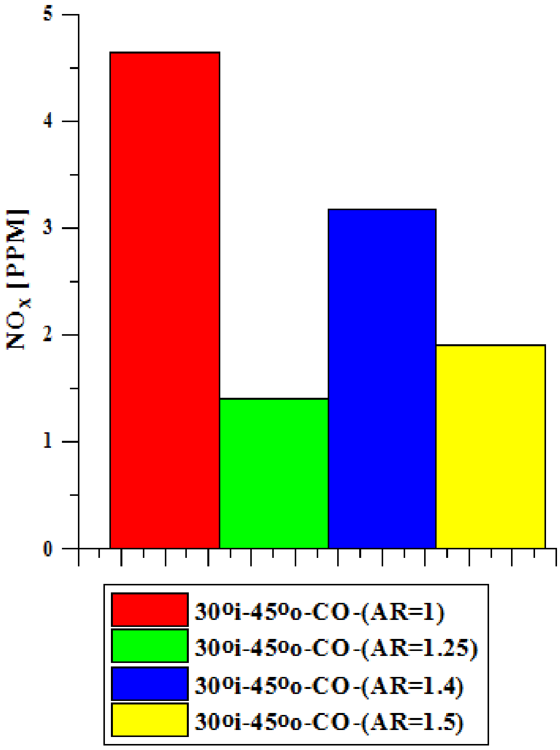



**Figure 12 Average $NO_X$ Concentration**

## IV. CONCLUSION

Using elliptic swirl leads to increase the turbulences and enhance the mixing of mixtures which leads to decrease the flame length in comparison with the circular swirl. It was found, experimentally, that the circular swirler gives the longest flame length relative to other Swirlers. Furthermore, it was found that increasing the inner angle leads to decrease the flame length. Switching from co- to counter swirl does not give a significant effect on the flame length. The range of the flame temperatures in the major and minor axis is roughly the same, since the combined effect of cross flow, plus the turbulences induced by the swirler overcomes the effect of elasticity and produces a homogeneous temperature distribution inside the combustor. During the investigation of swirl mode, co- and counter swirl, it was found that counter swirl performs better than the co-swirler. Where, the counter swirl produces higher flame temperatures and lower emissions concentrations than the co-swirler. Increasing the inner angle of the swirling flow leads to the enhancement of the combustion process. By varying the aspect ratios of the double elliptic Swirlers, AR=1, 1.25, 1.4 and 1.5, it was found that elliptic swirl with AR=1.25 produces higher flame temperatures and lower NOx concentrations than any other Swirlers of different aspect ratios. In addition, it could be concluded that increasing aspect ratio over unity decrease the CO emission. Furthermore, it was found that circular swirler produces higher emission concentrations relative to the other Swirlers.

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