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Effect of The Degree of Elipticity On The Combustion Performance Using Elliptic Double Swirlers

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Abstract: A comparative study was experimentally carried out on a LPG diffusion flame issuing from a co-swirl burner to highlight the swirler aspect ratio effect on the thermal and chemical flame structures. At the same fuel and air flow rates, three swirlers with aspect ratios of 1.25, 1.4 and 1.5 were compared to a circular baseline swirler, where all swirlers had the same inner and outer swirl angles, the same number of vanes and the same vane spacing. It was found that the ellipticity had a major influence on flame temperature values and their distribution along the furnace, whereas such temperature values are radially asymmetric. In this concern, the maximum temperature was recorded near the minor axis tip with all elliptical swirlers and the aspect ratio of 1.4 resulted in the overall maximum temperature value. In comparison to the case of the circular swirler, the flame was considerably shortened by the elliptical swirlers indicating that the recirculation zone was pushed further upstream particularly with the aspect ratios of 1.4 and 1.5. The flame had a bluish core whose volume increased with the increase of the aspect ratio indicating complete combustion near the fuel nozzle exit. The aspect ratio had a great effect in the levels of pollutant emissions, where the swirler with the aspect ratio of 1.5 caused a decrease of 55% in the level of NOx, 46% in the level of CO and 39% in the level of UHC in comparison to the circular baseline swirler.

I. INTRODUCTION

Over the last three decades strict regulations have been established regarding pollutant emission standards. Keen endeavors have been made to meet such restriction in modern gas turbine combustors design in addition to establishing a stable flame over the course of various operating conditions by providing means to control combustion instabilities. Passive means for controlling combustion instabilities have proven their potency in suppressing combustion instabilities and creating significant performance improvements at a relatively low cost. Such methods include using a burner with a non-circular geometry which has an effect in altering the way in which vortices are formed, also the use of solid bodies that has a desirable effect in stabilizing the vortex breakdown bubble and in the reduction of instabilities [1, 2, 3]. Imparting swirl to the fuel or air or both has its merits in achieving a stable flame in addition to enhanced mixing that is reflected upon less pollutant emissions and better combustion efficiency [4]. Swirl stabilized burners creates an aerodynamically recirculation zone that stabilizes the combustion process, where the centrifugal force creates an adverse pressure gradient that causes the flow to collapse inwards thus holding the flame in place [5]. The introduction of double swirl enhances the performance and introduces various parameters that are needed to be studied to achieve an optimum burner design. Such parameters include varying the angle of the inner and outer swirl and the way in which the inner and outer vanes are placed with respect to each other (whether a co-swirl or a counter-swirl scheme) as well as the proportions of air introduced through the primary and secondary zones. Sato H.,Mori M. and Nakamura T. [6]conducted atmospheric bench tests which illustrated that the double swirler staged combustor offers superior performance with a reasonably uniform temperature distribution in addition to achieving low levels of NOx emissions where values as low as 3ppm were recorded and achieving combustion efficiency of 99.9%. Mather and Maccallum, El-Mahhalawy F. M. [7] concluded that the double concentric streams is the best burner design to establish efficient and stable flame especially for diffusion flame in addition to that the swirling direction of the two jets was found to affect the flame structure and the size of the C.R.Z (central recirculation zone), the co-swirling of combustion air resulted in good fuel and air mixing in addition to that the preheating of the combustion air improved the flame stability, also the increase of swirl intensity improves combustion efficiency in addition to shortening the flame length and improving heat liberation, emissions are also reduced especially NOx which is in good agreement with the findings of [6].Mark D.Durbin and Dilip R. Ballal [8] performed studies on flame length, shape ,mixing, lean blow out (L.B.O) and optimum combustor configuration over a wide range of inner and outer vane angles, co vs counter swirl schemes and outer and inner air velocities .it was found that a decrease in inner air velocity and an increase in the outer vanes angle resulted in a decrease in the flame length also L.B.O was improved when the outer swirl intensity is increased. According to the conducted studies the optimum configuration was at an inner swirl angle of 45˚ and an outer swirl angle of 60˚ with a co swirl scheme and equal inner and outer air velocities. A comparison was set to discuss the effects of co and counter swirl schemes, it was found that counter swirl may generate a strong shear layer but the opposing motion of the air streams tend to nullify the swirling motion in the flow field however in the case of the co swirl high tangential momentum is generated but a weaker shear layer is established which explains why the co swirling flows spreads the air-fuel mixture to the combustor walls and produces a slightly shorter flame length. Bach T.Vu and Gouldin F.C. [9] stated that for varying the outer swirl number from the maximum co swirl conditions of 0.42 to the maximum counter swirl conditions of 0.38 the turbulent diffusion and dissipation of inner swirl significantly increases due to the effect of higher shear in the inter jet layer. For the counter swirl it could be seen that the turbulent mixing is highly intense and so the reaction is quenched in the inter jet shear layer. Under co swirling conditions ,since the inter jet shear mixing is not as strong, a long hot gas core extends from the front stagnation point and the reaction persists further downstream resulting in more efficient combustion while the counter swirl will quench the reactions causing higher values of emissions of carbon monoxide and unburned hydrocarbons. Gutmark and Ho [10] reported the mass entrainment and vortex induction characteristics for an elliptic nozzle within aspect ratio of 2. It was found that the entrainment ratio for an elliptical free jet was 3 to 8 times more than that of a circular or a planar jet. Clement et al [11] illustrated the benefits that the elliptical jets have over the circular ones by defining some physical properties of the flow those include: the generation of vortices of different sizes, enhanced mixing associated with the axis switching phenomenon which is dependent on the nozzle aspect ratio. Gutmark and Grinstein [12] discussed the applications of non-circular jets with improved small and large scale mixing in low and high speed reacting flows. They emphasized the enhanced combustor performance which is apparent in improved combustion efficiency, reduced flame instabilities and extended lean flammability limits in addition to noise suppression .Schadow et al [13] stated that free and confined reacting elliptical jets spread at a faster rate and the combustion efficiency is increased by 10 percent when compared to circular jets which was attributed to enhanced turbulent mixing in the fore end of the coaxial mixing reigon. Gollahalli [14] stated that gaseous fuel jets issued from elliptical ports entrain more air from the surrounding more than that issued from a circular port with an equivalent cross sectional area. Such feature is considered as a method of passive combustion control for modulating fuel and air mixing rates that governs combustion and pollutant emissions in diffusion and partially premixed flames .Gutmark et al [15] studied the effects of altering the burner geometry into an elliptic shape, the elliptic burner changed the way fuel, air and hot combustion gases mix resulting in enhanced mixing, the elliptic burner also achieved lower emissions while stabilizing the combustion by reducing the coherence of the large-scale vortices at the burner's exit in addition to significantly reducing in pressure and heat release oscillations.

In the light of the previous findings the current study is conducted to study the effect of the degree of ellipticity (swirler aspect ratio) on the performance of the double swirl diffusion burner in terms of emissions at the furnace exit and the flame temperature distribution along the major and minor axes experimentally.

II. EXPERIMENTAL TEST-RIG

The experimental test-rig shown in Figure 1. The combustion air is supplied to the burner by a centrifugal blower which is directly coupled to 1.5 hp, 2800 rpm single phase electric motor. The blower outlet is connected to the 1.5 in. air delivery line which contains a sharp edged orifice with a throat diameter of 2.2 cm for the air mass flow rate measurement. The adjustment of the desired air mass flowrate was carried out by a ball valve.

The furnace is air cooled and is of 70 cm long and has an internal diameter of 25 cm, the combustor was fired at atmospheric pressure with an excess air value of 20%. Standard LPG gas cylinders were used as a fuel source where the LPG gas was issued to the combustor through a through a ½ in. hose to the fuel pipe that is fitted with a 12 radial-hole nozzle at a flow rate of 13 LPM, each hole has a diameter of 2mm.

The cylinder is fitted with a gas regulator that maintains a constant gas flowrate from the cylinder, the regulator is fitted with a built in valve for flowrate control purposes and a ball rotameter for measuring the LPG gas volume flowrate. Both the gas and air flow rates were determined from the preliminary firing tests to fill the required combustor volume

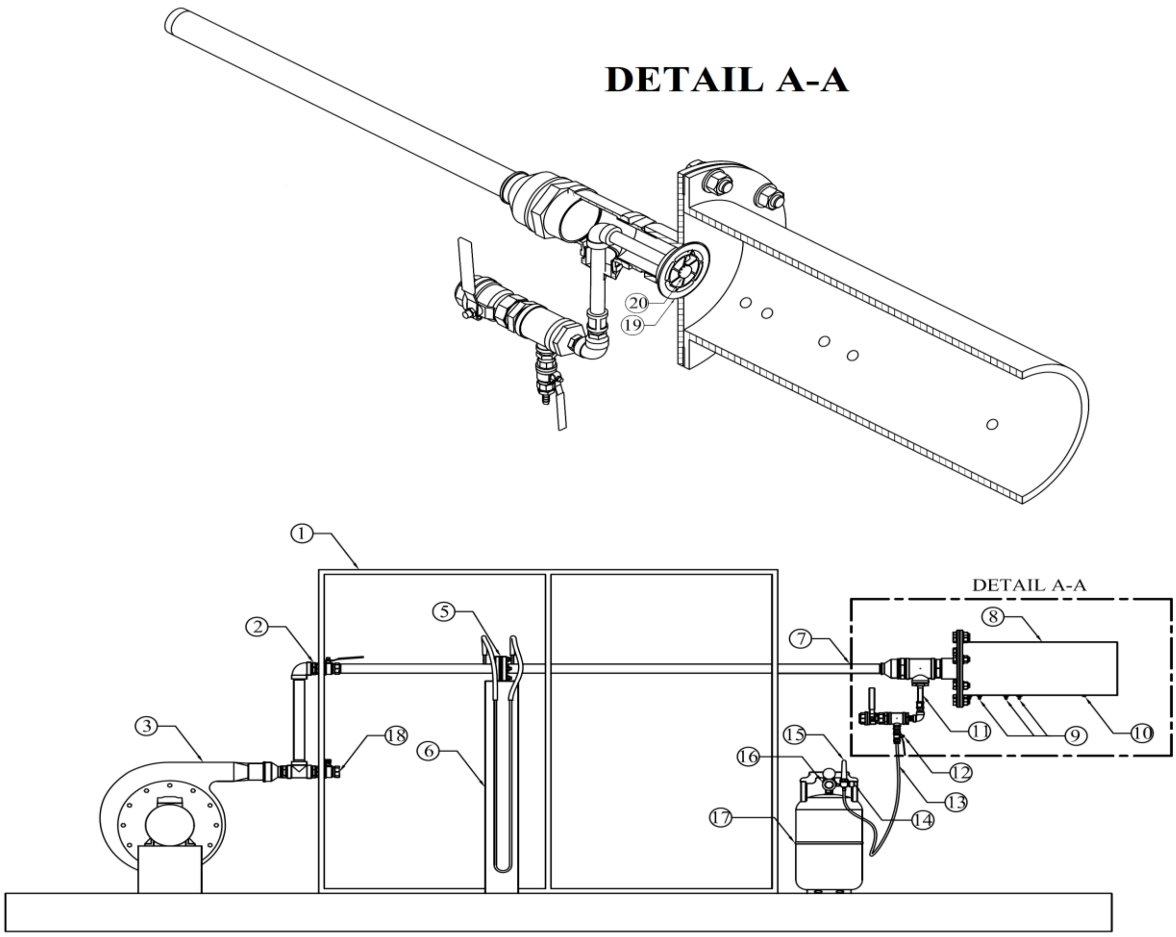
Temperature measurements were made using a platinum 13% Platinum-Rhodium thermocouple [S-type] with a bead diameter of 1 mm, the thermocouple was connected to a digital controller for cold junction compensation. In addition, a LANCOM-III gas analyzer with a digital display was used to measure values of CO,NOx and UHC at the furnace exit.

The burner was constructed of two coaxial pipes, the inner ½ in. fuel pipe where the fuel nozzle is fitted to a threaded bush at its end, the outer air pipe is 3 in. in diameter and flanged from its end. The flanged end is joined to the furnace by 8 bolts. The burner is provided with means for holding the swirler under investigation in place. Table 1 illustrates the main characteristics of the swirles under investigation:

Swirler	Aspect Ratio	Inner swirl angle	Outer Swirl Angle	S_{major}	S_{minor}	$S_{average}$
30-45-Circular	1	30	45	0.58	0.58	0.58
30-45-1.25-CO	1.25	30	45	0.58	0.59	0.585
30-45-1.4-CO	1.4	30	45	0.58	0.6	0.59
30-45-1.5-CO	1.5	30	45	0.58	0.62	0.6

Table 1

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 and two outer rings, a set of 8 straight inner vanes at an angle of 30˚ with the burner axis and 8 straight outer vanes at an angle of 45˚ with the burner axis were machined between the intermediate and outer rings, the number of vanes was chosen to facilitate the manufacturing process and to reduce the pressure drop. All vanes were made at a thickness of 2mm and with a degree of surface finish that is sufficient to minimize disturbances that may occur on the streamlines that have been affected by swirl.
The inner and outer vanes were arranged in a co swirl scheme which was proven to deliver a better overall performance and reduced emissions when compared to a counter inner-outer vane scheme as illustrated by Bach and Gouldin [9].



ELEVATION OF TEST RIG SHOWING THE MAIN PARTS							
1	METALLIC FRAME	6	U TUBE MANOMETER	11	0.5" FUEL PIPE TO NOZZLE	16	GAS REGULATOR
2	AIR FLOW RATE ADJUSTMENT VALVE	7	1.5" AIR PIPE	12	FUEL ISOLATION VALVE	17	LPG GAS CYLINDER
3	CENTRIFUGAL BLOWER	8	CYLINDRICAL FURNACE	13	CONNECTION HOSE	18	FUTURE EXTENSION
4	ELECTRIC MOTOR	9	THERMOCOUPLE ENTRY PORTS	14	GAS FLOW ADJUSTMENT VALVE	19	SWIRLER
5	AIR ORIFICE	10	GAS ANALYZER PROBE PORT	15	GAS ROTAMETER	20	FUEL NOZZLE

Fig. 1
Experimental Test-rig

The swirl number for a double concentric elliptic swirler is approximated as the average value of the swirl number of the major axis and that of the minor axis following in the same footsteps of the approach adopted by G. H. G. Anning et al [5].

$$S_{average} = \frac{S_{major} + S_{minor}}{2}$$

III. RESULTS AND DISSCUSION

A) Visual Flame Inspection:

Figs.2-A, 2-B, 2-C and 2-D represent images pertaining to the confined flames, where the flame distinctive features of each case are apparent. It is shown in Fig 2-A that for the case of circular baseline swirler the flame is dominated by a yellow color with a yellowish blue core and the flame has elongated wavy edges. This is attributed to soot formation owing to imperfect mixing. The effect of ellpticity is clearly shown in Fig.2-B, for the case of aspect ratio=1.25 the flame now has a blue core around the nozzle area indicating enhanced mixing at this area ,the flame has orange edges that are more apparent at the major axis tips. Fig. 2-C shows that for an aspect ratio of 1.4, the area of the blue core increases thus indicating an increase in the efficient mixing area, the flame edges became reddish blue in color. Fig 2-D illustrates that for an aspect ratio=1.5, the blue core area further increases indicating that the mixing is further improved. In addition to that the reddish blue edges are recessed and vanishes at the minor axis tips, the flame also takes a more elliptic shape.

Fig. 2-A
baseline circular swirler

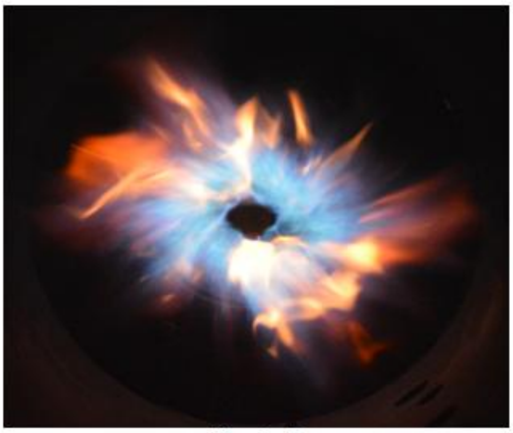


Fig. 2-B
Aspect Ratio 1.25

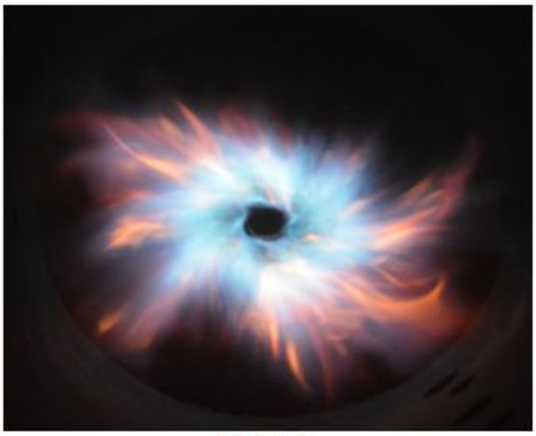


Fig. 2-C
Aspect Ratio 1.4

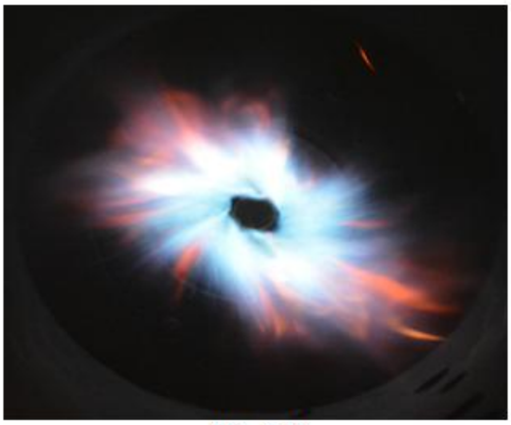


Fig. 2-D
Aspect Ratio 1.5

B) Radial Flame Temperature Distribution:

Radial flame temperature measurements were made along the major and minor axes of the swirlers under investigation at 4 different axial distances measured from the burner face corresponding to dimensionless furnace lengths Z/D of 0.16, 0.36, 0.84 and 1.08.

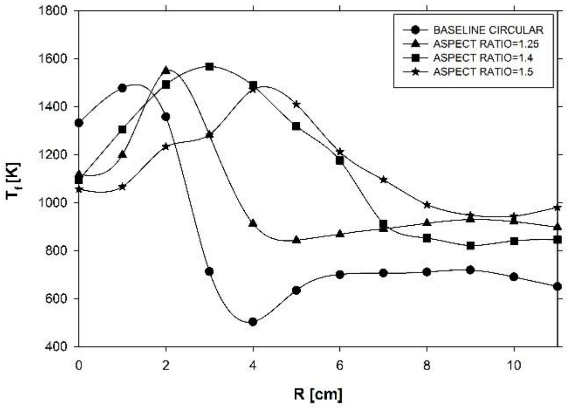


Fig. 3-A
Radial flame Temperature distribution along the major axis at Z/D=0.16

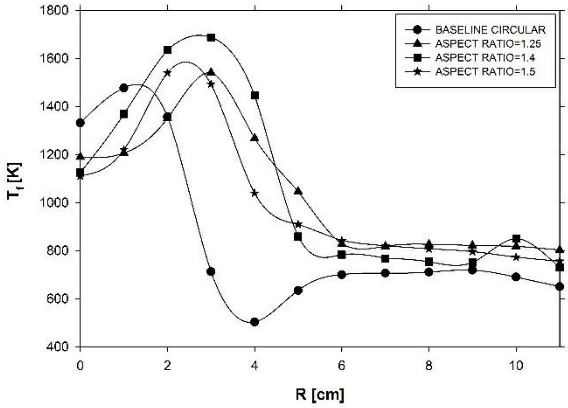


Fig. 3-B
Radial flame Temperature distribution along the minor axis at Z/D=0.16

Fig. 3-A shows that for a dimensionless furnace length Z/D of 0.16, it is shown that as the aspect ratio increases the temperature profile becomes more flattened ,the peak flame temperature slightly increase with the increase of aspect ratio for the aspect ratios 1.25 and 1.4 but it suffers a decrease for the aspect ratio 1.5. This may be attributed to excessive straining along the major axis due to increased aspect ratio. Fig. 3-B shows that the temperature profile has a narrower peak along the minor axis and the peak flame temperature is higher than that along the major axis. The peak flame temperature significantly increases with the increase of the aspect ratio where the maximum peak flame temperature is at an aspect ratio of 1.4 and then it suffers a decrease like the case of the major axis.

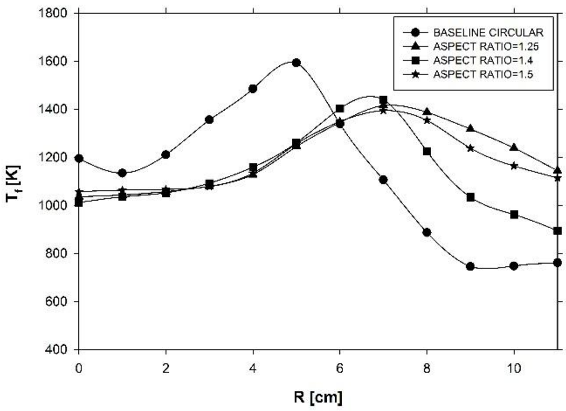


Fig. 3-C
Radial flame Temperature distribution along the major axis at Z/D=0.36

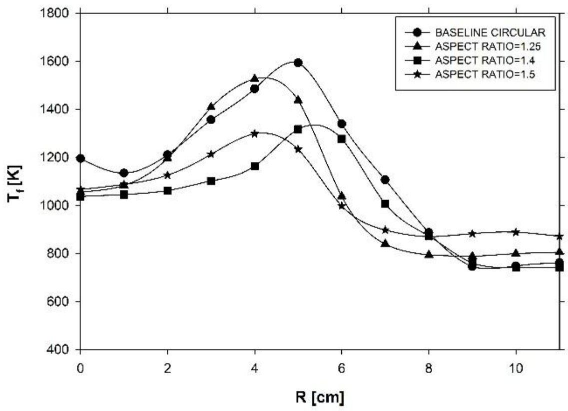


Fig. 3-D
Radial flame Temperature distribution along the minor axis at Z/D=0.36

Figs. 3-C and D show that at Z/D=0.36 the peak flame temperature of the circular swirl is increased compared to that at Z/D=0.16 while the peak flame temperature of the elliptic swirlers starts to decrease. The elliptic swirlers exhibited a more flattened temperature distribution along the major axis compared to that at Z/D=0.16 that was nearly similar for all the elliptic swirlers under investigation, for the minor axis it is shown that the peak temperature decreases with increasing ellipticity. Such trend may give an indication of shortening the flame length with increasing the aspect ratio of the swirler.

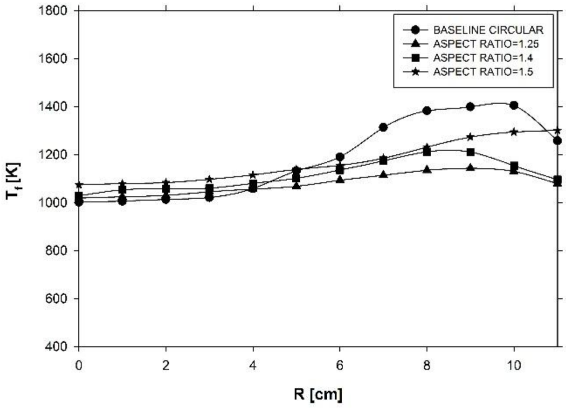


Fig. 3-E
Radial flame Temperature distribution along the major axis at Z/D=0.84

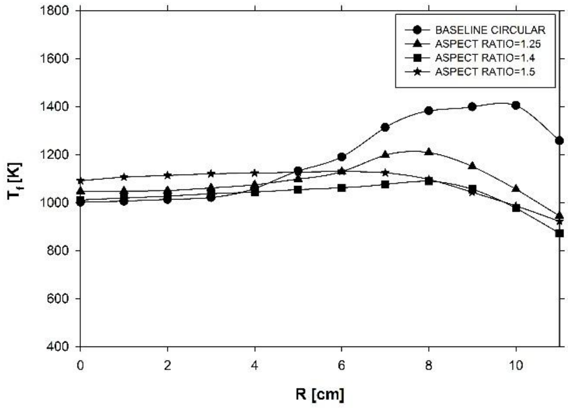


Fig. 3-F
Radial flame Temperature distribution along the minor axis at Z/D=0.84

Figs. 3-E and F show that at Z/D=0.84 that the elliptic swirlers exhibited a nearly constant temperature profile along most of the major and minor axes which is a desirable effect of the swirl. However, the circular swirler exhibited a higher temperature region that extended from R=6 to R=11cm, this shows that elliptic swirl has a significant effect in shortening the flame which would result in a shorter combustion chamber required and hence a more compact design.

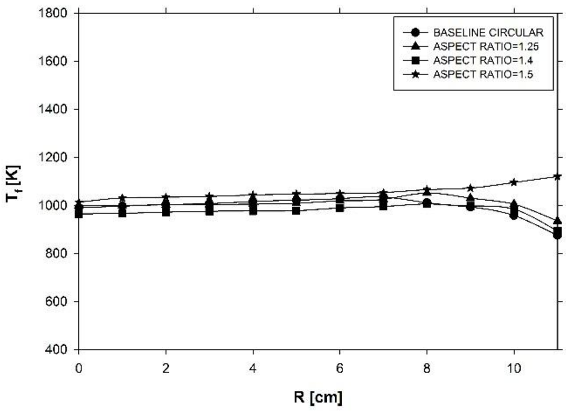


Fig. 3-G
Radial flame Temperature distribution along the major axis at Z/D=1.08

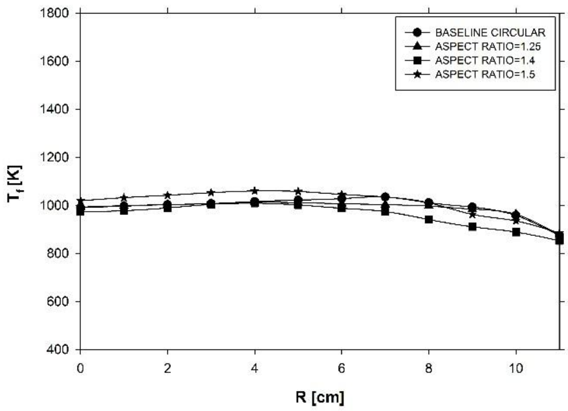
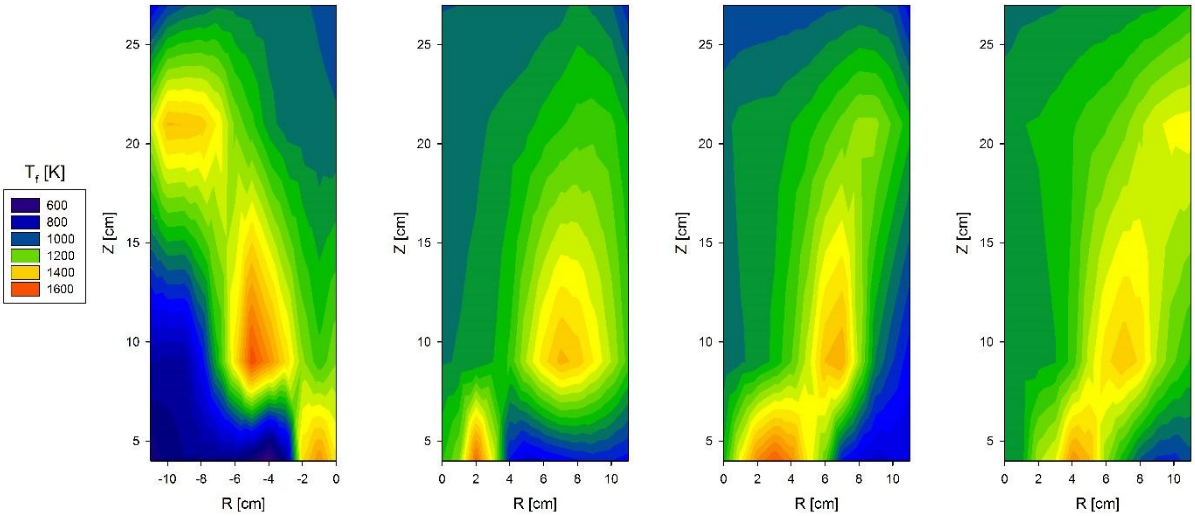


Fig. 3-H
Radial flame Temperature distribution along the minor axis at Z/D=1.08

In Figs. 3-G and H a nearly constant radial temperature profile occurs at Z/D=1.08 and the temperatures are nearly the same for all swirlers under investigation along both the major and minor axes suggesting that complete homogeneity is reached for all swirlers under investigation.

C) Flame Temperature Contours:

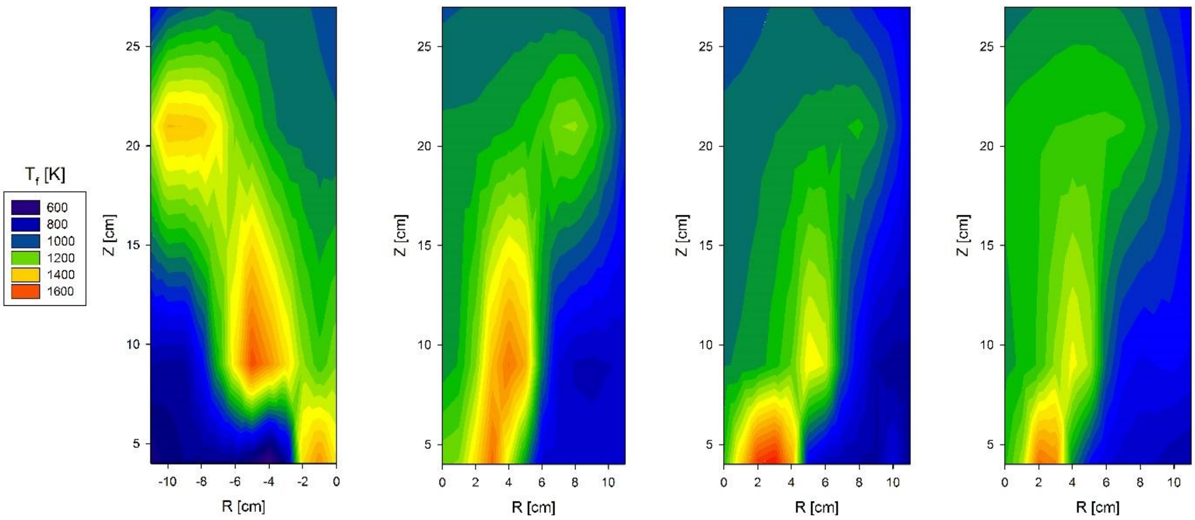
Figs. 4-A and B represents flame temperature contours along the major and minor axes respectively, it is clearly shown how changing the swirler aspect ratio alters the shape of the temperature field along both the major and minor axes. This may be linked to the fact that the elliptic swirler geometry modified how the mixing between air, fuel and hot combustion gases occur in the recirculation zones. The elongated shape of the elliptic swirler led to vortex interactions,vortex bending and self-induction which accordingly led to enhanced mixing and fortified the flame stabilization mechanism [15].



Baseline Circular **AR=1.25** **AR=1.4** **AR=1.5**

Fig. 4-A
Flame Temperature Contours along the Major Axis

Fig 4-A shows that for the circular baseline swirler the region of the peak temperature occurs at an axial distance of about 9cm from the burner's face. However, the region of peak temperature occurs at a distance of about 4cm for the elliptic swirlers. This indicates enhanced mixing near the nozzle area which would result in a shorter flame length. It is also shown that the peak temperature increases with the increase of the aspect ratio and starts to decrease again for the case of aspect ratio=1.5, this may be attributed to excessive strain rate suffered by the swirling flow so more heat transfer occurs from the hot reaction zone to the adjacent layers, thus a more uniform temperature distribution is achieved but at the expense of the peak temperature value.



Baseline Circular **AR=1.25** **AR=1.4** **AR=1.5**

Fig. 4-B
Flame Temperature Contours along the Minor Axis

Fig. 4-B shows that the peak temperature region along the elliptic swirlers minor axes is concentrated nearly at an axial distance of 4cm from the burner face as well, a higher peak flame temperature value was recorded at the minor axes compared to the values at the major axes for all the elliptic swirles under investigation. The highest peak temperature recorded was at the minor axis of the 1.4 aspect ratio swirler and the peak temperature starts to drop for the 1.5 aspect ratio swirler. It is observed that there is an asymmetric behavior for the temperature distribution along the minor and major axis of the same swirler ,the temperature

distribution shows that the recirculation region penetrated at different depths along the major and minor axes, the temperature contours exhibited less spreading along the minor axis compared to that along the major axis, the results are in good agreement with the previous findings of G. H. G. Anning et al where it was illustrated that there is a difference in the size and shape of the recirculation bubble along the major and minor axes of the elliptic swirler[5].

D) Emissions analysis:

Radial measurements of pollutant emissions were made at a dimensionless furnace length Z/D=2.24, concentrations of NOx,CO and UHC were measured for the swirlers under investigation and the average value of such emissions was calculated and plotted as shown in Figs. 5-A,5-B and 5-C.

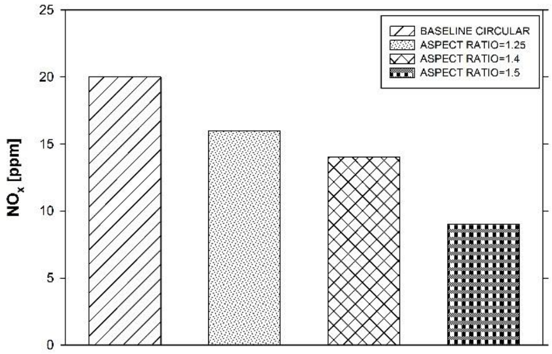


Fig. 5-A
Average NOx values

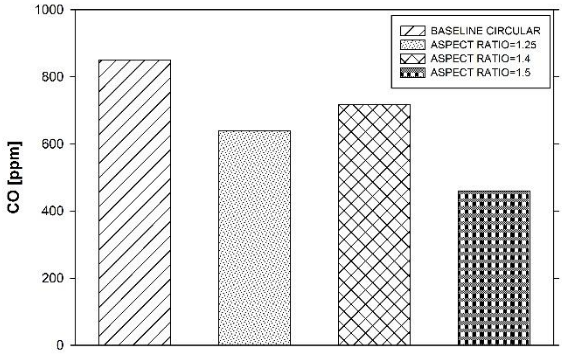


Fig. 5-B
Average CO values

Fig. 5-A shows a comparative bar chart of the average values of NOx emissions for the swirlers under investigation in ppm. It is shown that increasing the aspect ratio has a desirable effect in reducing the amount of the NOx formed, where there is a decrease of 20% in the amount of NOx formed for the case of aspect ratio=1.25 compared to the values of the baseline circular swirler, a decrease of 30% for the case of aspect ratio=1.4 and a very significant decrease of 55% in the case of aspect ratio=1.5. This may be explained by the fact that when a single digit ppm NOx is approached the significance of prompt NOx starts to appear which is generally smaller compared to the values of thermal NOx, prompt NOx is formed in the primary zone of the diffusion flame where it is formed due to mixing deficiencies. Since the elliptic swirler enhances mixing its effect is reflected upon the reduction in the amount of NOx formed, where the value of NOx decreases with the increase in the aspect ratio.

Fig. 5-B shows the average values of CO concentrations , the amount of CO formed is reduced by 24.7% for the case of aspect ratio=1.25 due to enhanced mixing ,the 1.4 swirler exhibited a decrease of 15.6% in the CO concentration. Such value is lower than the amount of decrease in the 1.25 swirler but still higher than that of the circular baseline swirler, this may be explained by the fact that since the 1.4 swirler recorded the highest peak temperature that is when coupled with high residence time induced by vortices formed in the vicinity of the high temperature region promotes dissociation. So this adverse effect reduced the effect of enhanced mixing in the reduction of the amount of CO formed. In the case of the 1.5 swirler there is a significant decrease of 46% owing to further enhancement in mixing.

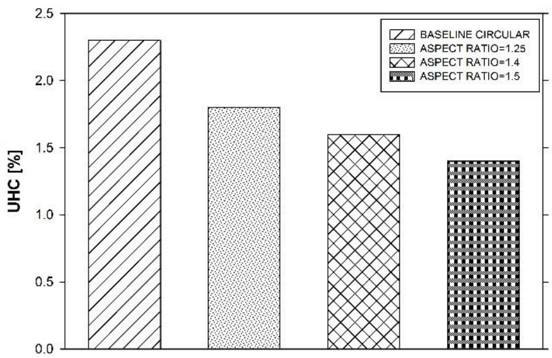


Fig. 5-C
Average UHC values

Fig. 5-C shows that there is a decrease in the amount of unburnt hydrocarbons with the increase of the aspect ratio due to the improved mixing of the elliptic swirl, the 1.25 swirler exhibited a decrease of 21.7% in the amount of UHC, a decrease of 30.4% in the case of the 1.4 swirler and a decrease of 39% for the 1.5 swirler.
The previous results came to emphasize the previous findings of Gutmark on the role of elliptic swirl in the reduction of pollutant emissions when compared to a conventional circular swirl owing to the altered dynamics of vortex interaction within the shear layer which in turn enhances air and fuel mixing [15].

IV. CONCLUSIONS

1-The elliptic swirl has a strong effect in shortening the flame. This is shown by the fact that the peak flame temperature of the elliptic swirler is recorded at Z/D=0.16 whereas the peak flame temperature of the circular baseline swirler was recorded at a Z/D=0.36, the radial flame temperature profile reached a nearly constant value at Z/D=0.84 for the elliptic swirlers while the temperature profile of the circular baseline swirler was completely flattened at Z/D=1.08.
2-The peak flame temperature was recorded nearly at the tip of the minor axis at Z/D=0.16 for the elliptic swirlers where its value increases with the increase of aspect ratio reaching an absolute peak at aspect ratio=1.4. However, the peak temperature decreases for the aspect ratio of 1.5 due to excessive strain rate and shearing, the 1.5 swirler exhibited a comparatively more uniform temperature profile throughout.
3-The elliptic swirler demonstrated an asymmetric behavior along the major and minor axes, where the temperature profile is flattened with the increase of the aspect ratio especially along the major axis, the temperature profiles exhibited a narrower distribution along the minor axis.
4-The improved mixing caused by the elliptic swirl has a noticeable effect in the reduction of pollutant emissions, where the elliptic swirl with aspect ratio=1.5 showed significant reductions in the amount of NOx, UHC and CO formed.

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