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The Effect of Different Swirling Flow Patterns on the Performanceof a Domestic Single Ring Burner

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Abstract: *In this research, we studied the swirling effect on a single ring gas domestic burner were the testing was performed on3 patterns of flow orientation: Swirl flow and Star pattern swirl and the radialflow as a Benchmarking burner.The influence of the pan height to the flame frontand Reynolds number has been introduced as the changing conditions. To study the improvement of future domestic gas burners by increasing thethermal efficiency as well as decreasing CO emissions, LPG was used as the testing gas for the examination of these burners. The results indicated that, usingthe swirl motion improved the thermal efficiency and CO emissions, but for the Star pattern burner the CO emissions improved evidently.Increasing the pot heightfrom the burnerfront flame decreased the thermal efficiency and CO emissions under all operating conditions due to lower pigmentation of the flame to the pan bottom which reduces the heat transfer from the flames to the heated pan.For the Swirl flow burner, the efficiency increased by 2.7% from the benchmarked burner. On the other hand, the CO emission decreased by 80% for the star pattern burner from the benchmark due to two reasons increased first the gaps between each flame length which allowed more air to reach the flames and help complete the combustion process secondly the increased flame length because of impinging flames increased the inertia of the flow which resulted into propagation in the radial dimension decreasing the contact with the heated load.*

Keywords*: Swirl burners; Domestic burner; Thermal efficiency, Combustion Emissions, Star Pattern.*

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I. Introduction

Domestic gas combustion burners are essential in all cooking household appliances including professional kitchens and restaurants. Developing the burners to be more efficient and safe for the domestic use in a task that manufacturing companies in the industry are taking as a duty to improve and enhance such vital component and on the strict level as the international standards are releasing more constraining regulations to increase pedestrian safety by reducing the consumed energy of burners and also reducing formation of unburnt elements such as “CO, CO_x and NO_x “.

Liquefied Petroleum Gas (LPG) is the most common used gas for the domestic use, since it was abundant from the resources point of view in the last 60 years, while the current shift is towards the NG as many fields are been discovered containing a large reservoir for this matter.

For Domestic burners the flame is considered stationary flame, and this type of flame is divided into three classes: Aerated flames, Partially-aerated flames and Non-aerated flames [1-6]. The domestic burners in market are commonly partially-aerated as the burners are designed to be naturally aspirated. The partially aerated burner’s properties have relatively high efficiency and good combustion properties [6, 12].

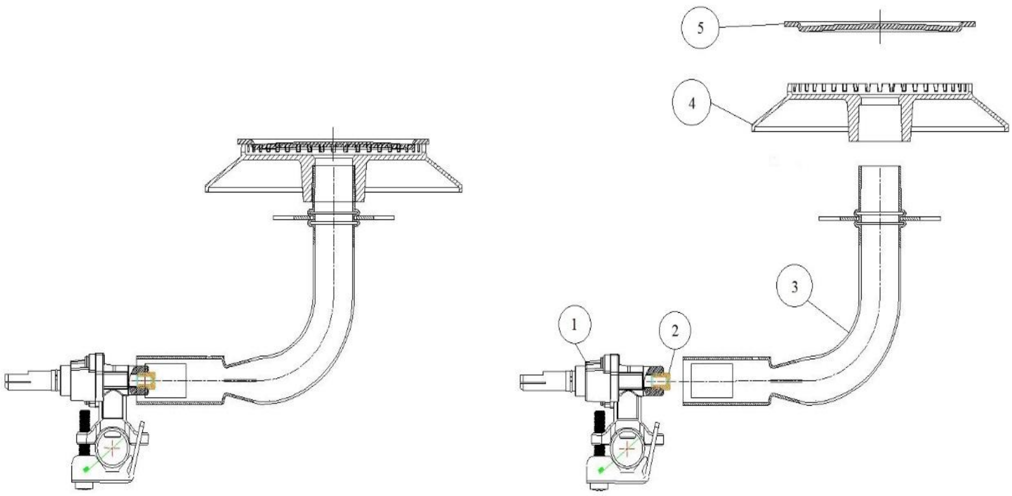


Figure 1 Venture tube assembly

In order to improve thecombustion behaviors of this premixed single ring burner,reducing energy consumption andpollutant emission swirling flow has been used[7]. There are multiple types of burners used in the domestic cooking gas burners. These types are indicated by: burner sizes, power, number of rings, number of ports, types of ports and angle of impinging .Upon this approaches researches have been done to provide more efficient and reliable appliances, and the focus of this research is on domestic gas operated cooking appliances specifically the hob burners [7-11].

Swirling flow conducted to the domestic gas burners werestudied variously with different designs. All of them concluded that, using swirling flow to enhance the burner thermal efficiency [6-11]. And a swirl flow has a positive effect on the CO emissions [13-19].

The effect of the mixture Reynolds number and pan height for three single ring burners radial, swirl and star pattern on the thermal efficiency and CO % has been studied using LPG [7].It was found that swirling flow increase the thermal efficiency in general and slight decrease in emissions.

[20, 21] used natural gas to study the efficiencies and emissions of domestic burners. They found that the thermal efficiencies and the emissions produced from the burner are effected by the thermal input andtheload height to flame length ratio. Increasing the pot height to flame length ratio or the thermal input, the burner thermal efficiency increasing. Also with either thermal input ratio or pot height to flame length,the NO_x and NO generally rise.

Also other parameters were studied to evaluate its effect on the performance of the burner, some of these parameters are, the air to fuel ratio or equivalence ratioand swirl number [14].

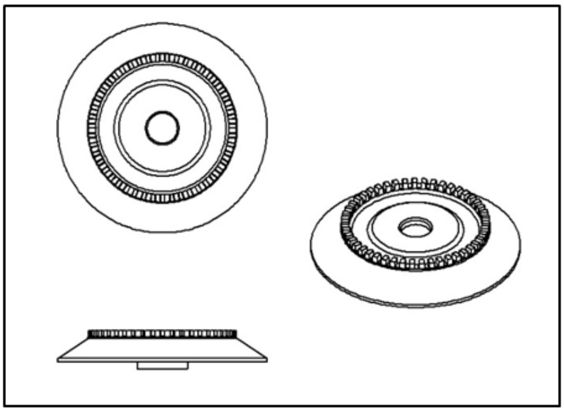
Flame impinging is a new approach for developing burners with lower CO emissions, and this is achieved by impinging two neighboring flame fronts together forming one flame front. The aim of this idea is to utilize the momentum of the jets at an angle that introduces a turbulent motion in impinging flame front allowing more air and fuel mixing.[22] This parameter is affected by the flame length and speed as flames tend to attract each other when the flame speeds are higher[23].

In this study all of these parameters are joined together in a comparative form to evaluate which are the effective parameters on improving the performance of domestic gas burner. The study focuses on combining the swirl effects of a single ring burner that operate on a partially premixed mixture flow configuration, with the target of enhancement combustion characteristics by the aid of the swirl effect.

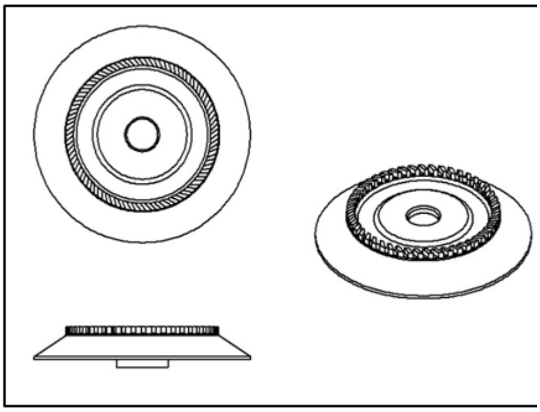
II. Test rig and experimental procedure

In this research different swirling flow patterns of single ring burner is investigated to enhance the CO emissions and the thermal efficiency for the premixed flame through created using a venture tube where a gas jet momentum helps airentrainment rate of the jets.

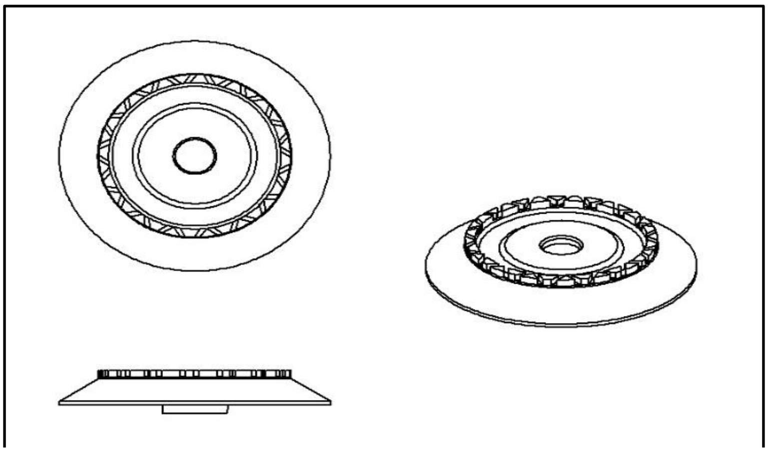
The burners designed are based on a single ring of slot jets ports along the circumference. The non-swirled burner shown in Fig. 1(a) Single ring radial flow burner The single ring burner is a flow angle of 90° burner with 47 ports of flame at an inclination angle of 0° at a diameter of 90 mm. Single ring swirl flow burner Fig. 1(b) a single ring burner that has a swirl angle of 25°, the burner is with 47 ports of flame at an inclination angle of 0° at a diameter of 90 mm.Single Ring Star pattern burner Fig. 1(c) The single ring burner is a swirl angle of 25° burner with 37 ports of flame of impinging flames at an inclination angle of 0° at a diameter of 90 mm.



2.a Radial Burner



2.b Swirl Burner



2.c Star Pattern Burner

Figure 2 Schematic Design for the burner with the different angles for indicating the design configuration.

Fig. 3 shows the schematic diagram of the experimental setup.The test rig designed for this test was basically a connection between a burner gas tap and a LPG gas tank. A wet gas flowmeter is used to measure the volume of gas flow rate Fig. 4. Also a pressure regulator with a calibrated pressure gauge are used to indicate the pressure and providing the fuel to the burner at 30 mbar. The burner is naturally aerated,the flame appearance forthese burners werepictured, using a 24 mega pixels digital camera. In Fig. 5 the position of the camera is relative to the flame appearance was fixed in order to keep the size of the produced images the same.

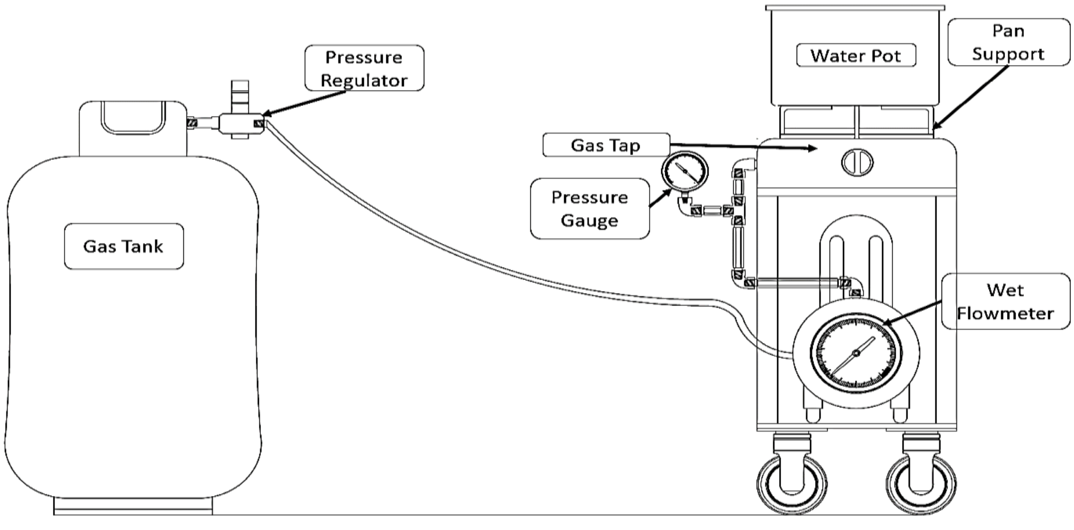


Figure 3 Schematic Drawing for the test rig

Figure 4 Flow meter 1 liter

All burners were connected to a custom-builttest rig with all the measuring tools required including calibrated water temperature, thermal anemometer and environmental condition indicator. The water temperature variation with time was measured to calculate the thermal efficiency using calibrated thermocouple type K. Also, a hood collector was used to collect the combustion exhaust gases to measure the CO concentration as shown in Figs. 5.

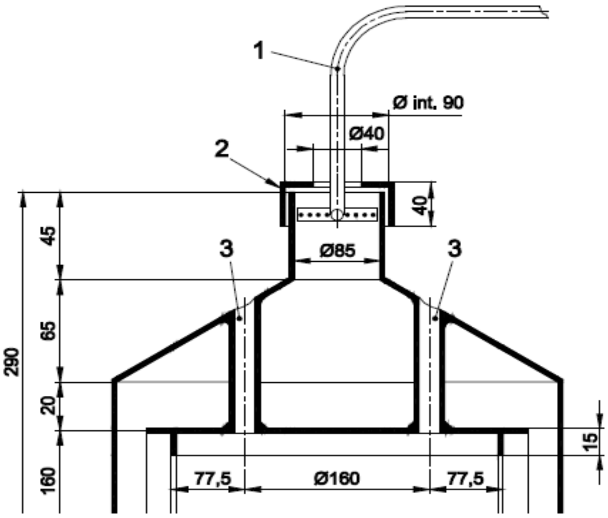


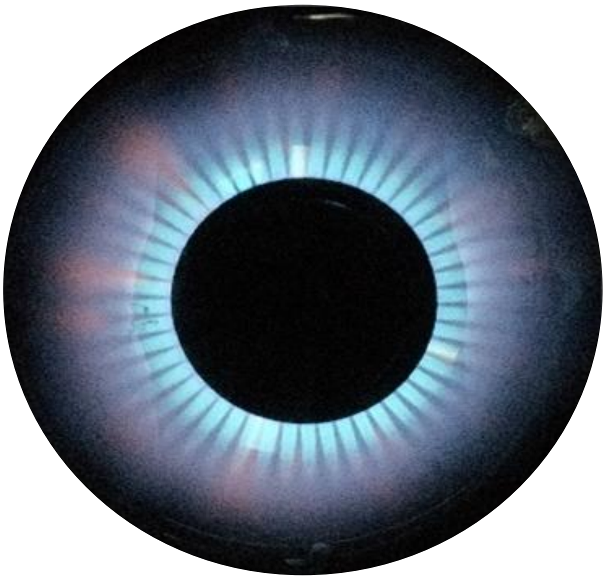
Figure 5 Flue Gas Collector Hood

Figure 6 IR gas analyzer

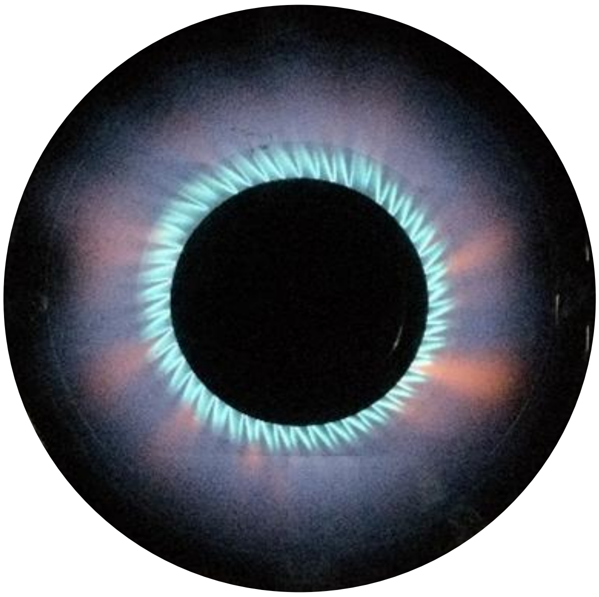
According to [6], the products of the combustion emissions are measured by using a sampling tube as shown in Fig. 4. This tube is connected to the Infrared gas analyzer to measure the CO emission shown in Fig. 5. The sampling tube located away from the loading vessel edge and from the pot bottom according to the International Standard EN 30[24, 25].

The averaged three times measurements reading was conducted, concluded and used to calculate the uncertainty according to Kline and McClintock [26] method.

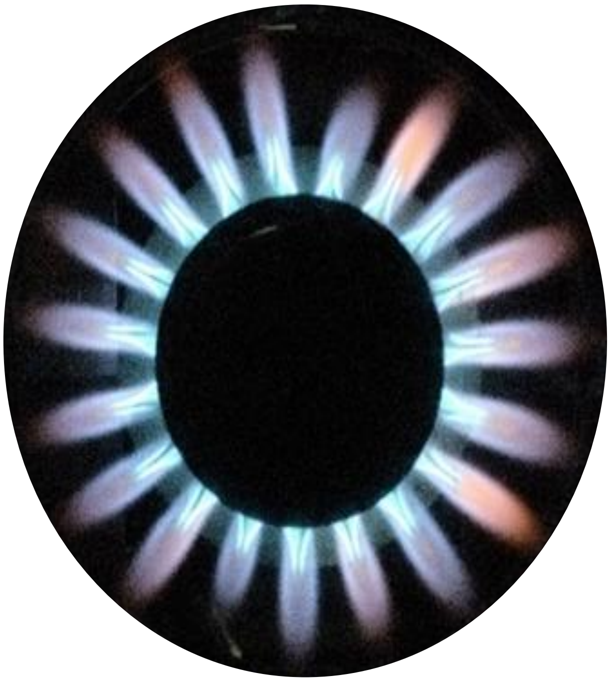
The fuel flow rate measurement has anaccuracy of 0.24% and a repeatability of 0.15% of its full scale. The error was ±0.3^{o}C. For the water temperature. Also, the maximum uncertainties and minimum uncertainties for CO are 9.5 % to 2.1 %, respectively.



7.a Radial Flame Shape



7.b Swirl flame Shape



7.c Star pattern flame Shape

Figure 7 flame burner shapes

III. Thermal Efficiency calculation and Combustion Emissions

Three different burners design were tested at different air to fuel ratio (A/F), pan height and burner powerto indicate their effecton the burner performance and to find the most suitable and optimum condition for each burner design.

In order to find the thermal efficiency the International Standard EN 30 [24, 25] test and calculated from the following equations:

$$\boldsymbol{EE_{gasburner} = \frac{E_{theoric}}{E_{gasburner}}} \quad \textbf{(1)}$$

$$\boldsymbol{E_{theor} = 4.186 \times 10^{-3} \times m_e \times (t_2 - t_1)} \quad \textbf{(2)}$$

$$\boldsymbol{E_{gasburner} = V_c \times H_s} \quad \textbf{(3)}$$

$$\boldsymbol{m_e = m_{e1} + 0.213 m_{e2}} \quad \textbf{(4)}$$

$$\boldsymbol{V_c = V_{mes} \times \frac{p_a + p - p_w}{1013.25} \times \frac{288.15}{273.15 + t_g}} \quad \textbf{(5)}$$

Where;

$E_{gas\ burner}$: energy content of the consumed gas for the prescribed heating in MJ and rounded to the first decimal place;

$E_{theoric}$: theoretic minimum required energy for the corresponding prescribed heating in MJ and rounded to the first decimal place.

m_e: is the equivalent mass of the pan filled

m_{e1} : is the mass of the water used in the pan

m_{e2} : is the mass of the aluminum corresponding to the pan and its lid (the mass m_{e2} to be taken into account will be the mass measured).

V_c : is the volume of the dry gas consumed, in cubic meters, determined from the measured volume, by the following formula:

V_{mes} : is the measured gas volume, in cubic meter

p_a : is the atmospheric pressure, in mbars

p : is the gas supply pressure at the point where the heart input is measured, in mbars;

p_w : is the partial vapor pressure, in mbars;

t_g: is the gas temperature at the point where the heat input is measured, in degrees Celsius;

H_s : is the gross calorific value of the gas

On the other hand, to measure the combustion emissions the international standard EN-30European Standard [24, 25] is used. In this standard the combustion emission is evaluated by measuring the CO concentration in the air and water vapor free products (neutral combustion) as shown in the following equation:

$$(CO)_N = (CO)_M \times \frac{(CO_2)_N}{(CO_2)_M} (6)$$

$(CO)_N$: is the volumetric percentage of carbon monoxide content relative to the dry, air free products of combustion;

$(CO_2)_N$: is the volumetric percentage of carbon dioxide calculated for the dry, air-free products of combustion;

$(CO)_M$:is the volumetric percentages of carbon monoxide

$(CO_2)_M$:is the volumetric percentages of carbon dioxide measured in the dry sample during the combustion test.

All experiments were conducted on different three A/F ratio 22.24, 23.7 and 25.8 while the pan height was conducted on three different levels 20, 22 and 24 mm. These pan heights producing three different dimensionless pan heights to outer burners diameter H/d = 0.222, 0.244 and 0.266 respectively, where H is the distance between flame and the bottom of the heated Pan while d is the outer diameter of the burner which 9 cm in diameter.

As a result, three values of Reynolds number were calculated to be 1580, 1800 and 2030 for A/F ratio 22.24, 23.7 and 25.8 respectively using equation 7.

$$Re = \frac{VxD}{\nu} (7)$$

Where;

V: Mean Velocity in the venture tube (m/s)

D:Venture tube diameter (m)

ν: Kinematic viscosity (m^2/s) ≈$1.55x10^{-5}$ m^2/s

IV. Results and discussions

A comparison is illustrated between the thermal efficiency and emissions performance each tested for single ring domestic burner is presented in this research. The influence of the Re on burner thermal efficiency and CO %are investigated at different pan heights for the twonewsingle ring burner designs compared with the benchmark one.

4.1 Effect of Reynolds Number, Re:

Figs. 8 (a,c and e) represent the variation of the thermal efficiency versus Reynolds number for all burners used in this investigation at different H/d = 0.2, 0.244 and 0.266 respectively. From these figures, it is observed that the thermal efficiency increases with Re for all flames at all burner to pot distance, this is because increasing the fuel supply to the burner the thermal efficiency increases due to the increase in the heat energy which is proportional to the fuel supply.

On the other hand,swirlburner exhibited the greatest thermal efficiency among the other twoburners for all values of Re and H/d as shown in Figs. 8 (a,c and e). For example, the highest thermal efficiency at H/d =0.222 and Re 2030 for the benchmarking cooker was 60.4% and 58.8% for swirl burner while it was 51.9% star burner as shown in Figure 8(a).

In general, using swirling flow in the cookers achieve higher thermal efficiency than radial benchmark at all Reynolds numbers due to high jet momentum between jets which enhance the mixing between the fuel and air as a result a complete combustion will occur which means higher flame temperature.

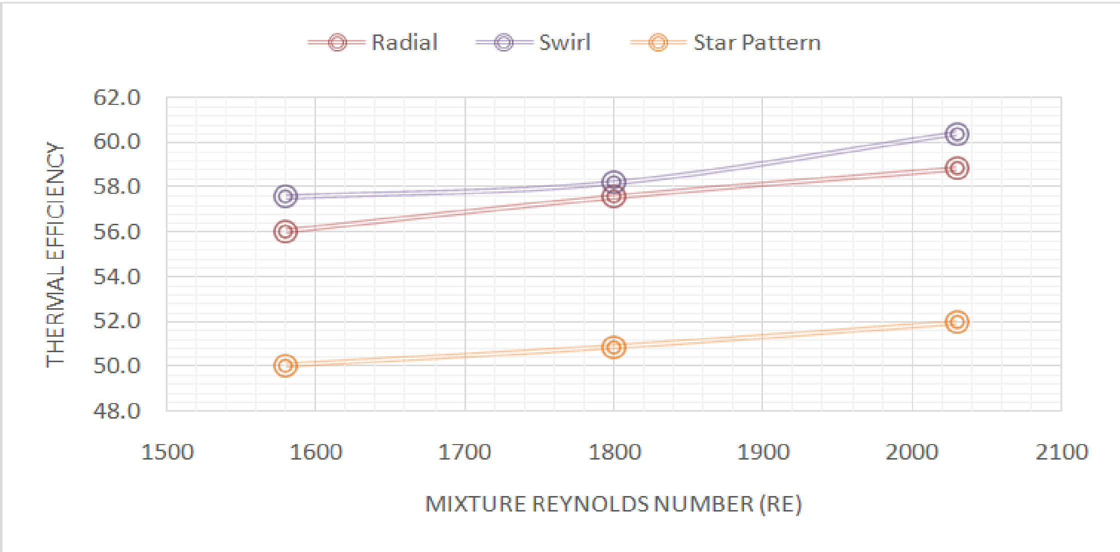


Figure 8(a) Thermal Efficiency vs. Reynolds number for three singleat different H/d = 0.222

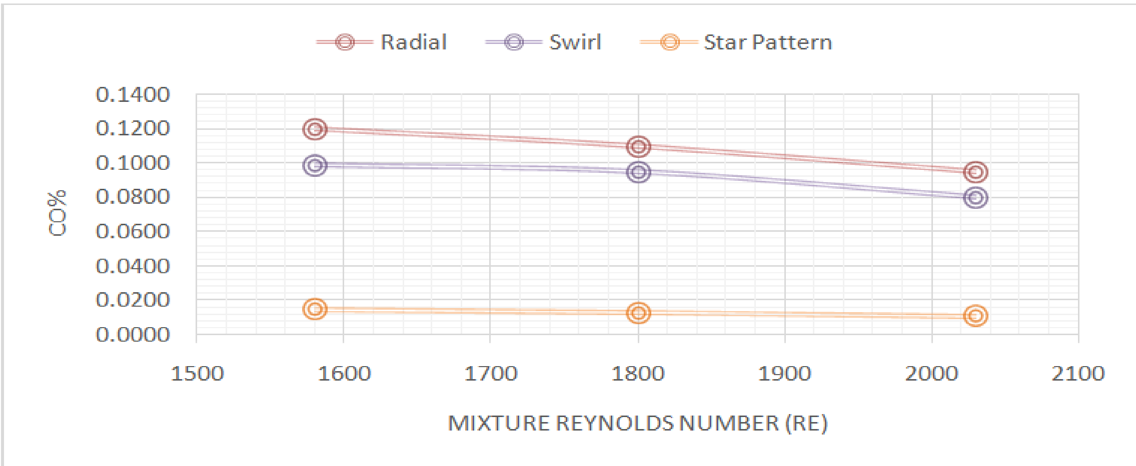


Figure 8(b) Combustion Emissions vs. Reynolds number for three singleat different H/d = 0.222

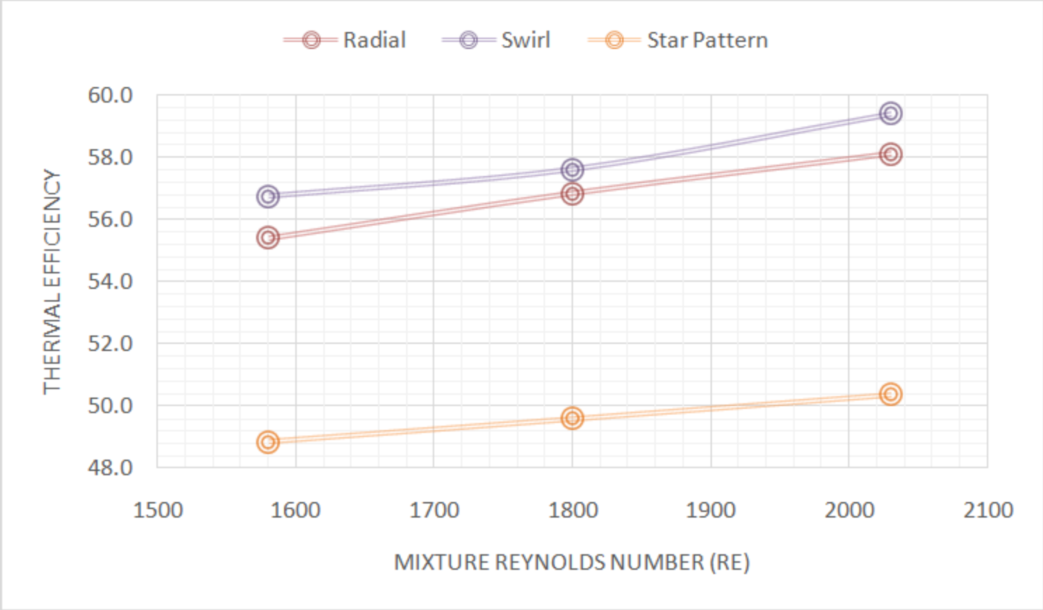


Figure 8(c) Thermal Efficiency vs. Reynolds number for three singleatdifferent H/d = 0.244

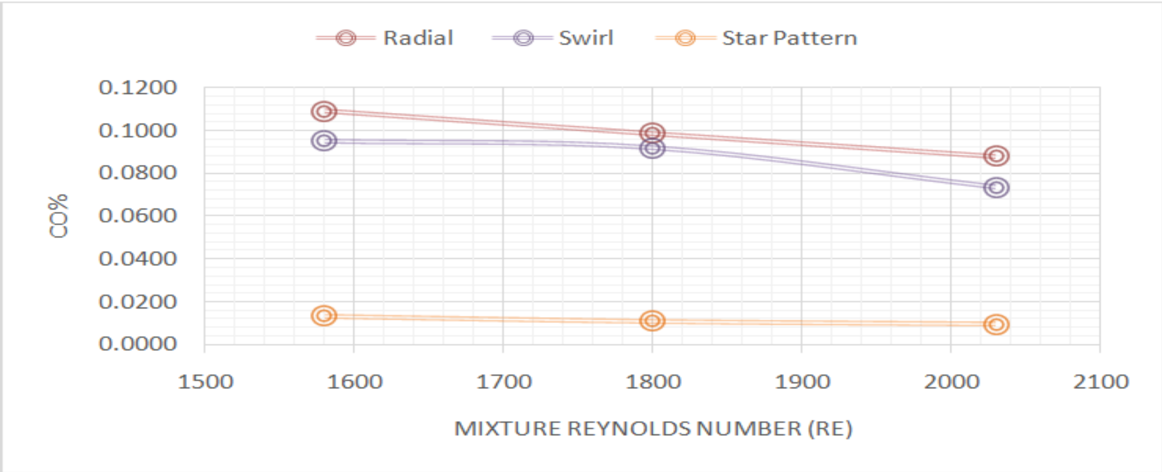


Figure 8(d) Combustion Emissions vs. Reynolds number for three singleat different H/d = 0.244

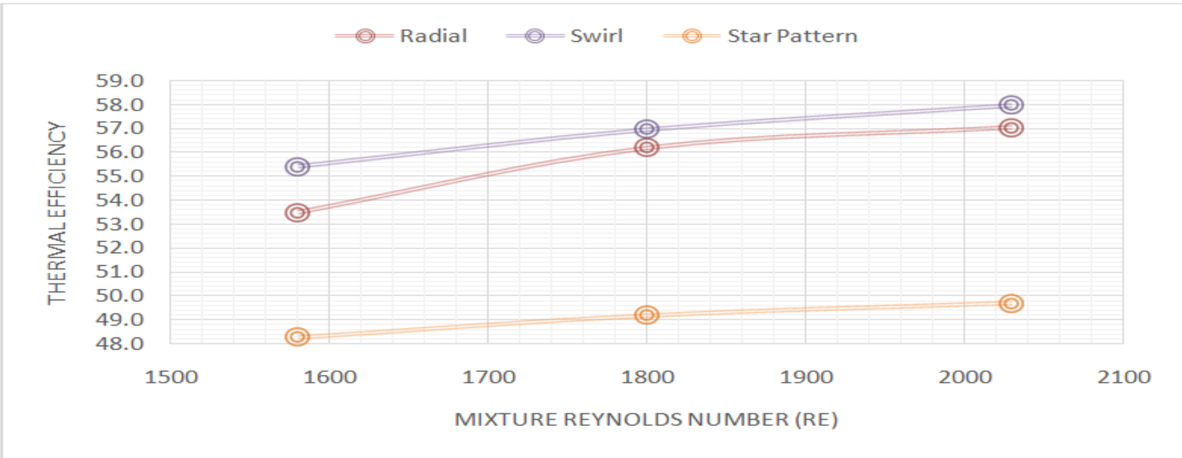


Figure 8(e) Thermal Efficiency vs. Reynolds number for three singleat different H/d = 0.266

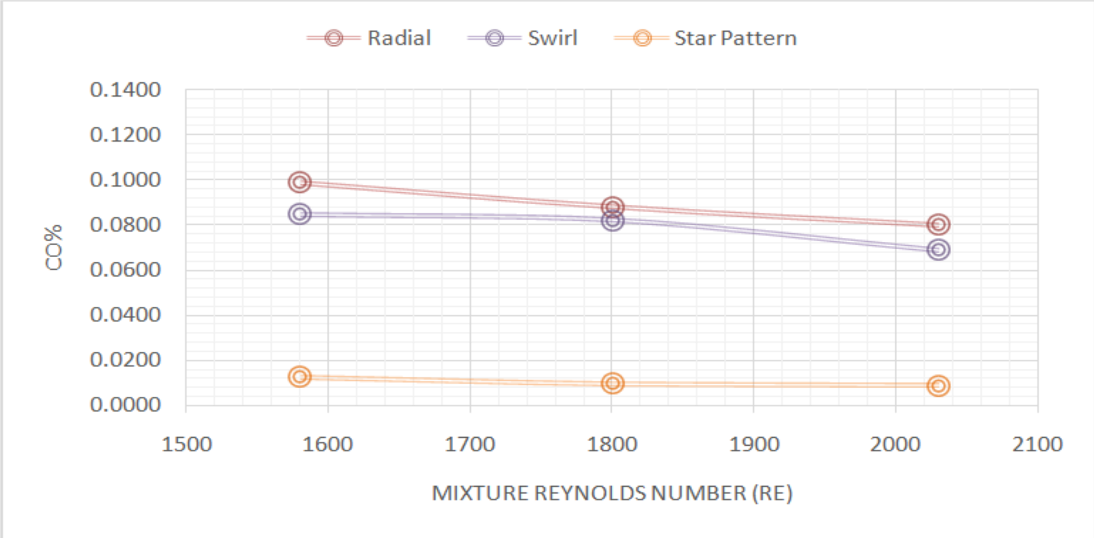


Figure 8(f) Combustion Emissions vs. Reynolds number for three singleat different H/d = 0.266

Furthermore,comparing between the other two burners design at all values of Reynolds number shows that the swirl burner produced the highestthermal efficiency reaching 60.4%, followed by benchmarked burnerwith 58.8% then the star pattern cooker 51.97%. For more explanation flame photoswere taken at Re = 1850 for all burner cookers used in this investigation as shown in figure 7.

For benchmark burner cooker as shown in Fig7(a) the flame produced from the ring was short compared with the other burners which decrease the air entrainment between the flow gases and the surrounding air. In case of swirl flow,the flame was long blue color flame with reddish appearance at its ends and the produced flame seems to rotate with aswirl angle relative to the ring tip.

In figure 7(c) the produced flame from the ring jets ring is long and look like star. In this burner each two-oppositejets are very close and almost form one contact flamewith high impinging effect which increase momentum and consequently the mixing between the fuel and air and also led to a radial propagation of the flame.

Further Fig.7 (b) shows that, at the same values of H/d= 0.222, swirl burner emits lessCO emissions than the other burners followed by radial one. The burner that contained swirling motion showed lower emissions because the swirl ring enhanced the mixing properties of the flame. In general radial and swirl burner produce higher CO emissions than the Star one by more than 60% decrease, this is because the star pattern allows more air to reach the inner of the burner.In thiscase the residence time extended but contact area with the flames was reduced along with good mixing, as a result a complete combustion will take place with lower CO%for example at Re= 2030 emissions were about 0.014% while the swirl and radial burners were 0.085% and 0.09% respectively. The same conclusion was found at H/d 0.244 and 0.266 as shown in figures 8.d and 8.f.

As a conclusion for swirl flow showed an improvement in the efficiency by2.7% more than the benchmarked burner, but a slight improvement in the combustion emissions at the same H/d and same Re of almost 12%.

For swirl flow showed even higher efficiency than of the radial burner with 2.1% improvement in the thermal efficiency, as a result of the intensive swirling action, the CO emissions were even lower for the same reason that improved the efficiency reaching about 12% lower emissions than the reference burner.

For star pattern burner it showed a lower efficiency by 11% than other designs, but with a better enhancement in the emissions due to the fact the star pattern allows more air to reach the flame ring of the burner to enhance the combustion, the enhancement was 80% better than reference burner emission wise.

4.2 Effects of the pot height:

The mixing between the air and fuel resulting from thenewly designed burner extended the combustion residence time and the coefficient of heat transfer between the vessel and the flame increased.

The variations of both CO % and the thermal efficiency for all burners and the vessel height at Re 2030 is shown in Fig.8(e) and 8(f) . These figures illustrate that as the vessel height increases, the thermal efficiency decreases for all types of burners used in this study. At H/d = 0.222The maximum thermal efficiency was observed, as shown in Fig.8(a). As the pot bottom height increased, the combustion producestends to have a less chance of interacting with the vessel bottom at the highest pot height and Re 2030 benchmarking, swirl and star pattern burners the following CO emission percentages 0.08%, 0.068% and 0.008% see Fig. 8(f), and combustion gases

also tends to be cooled due to mixing before contacting the vessel withthe ambient air which decreased the heat transferred to the vessel and as a result, decreasing the thermal efficiency.
On the other hand, decreasing the pot height, increased the flame impingement with the vessel which increases the contact surface between the flames and the vessel and consequently increasing the thermal efficiency forallburners for example at H/d 0.222, 0.244 and 0.266 for the star pattern burner efficiencies were 50.03%, 48.85% and 48.27% as shown in Fig. 8(e).

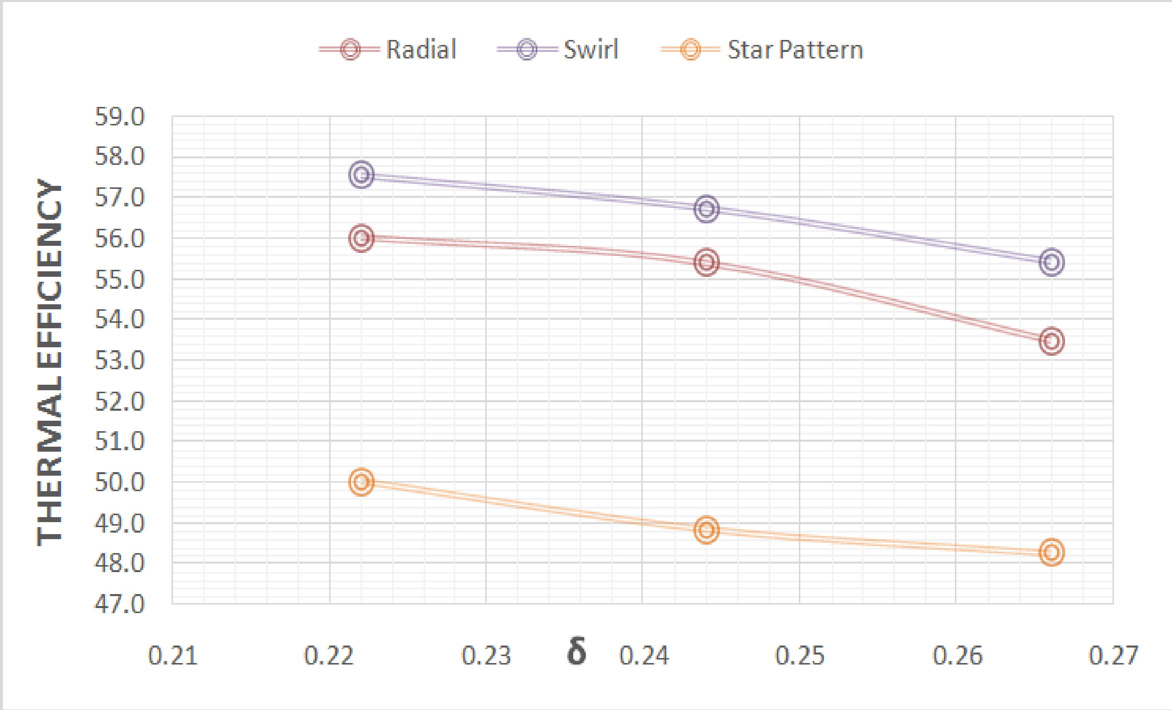


Figure 8(a) Chart for thermal efficiencies of three singlering burner types at Re 1580

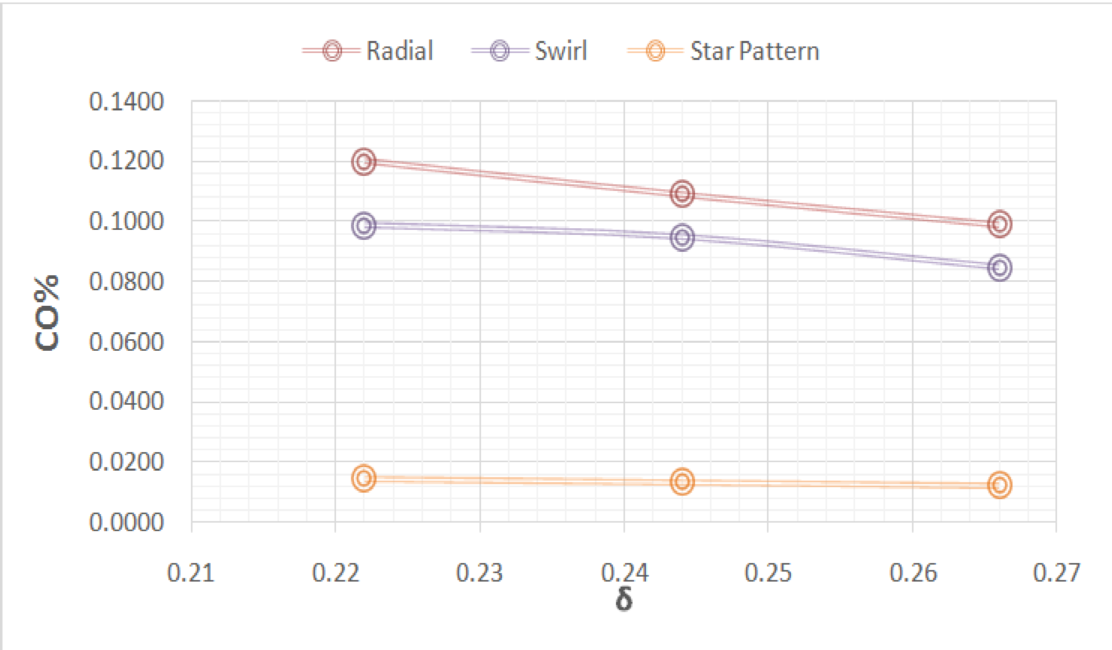


Figure 8(b) Chart for combustion emissions ofthree singlering burner types Re 1580

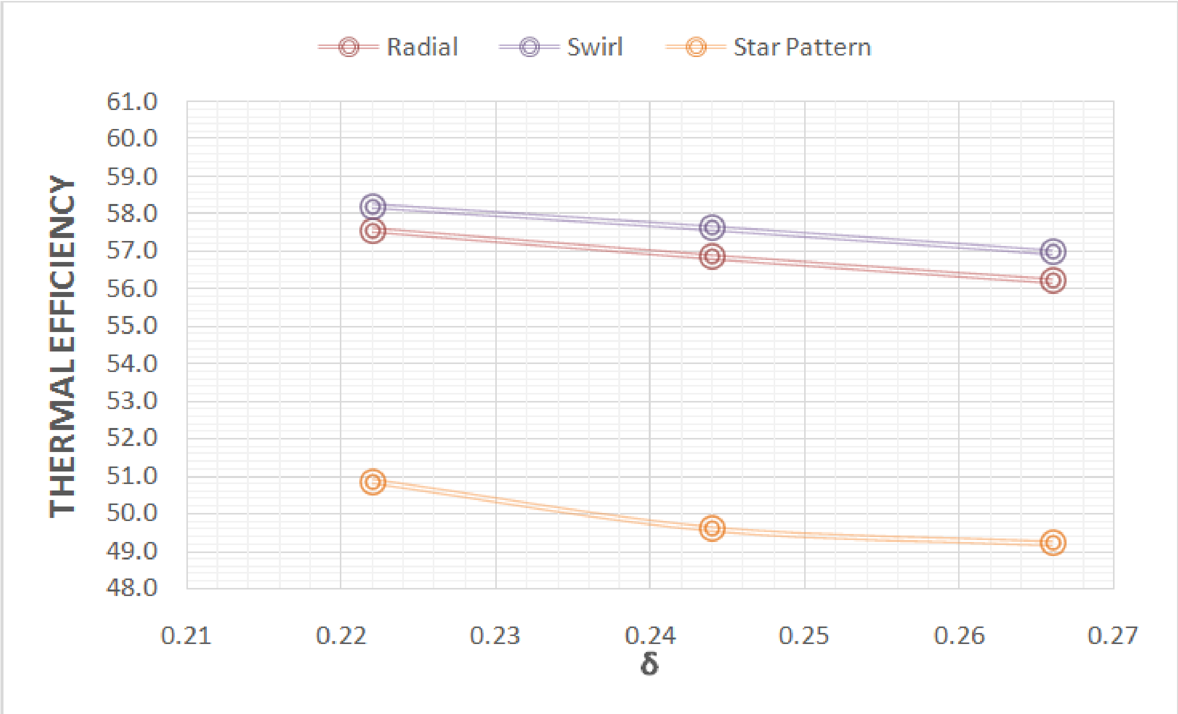


Figure 8(c) Chart for thermal efficiencies of three singlering burner types at Re 1800

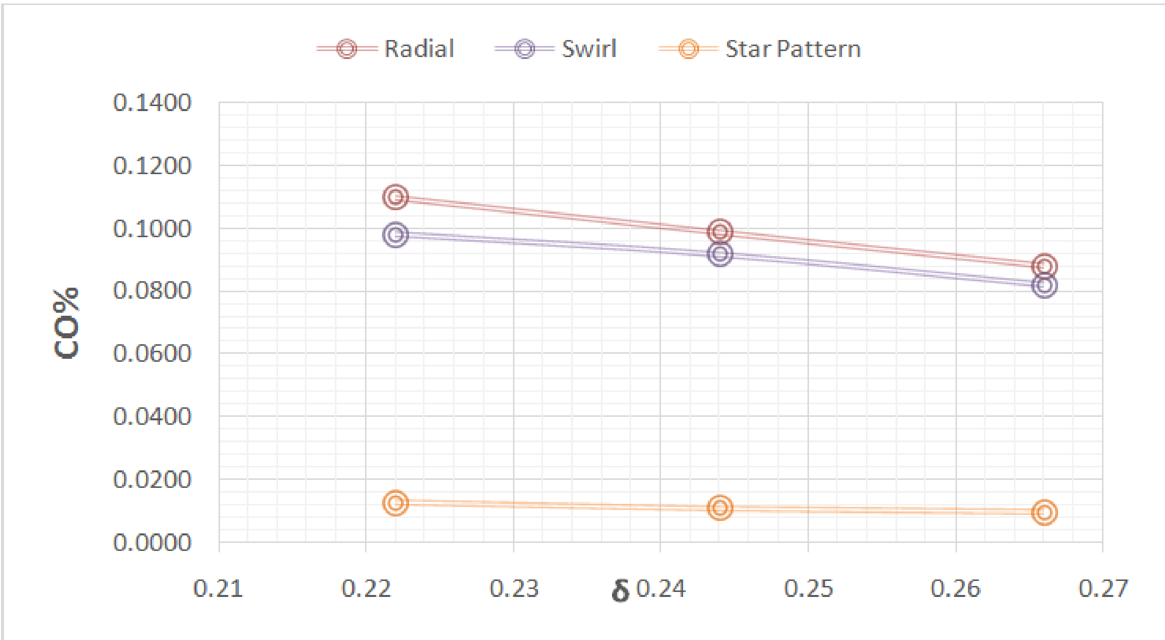


Figure 8(d) Chart for combustion emissions of three single ring burner types Re 1800

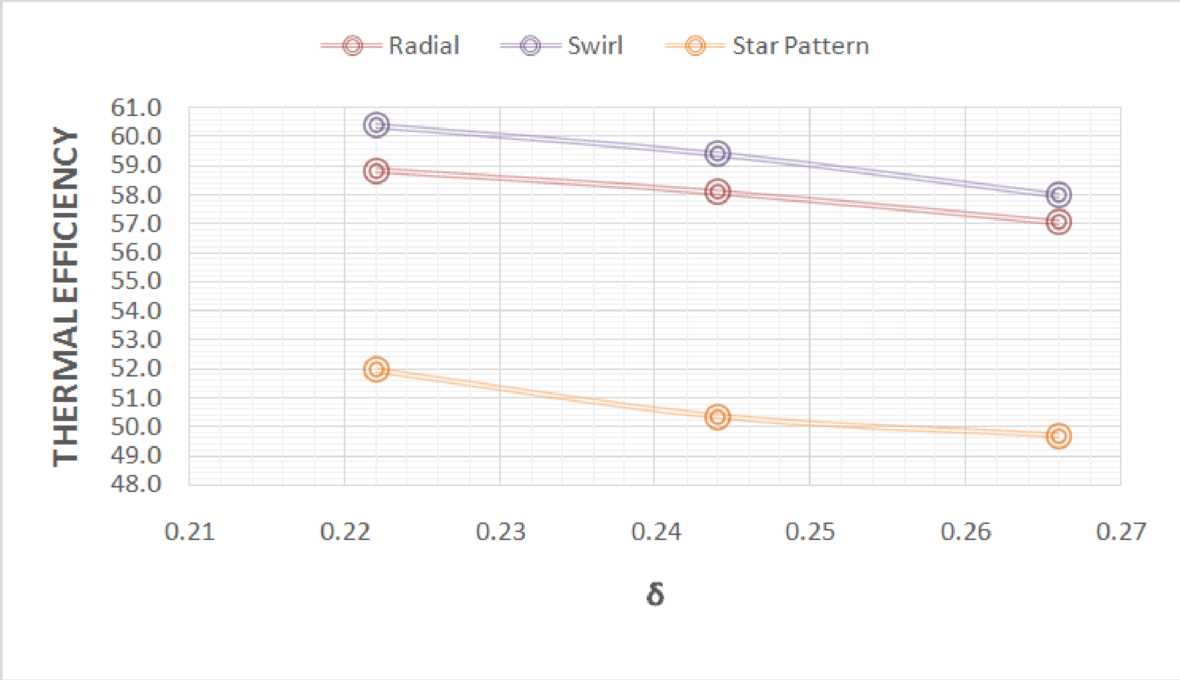


Figure 8(e) Chart for thermal efficiencies of three singlering burner types at Re 2030

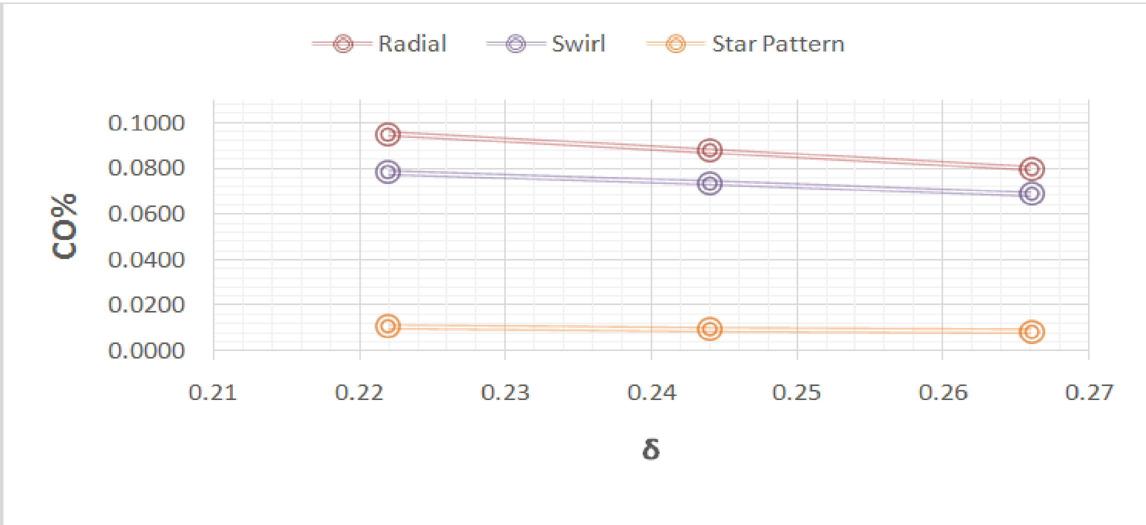


Figure 8(f) Chart for combustion emissions of three singlering burner types Re 2030

V. Conclusion

In conclusion to all presented results let's have a glimpse to see comparatively how each burner performed.

For the combustion emissions (CO %), burners that contained the swirling motion gave lower emissions, the three burners produced emissions as follows Radial burner 0.09%, Swirl 0.08% star pattern was the lowest with 0.01% emissions and this is due the larger turbulent force developed by theswirl flames, the Star pattern burner also allows sufficient amount of air to pass the and reach the flames freely which reduced evidently the combustion emissions relatively to the other burners designs.

From the thermal efficiency prospective the swirl burner gave the highest thermal efficiency reaching almost 60.4% followed by the radial burner 58.8% and the Star pattern burner 51.97%, and this leads us to the conclusion as was shown in previous studies that the swirling motion improves the efficiency of the burner because of enabling the flames from interacting for a longer period of time with the bottom of the heated pan, physicallywe may conclude that this happens due to the fact that the swirl tends to create an intensiveswirling action along with angular momentum to enable the heat to be transferred to the heated load, and the highest thermal efficiencies for all burners where maintained at the lowest pot height and biggest Reynolds number.

So finally to have as a compromise for an enhanced efficiency and lowered combustion emissions the Swirlburner would be promising to study more, and more cases must be designed for the star pattern burner adding an inclination angle to enhance the contact between the flames and the heated load.

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