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Thermal and combustion characteristics of a double ring burner with different swirling flow patterns

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Abstract. The swirling effect on the gas hob of double ring domestic LPG burner was investigated using 4 patterns of swirl orientation: Co swirl, Counter swirl, Star pattern swirl and, the radial flow as a Benchmarking cooker burner. To improve future domestic gas burners thermal efficiency and CO emissions of these burners are compared using LPG. The influence of Reynolds number and the pan height above the flame (as normalized by the Burner outer diameter) has been studied. The results showed that using swirl motion increased both the thermal efficiency and CO emissions, except for the Star pattern burner whereby the thermal efficiency increased while the CO emissions decreased. Increasing the pan height to the burner outer diameter 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 counter flow burner, the efficiency increased by 2.1% from the radial one while it increased by 1.7% and 0.9 % for the co swirl and star pattern respectively. On the other hand, the CO emission decreased by 33% for the star pattern burner from the benchmark one.

Keywords: Swirl; Domestic Burner; Double ring burner

1. Introduction

Most common domestic double ring cookers using premixed flames are used in heating throughout the world because its combustion products are relatively clean [1-6]. In order to improve the combustion performance of this premixed double ring burner, reducing energy consumption and pollutant emission swirling flow has been used [7]. Upon this approach, 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]. 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 [7-11]. Liquefied Petroleum Gas (LPG) is the most commonly 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 [6]. The domestic burners in the market are commonly partially- aerated as the burners are designed to be naturally aspirated. The partially aerated burner's properties have relatively



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high efficiency and favorable combustion properties [6, 12]. Swirling flow conducted to the domestic gas burners was studied variously with different designs. All of them concluded that, using swirling flow to enhance the burner thermal efficiency [6-11]. Also using swirl flow decrease the CO emission [13-19]. Some investigation studied the effect of the swirling of the inner ring in a double ring burner [7,8] and some studied swirling both rings together at different mixture pressure [19], while others studied the swirling for the outer ring in a double ring burner [9,10]. The effect of the Mixture Reynolds number pan height for three single ring burners radial, counter swirl and co-swirl domestic burners on the thermal efficiency, CO % has been studied using LPG [7]. They found that swirling flow increase the thermal efficiency in general while using co swirl flow in double ring burner producing less CO emissions and high thermal efficiency than counter one. [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 affected by the thermal input effecting and the load 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 ratio and 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 allow for 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 these parameters are joined together in a comparative form to evaluate which are the effective parameters for improving the performance of domestic gas burner. The study focuses on combining the swirl effects of a double ring burner that operate on a partially premixed mixture flow configuration, with the target of enhancement combustion characteristics with the aid of the swirl effect. To achieve this, three double flame rings burners have been manufactured using CNC machine to study the effects with as many configurations as possible.

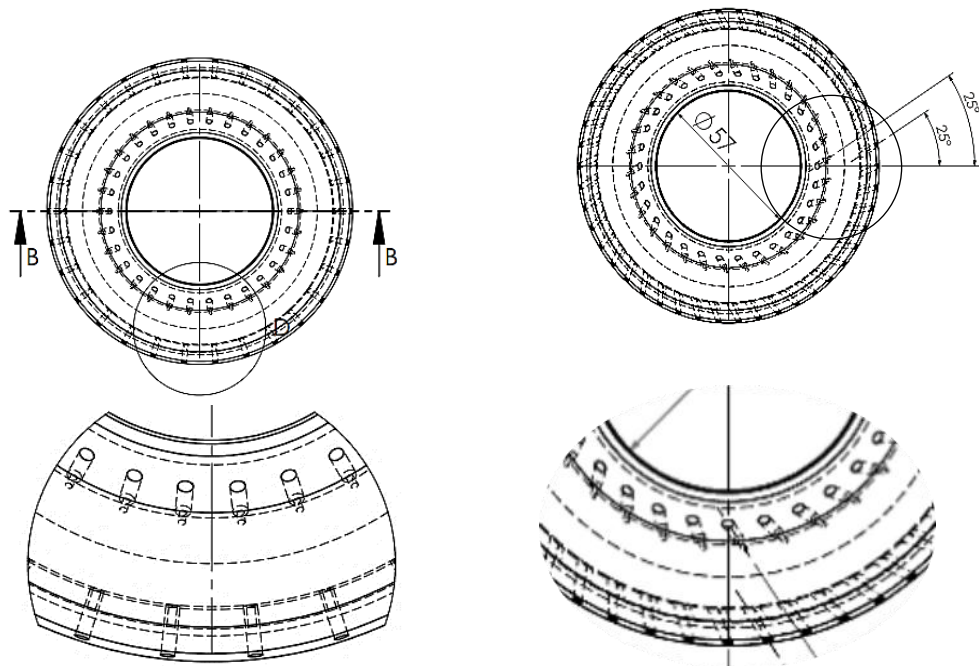
2. Test rig and experimental procedure

In this study different swirling flow patterns of double ring cooker is investigated to enhance the CO emissions and the thermal efficiency for the premixed flame through high gas jet momentum air which increases the entrainment rate of the jets.

Some cookers are based on a double ring of a slot or round jets along the circumference of the burner in the market. The non-swirled burner shown in Fig. 1(a) is used as a benchmarking one. Radial ports in the inner ring direct the flame jets to flow radically and upward towards the horizontal plane with an angle of 45° while it is slightly upward with 10° in the outer ring. The total number of jets in the inner and outer ring is 30 and 45 respectively, with 2mm diameter each. In this study, new three designs using swirling flow are proposed, co swirl, counter flow and star flow pattern. The new three swirl burners have the same inner and outer upwards angles and total exit area as the Benchmarking one. The four burners have the same outer and inner ring diameter of 120 and 70 mm respectively.

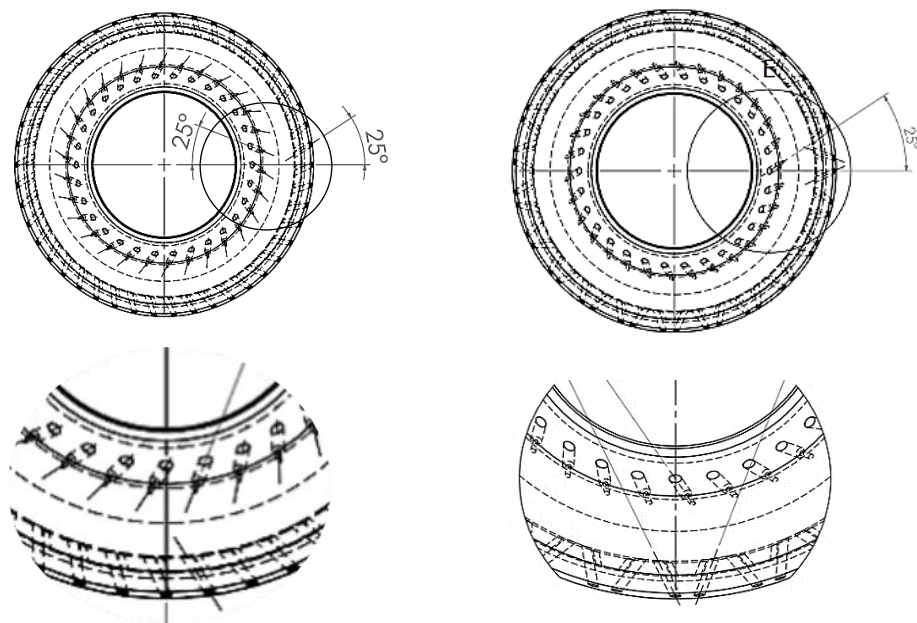
The first double ring burner I is produced by co swirling flow in both outer and inner rings, as shown in Fig 1(b). The inner and outer rings have the same swirl angle 25° and same direction. The second double ring burner II is producing two opposite direction from an inner and outer ring with the same swirl angle 25° as shown in Fig 1(c). While the third one is called star pattern burner III, with opposite direction of flow jets in the outer rings for every two jets while the inner ring has a 25° swirl flow angle as shown in Fig 1(d).

Figures. 2 and 3 show the schematic diagram of the experimental setup. The test rig built for this test was basically a normal connection between LPG gas tank and a burner venturi tube. A wet gas flowmeter is used to measure the volume of gas flow rate. Also, a pressure regulator with a calibrated pressure gauge is used to indicate the pressure and providing the fuel to the burner at 30 mbar. The suction throat for natural aeration is found at the burner inlet.



(a). Benchmarking (Radial burner)

(b). Burner I (produced by co swirling flow in both outer and inner rings with the same swirl angle 25°)



(c). Burner II (producing two opposite direction from inner and outer ring with the same swirl angle 25°)

(d). Star pattern burner III (with opposite direction of flow jets in the outer rings for each two jets while the inner ring has a 25° swirl flow angle)

Figure 1. Schematic design for the burner with the different angles for indicating the design configuration.

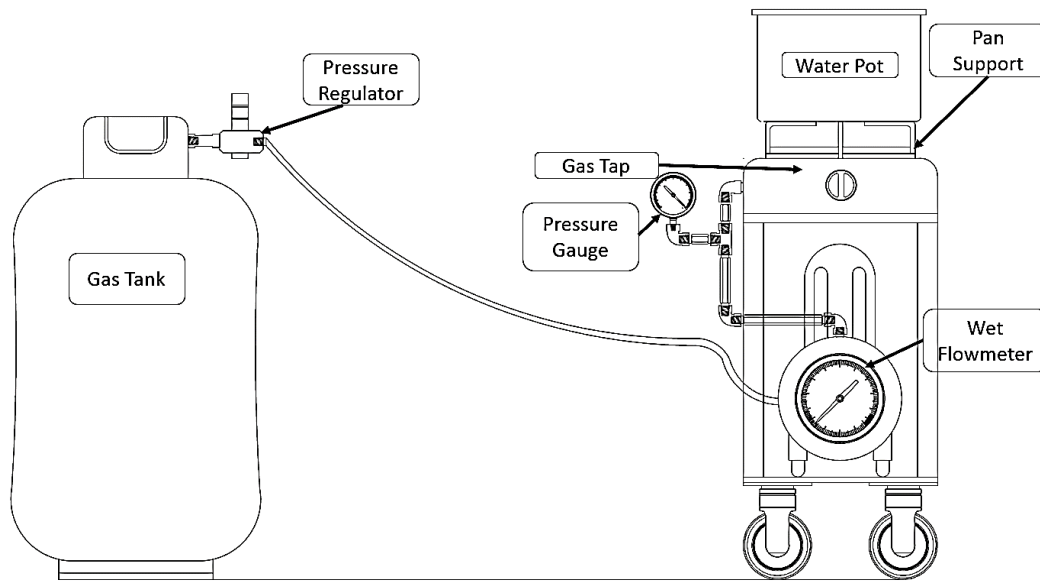


Figure 2. Schematic Drawing for the test rig



Figure 3. Picture for the test rig

The produced flame appearance from these burners was obtained, using a digital camera with imaging rate 60 frames per second, and 32 Megapixels. The position of the camera relative to the flame appearance was fixed in order to keep the size of the produced images the same. All burners were connected to a custom-built test 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. 4 and 5.

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. The sampling tube located away from the loading vessel edge and from the pot bottom according to the International Standard EN 30-2-1/2015 [24, 25].

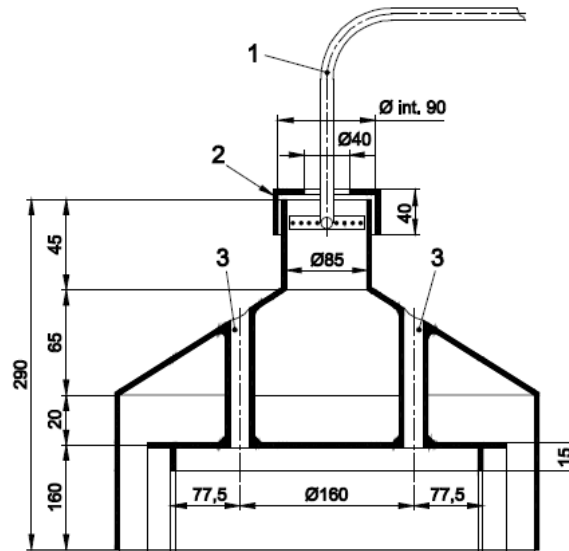


Figure 4. Flue Gas Collector Hood



Figure 5. Picture of the hood used with the IR gas analyzer

The averaged three times measurements reading was conducted, concluded and used to calculate the uncertainty according to Kline and McClintock [25] method.

The fuel flow rate measurement has a repeatability of 0.15% of its full scale and 0.24% accuracy. The error was $\pm 0.30^\circ\text{C}$. For the water temperature. Also, the maximum uncertainties and minimum uncertainties for CO are 9.5 % to 2.1 %, respectively.

3. Thermal efficiency calculation and combustion emissions

Three different burners design were tested at different air to fuel ratio (A/F), pan height and burner power to indicate their effect on 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 equation

$$EE_{gas\ burner} = \frac{E_{theoric}}{E_{gas\ burner}} \quad (1)$$

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

$$E_{gas\ burner} = V_c \times H_s \quad (3)$$

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

$$V_c = V_{mes} \times \frac{p_a + p - p_w}{1013.15} \times \frac{288.15}{273.15 + t_g} \quad (5)$$

where;

EE_{gas burner} : energy efficiency of a gas burner in % and rounded to the first decimal place;

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 heat 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-30 European 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:

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

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

(CO₂)_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

(CO₂)_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 = 0.166, 0.183 and 0.2 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 12 cm in diameter.

As a result, three values of Reynolds number were calculated to be 1508, 1800 and 2040 for A/F ratio 22.24, 23.7 and 25.8 respectively using equation 7.

$$Re = \frac{V \times D}{\nu} \quad (7)$$

where;

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

D: Venture tube diameter (m)

ν : Kinematic viscosity (m²/s) $\approx 1.55 \times 10^{-5}$ m²/s

4. Results and discussions

A comparison between the thermal and emission performance of the four-double ring domestic burner designs is presented in this research. The influence of the Re on burner thermal efficiency and CO % are investigated at different pan heights for the three new double ring burner designs compared with the benchmark one.

4.1. Effect of Reynolds number, Re:

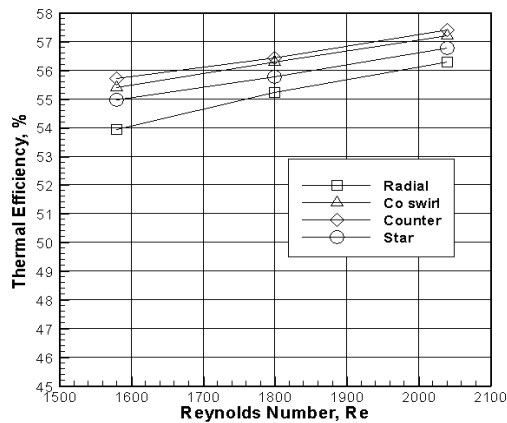
Figure 6 (a, c and e) represents the variation of the thermal efficiency versus Reynolds number for all burners used in this investigation at different H/d 0.166, 0.183 and 0.2 respectively. While Figs 6(b, d and f) represent the variation of the CO % versus Reynolds number for all burners used in this investigation at different H/d 0.166, 0.183 and 0.2 respectively. From Figs. 6 (a, c, and e), 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, counter swirl double ring burner exhibited the greatest thermal efficiency among the other three cookers for all values of Re and H/d as shown in Figs. 6 (a, c, and e). For example, the highest thermal efficiency at H/d = 0.166 and Re 2040 for the benchmarking cooker was 56.29% and 57.2% for co swirl burner while it was 57.4% and 56.67% for the counter swirl and star burner respectively as shown in Figure 6(a).

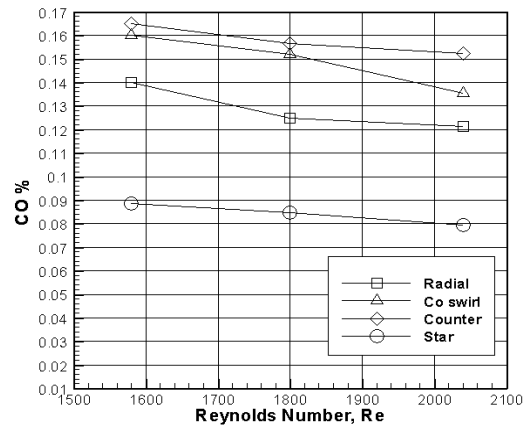
In general, using swirling flow in the cookers achieve higher thermal efficiency than radial benchmark at all Reynolds numbers due to high jet momentum and shearing effect between jets which enhance the mixing between the fuel and air, as a result, complete combustion will occur.

Furthermore, comparing between the other three burners designs at all values of Reynolds number reveals that the counter swirl cooker producing highest thermal efficiency reaching 57.4%, followed by co swirl cooker with 57.2% then the star pattern cooker 56.76%. For more explanation, flame photos were taken at Re = 1850 for all burner cookers used in this investigation as shown in figure 7.

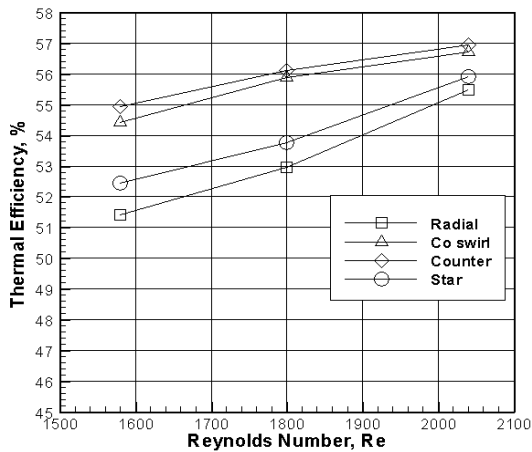
Further Fig. 6(b) shows that, at the same values of H/d = 0.166, burner II emits higher CO emissions than the other burners followed by burner I. The burners that contained swirling motion in the outer flame ring showed higher emissions because the outer swirl ring forms an enclosed ring with no gaps in between the flame lengths that entraps the inner ring from getting enough secondary air to help complete the combustion for the inner ring.



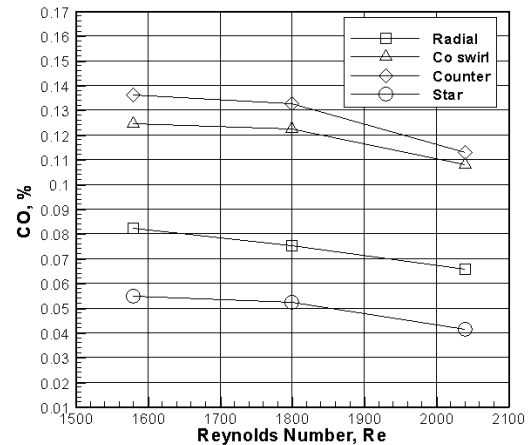
(a) Thermal Efficiency vs. Reynolds number for all cookers at different $H/d = 0.166$



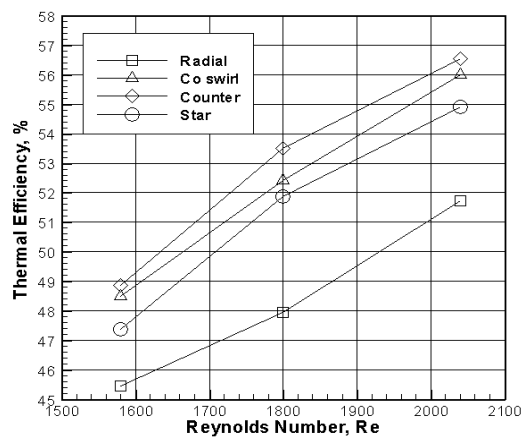
(b) Combustion Emissions vs. Reynolds number for all cookers at different $H/d = 0.166$



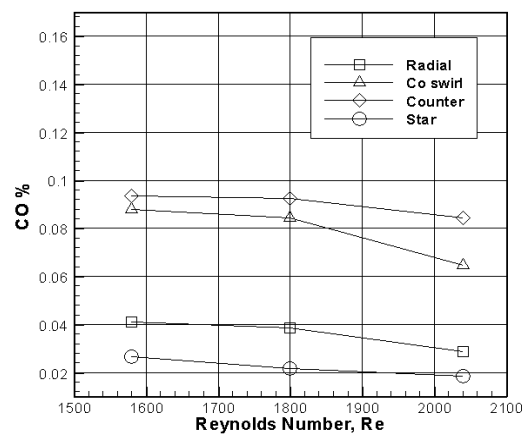
(c) Thermal Efficiency vs. Reynolds number for all cookers at different $H/d = 0.183$



(d) Combustion Emissions vs. Reynolds number for all cookers at different $H/d = 0.183$

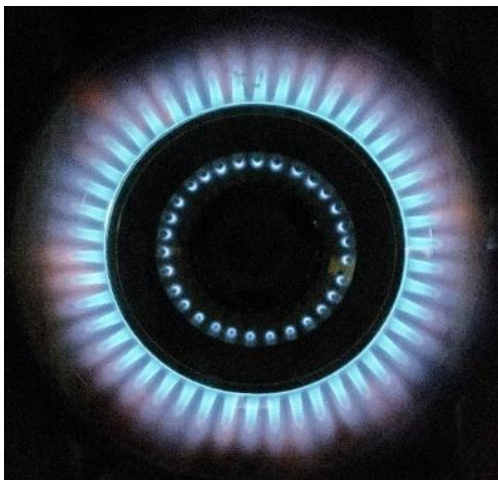


(e) Thermal Efficiency vs. Reynolds number for all cookers at different $H/d = 0.2$

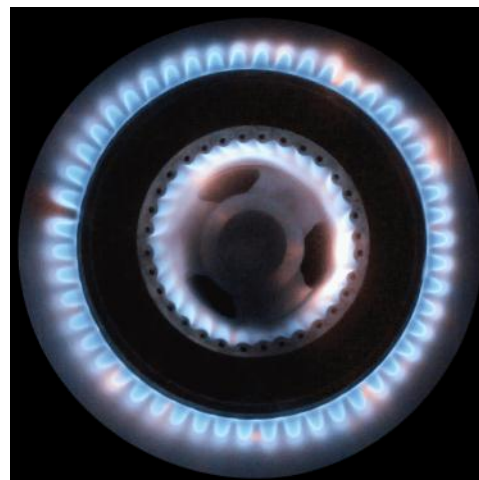


(f) Combustion Emissions vs. Reynolds number for all cookers at different $H/d = 0.2$

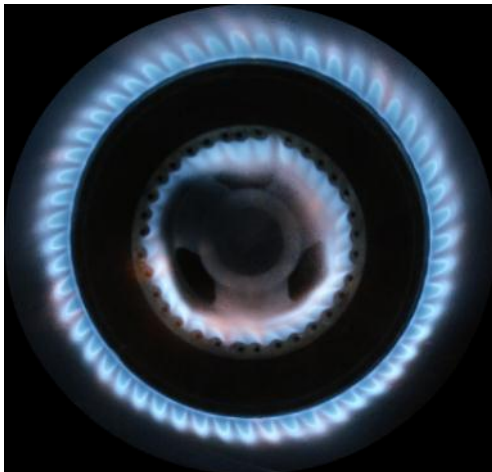
Figure 6. Thermal efficiencies and combustion emissions at constant H/d



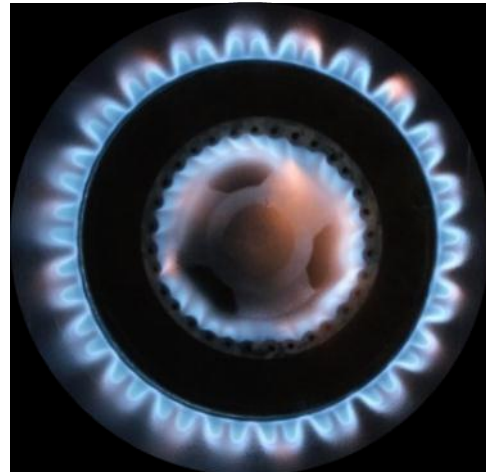
Radial Burner



Co swirl flow burner



Counter swirl flow burner



Star pattern burner

Figure 7. Flame shapes at $Re = 1500$ for all burners

The high intensity of swirl produced by burner II gave higher CO%, due to the opposite directions for the flows compared with burners I, III and the benchmark one generates lower emission out of the other design. In general swirling burners I and II produce higher CO emissions than the Star one (burner III) by more than 40% difference, this is because burner III allows more air to reach the inner ring of the burner, as in this case the residence time extended along with good mixing and also in addition the coefficient of heat transfer between the flame and the pot increases, as a result a complete combustion will take place with lower CO% for example at $Re = 2040$ emissions were about 0.07% while the counter swirl and co swirl flow burners were 0.15% and 0.13% respectively, which is almost half the emissions. The same conclusion was found at H/d 0.183 and 0.2 as shown in Figs. 6 (d and f). Also, for benchmark cooker, as shown in Fig 7(a) the flame produced from the inner ring was short compared with the other three burners which decrease the entrainment between the flow gases and the surrounding air while in the outer ring is long with radial appearance. The flame torches in both inner and outer rings are normal to the burner tip as shown in Fig 7(a).

In case of same and opposite direction swirl rings, the inner flame was long blue color flame with a reddish appearance at its ends and the produced flame seems to rotate with an inclined angle relative to the ring tip as shown in Figs 7 (b and c).

In Fig. 7(d) the produced flame from the outer counter jets ring is long and look like a star. In this burner, each two-opposite jets are very close and almost form two contact torches with a high shearing effect which increase momentum and consequently the mixing between the fuel and air.

As a conclusion for Burner I the co swirl flow showed an improvement in the efficiency by 1.7% more than the benchmarked burner, but a slight deterioration in the combustion emissions at the same H/d and same Re of almost 8% higher emissions.

For burner II counter swirl flow showed even higher efficiency than of burner I with 2.1% improvement in the thermal efficiency of the radial benchmark, as a result of the intensive swirling action between the outer and the inner ring of the burner, the CO emissions were even higher for the same reason that improved the efficiency reaching about 25% higher emissions than the reference burner.

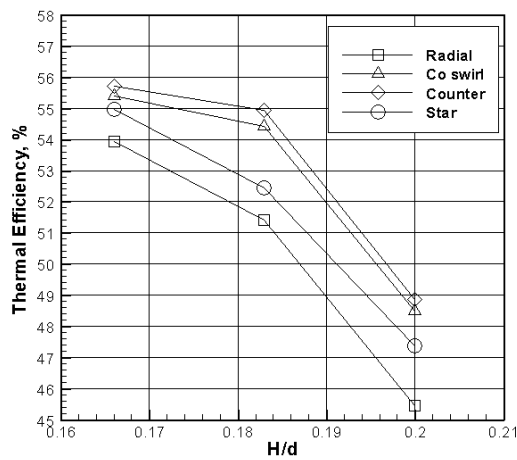
For burner III inner swirl flow with star pattern on the outer ring showed lower efficiency by 1% than burners I and II, but with a better enhancement in the emissions due to the fact the star pattern allows more air to reach the inner ring of the burner to enhance completing the combustion, the enhancement was 33% better than reference burner.

4.2. Effects of the pot height:

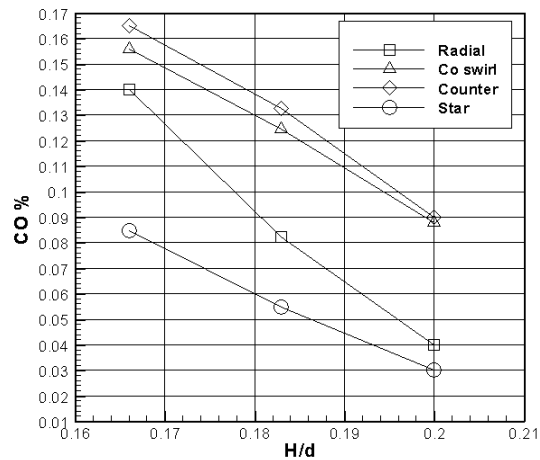
The mixing between the air and fuel resulting from the design of the swirling burner of I, II and III extended the combustion residence time and the coefficient of heat transfer between the vessel and the flame increased.

The variations of both CO % and the thermal efficiency for all burners and the vessel height at $Re = 2040$ 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 $H/d = 0.166$ The maximum thermal efficiency was observed, as shown in Fig. 8(a). As the pot bottom height increased, the combustion produces tends to have a less chance of interacting with the vessel bottom at the highest pot height and Re 2040 benchmarking and burners I, II, III emitted the following CO emission percentages 0.02%, 0.064%, 0.084%, and 0.018% see Fig. 8(f), and combustion gases also tend to be cooled due to mixing before contacting the vessel with the ambient air which decreased the heat transferred to the vessel and as a result, decreasing the thermal efficiency.

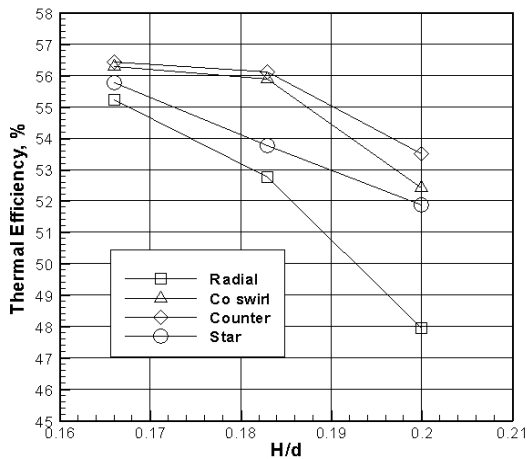
On the other hand, decreasing the pot height, increased the flame impingement with the vessel which increases the contact surface between the flames and the vessel and consequently increasing the thermal efficiency for all burners for example at H/d 0.166, 0.183 and 0.2 for the star pattern burner efficiencies were 56.76%, 55.91% and 54.9% as shown in Fig. 8(e).



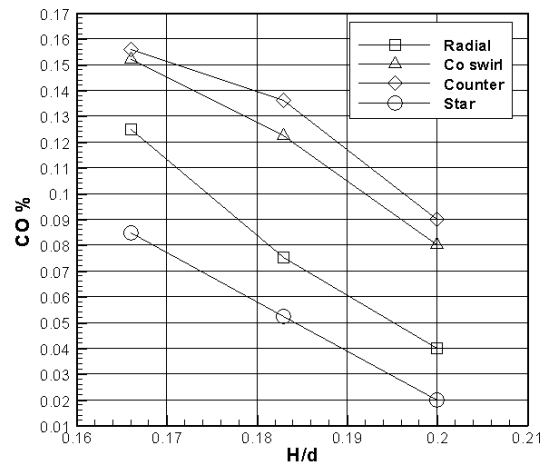
(a). Chart for thermal efficiencies of four double ring burner types at Re 1580



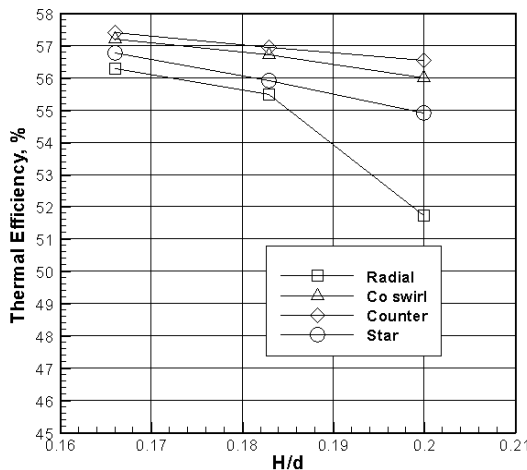
(b). Chart for combustion emissions of four double ring burner types Re 1580



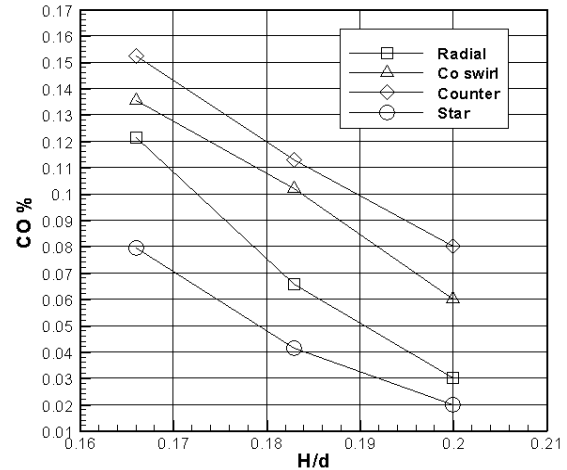
(c). Chart for thermal efficiencies of four double ring burner types at Re 1800



(d). Chart for combustion emissions of four double ring burner types Re 1800



(e). Chart for thermal efficiencies of four double ring burner types at Re 2040



(f). Chart for combustion emissions of four double ring burner types Re 2040

Figure 8. Thermal efficiencies and combustion emissions at constant Re

5. Conclusion

From the thermal efficiency prospective, the Counter swirl burner gave the highest thermal efficiency reaching almost 57.4% followed by the Co swirl burner 56.94% and the Star pattern burner 56.72% then the radial burner 56.29%. This means that the swirling motion improves the efficiency of the domestic burners as it is increasing the residence time. The swirl motion shows its high performance at the state when developing a counter swirl between the inner ring and the outer ring. This is because the inner swirl tends to create an intensive counter swirling action to the outer ring enabling more heat to be transferred to the heated load.

Regarding the combustion emissions (CO %), all burners that contained the swirling motion gave higher emissions as follows Radial burner 0.12%, Co Swirl 0.13%, Counter swirl 0.15% and star pattern was the lowest with 0.07% of CO emissions. This is due to two reasons: first the long time of the flames being in contact with pan bottom leads to the quenching which results in a higher rate of CO% in flue gases from the combustion, secondly the burners with swirl in the outer ring created a flame shield around the inner ring resulting in lowering the secondary air rate from reaching the inner flame ring which increased the rate of unburnt fuel, this down point was not apparent in the Star pattern burner as it allows a sufficient amount of air to pass the and reach the center which reduced evidently the combustion emissions relative to the other burner designs.

As a conclusion, to have as a compromise for enhanced efficiency and lowered combustion emissions the Star patterned double ring burner would be promising to study more.

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