

## The Effect of Products Cooling on the Pollutants Emission from a Continuous Combustion Chamber

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### ABSTRACT

This paper presents the effect of products cooling on the pollutants emission of (carbon monoxide [CO], unburned hydrocarbon [UHC], nitrogen oxide [NO<sub>x</sub>], and Soot) from a continuous combustion chamber. Products cooling technique was accomplished by installing heat exchanger in the way of the exhaust gases. The water flow rate through heat exchanger was varied from 0 to 30 liters per minute with 10 liters per minute increment. With a droplet size of 80 μm for gas oil fuel and kerosene fuel, and local equivalence ratio was varied from 0.8 to 1.4. When using the products cooling technique it was found that the NO<sub>x</sub> is inversely proportional with increasing the water flow rate through heat exchanger with the maximum decrease in NO<sub>x</sub> emissions of 18.76%. But , CO , UHC and soot are directly proportional to increasing the water flow rate through heat exchanger as the maximum increase in CO , UHC and soot were (27.43%,26.32%,19.87%) respectively .also found the emissions from gas oil fuel more than kerosene fuel .

**Keyword:** Products Cooling, Pollution, Emissions, Continuous Combustion Chamber.

### تأثير تبريد نواتج الاحتراق على انبعاث الملوثات من مسجرة احتراق ثابتة الضغط

#### الخلاصة

تم أنجاز دراسة عملية حول تأثير تبريد نواتج الاحتراق على انبعاث الملوثات احادي اوكسيد الكربون (CO)، الوقود الغير محترق(UHC)،اكاسيد النيتروجين(NO<sub>x</sub>) بالإضافة الى السخام من حجرة الاحتراق المستمر. عملية تبريد النواتج تمت بوضع مبادل حراري في طريق غازات العادم. تدفق الماء عبر المبادل الحراري تم تغييره من 0 الى 30 لتر في الدقيقة بزيادة مقدارها 10 لتر في الدقيقة في كل مرة , قطر قطيرات الوقود 80 مايكرومتر عند استخدام زيت الغاز و الكيروسين كوقود وذلك بزيادة ضغط التدفئة وكذلك النسبة المكافئة المحلية قد تراوحت بين 0.8 الى 1.4.

عند استخدام تقنية تبريد نواتج الاحتراق وجد أن NO<sub>x</sub> يتناسب عكسيا مع زيادة تدفق الماء من خلال المبادل الحراري وأن الحد الأقصى في خفض انبعاثات NO<sub>x</sub> هو 18.76٪. في المقابل، CO، UHC والسخام ويتناسب طرديا مع زيادة معدل تدفق الماء خلال المبادل الحراري وأن أقصى زيادة في CO، UHC والسخام هي (27.43٪، 26.32٪، 19.87٪). ووجد أن الانبعاثات من زيت الغاز تكون أكثر من الانبعاثات الناتجة عن وقود الكيروسين.

## INTRODUCTION

Fossil fuels are the main source of energy for domestic power generation while the other energy sources, such as solar energy, wind energy and nuclear energy still represent less than 20 percent of total energy consumption. Therefore, combustion of fossil fuels is being humanity's oldest technology. This remains a key technology for today and the foreseeable future. It is well known that combustion not only generates heat, which can be converted into power, but also produces pollutants, such as soot, carbon monoxide (CO), and Unburned hydrocarbon (UHC).

The effort is now focusing on studying the key parameters and technique which can reduce the concentration levels of pollutant in exhaust gases. The main parameters expected to influence these emissions are fuel droplets size, equivalence ratio, products cooling and fuel type<sup>[1]</sup>.

Joanne M. and Williams<sup>[2]</sup> studied the effect of water cooled, premixed burner soot deposition from two rich ethylene/air flames ( $\phi=2.52$  and  $\phi=2.76$ ). The rates of soot deposition from both uncooled stainless steel plate and a cooled copper plate were used to support stainless steel and copper sample square plates, respectively within the flame. It was found that using a cooled copper plate increases the soot accumulation at the outer surface of the cooled copper plate but when using uncooled stainless steel plate, the soot emission will be less than in the case of using cooled copper plate.

Mohammad Nazri Mohd. Jaafar et.al.<sup>[3]</sup> Investigated the effect of products cooling on the gaseous fuel burner by placing heat exchanger in flue gases stream to cool the products. The products cooling process increases the CO and UHC emission but reduces the NO<sub>x</sub> emission due to reducing the residence time and quenching the flame. This study was accomplished at a different equivalence ratio and constant pressure drop across the heat exchanger.

Mohammad Nazri Mohd. Jaafar et.al.<sup>[4]</sup> studied the effect of products cooling on a continuous combustion combustor operating by gaseous fuel at different pressure losses. This study was accomplished by placing the heat exchanger in the flue gas stream to exchange heat between the flue gases and heat exchanger. The cooling medium used in the heat exchanger was water. The products cooling process at the different pressure losses caused flame quenching and reduced the residence time. In this situation, the amount of UHC emission and CO emission was increased, but the amount of (NO<sub>x</sub>) emission was decreased due to the lower combustion temperature resulted from decreasing the residence time and heat exchanger cooling effect. Also, it was found that the increase in the pressure drop in continuous combustion combustor will increase the reduction in (NO<sub>x</sub>) emission and increase other pollutants emission so that the level of fuel consumption in burner will be increased. This study was accomplished at different equivalence ratios and pressure drop across the heat exchanger.

### Experimental work:

Figure (1) shows the rig that is completely manufactured and used in this study. The liquid fuel is stored in fuel tank and forced in fuel injection system by compressed air, which is supplied by reciprocating compressor. The compressed air is also used to atomize the liquid fuel in order to generate very small size droplets. The liquid fuel is directly sprayed into combustion chamber via the four-point air blast atomizer and measured by using liquid flow meter. The main air flow from the blower is forced through nine holes surround the atomizer as shown in figure (2) and measured by using differential pressure method (orifice plate). The test rig include heat exchanger which can reduce the temperature of the exhaust gases, the circulated medium in heat exchanger is water the flow in heat exchanger varied from 0 to 30 liters per minute in 10 liter per minute increment, the heat exchanger include thermocouple type [k] that connected to digital thermometer and selector switch is used to observe the temperature when reached the steady state reading through the experiment to start collecting the gas analyzer and smoke meter readings. The size of fuel droplets in the spray can be reduced by increasing the atomization pressure of air supplied to the air blast. The amount of air used in atomization is measured by

using air flow meter, and its pressure measured by Borden gauge. The fuel droplets size can be measured by using light source, lenses, and camera as shown in figure (3). The measuring of the droplet sizes is achieved by rapid photographing of group droplets shown in figure (4). The rapid photographing was done by a high speed camera type power shot from G5 Canon Digital Camera. The exposure time of the camera ranges from 15 to 1/2000 s. The size of the droplets was magnified by using lenses fixed to the camera. The group of the droplets was lighted by the high intensity light source. The two flashers work only during the short period of time needed to photograph. The picture is obtained and the diameters of the droplets found in the picture are measured by comparing with the diameter of the wire that is also found in the same picture as it is indicated by camera. From knowing the amount of air and fuel which participated in combustion process may be calculated equivalence ratio as show in appendix (A). A small (10 mm base diameter) air-LPG pilot flame which is continuously sustained, and serves as an igniter source for the main fuel-air spray mixture. Carbon monoxide, nitrogen oxide and unburned hydrocarbon emissions are measured by using exhaust gas analyzer as show in figure (5-A), while soot emission is measured by using smoke –meter as show in figure (5-B).

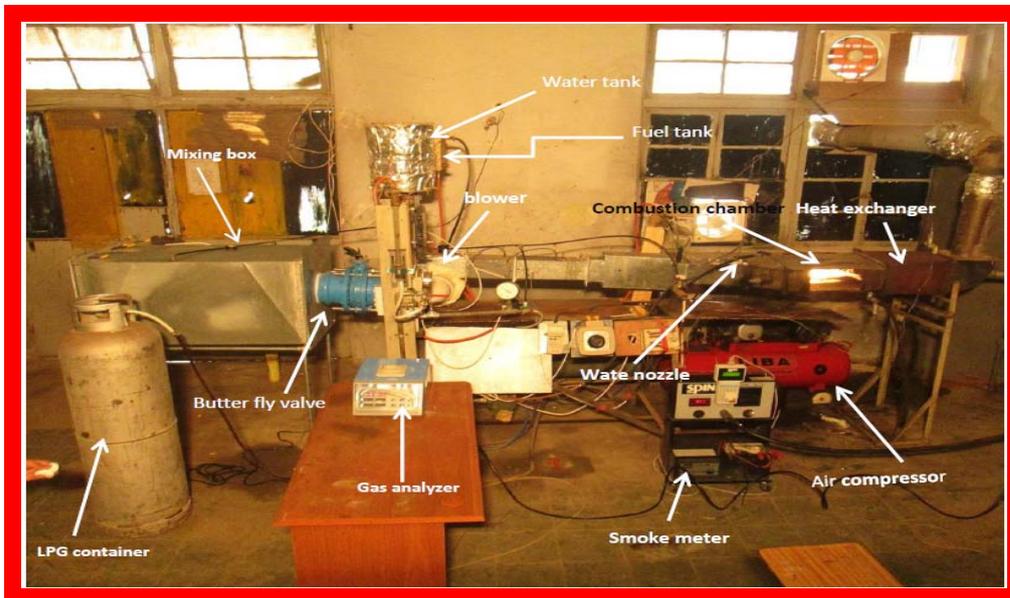


Figure (1): the test rig.

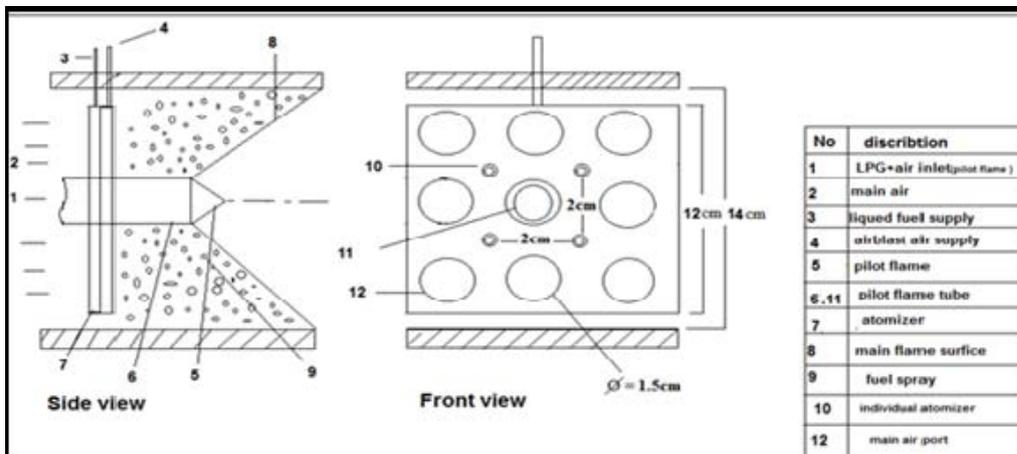


Figure (2): Schematic diagram of flame holder.

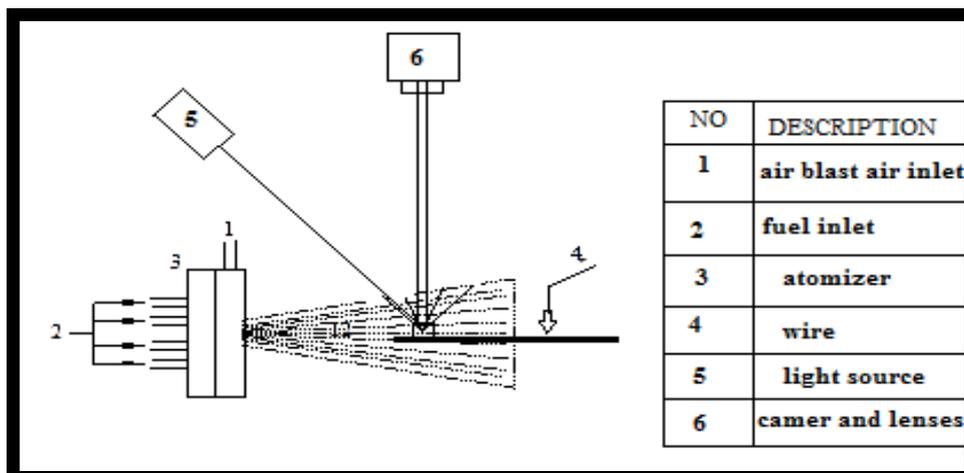


Figure (3): Droplet size measurement system.



Figure (4): Measurement of droplet diameter comparing with wire diameter

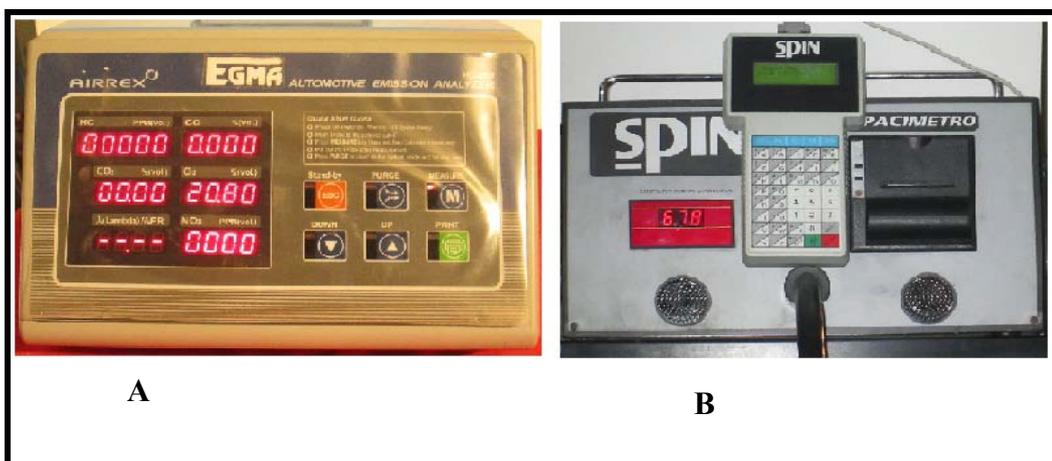


Figure (5): Gas analyser and smoke meter devices.

**Results and Discussion:**

Experiments were conducted on two types of liquid fuels namely, gas oil and kerosene. The effect of products cooling, fuel droplets size and equivalence ratio on pollution emissions and graphically shown here under.

**Products cooling**

Products cooling are accomplished via placing heat exchanger at particular distance from the flame this arrangement lead to flame cooling and reducing the combustion temperature, as well as, the residence time. The CO, UHC and soot emissions are increased but the level of NO<sub>x</sub> decreased due to the reduction in the combustion temperature [4, 3, and 2].

Figure (6) and figure (7) shows that for gas oil fuel when increasing the amount of water flow through the heat exchanger from 0 to 30 L/min, the corresponding increases in CO and UHC emissions are (21.875%,21.36%) respectively, at  $\Phi=1$  and fuel droplet size 80  $\mu\text{m}$ . This behavior of CO and UHC attributed to that the products cooling causes flame cooling and reducing the residence time [3, 4].

For gas oil fuel, figure (8) manifests the inverse proportionality of NO<sub>x</sub> emissions with increasing the amount of water flow rate through the heat exchanger. When increasing the amount of water flow rate through the heat exchanger from 0 to 30 L/min, the decrease in NO<sub>x</sub> emissions is (7.89%) at  $\Phi=1$  and fuel droplet size 80 $\mu\text{m}$ . This behavior of attributed to the products cooling which causes a reduction in flame temperature and residence time [3, 4].

For gas oil fuel, figure (9) manifests the inverse proportionality of soot emissions with increasing the amount of water flow rate through the heat exchanger. When increasing the amount of water flow rate through the heat exchanger from 0 to 30 L/min, the increase in soot emissions is (15.22%) at  $\Phi=1$  and fuel droplet size 80 $\mu\text{m}$ . This behavior attributed to that the products cooling that reduced the residence time which lead to uncompleted combustion so that the soot emissions will increase [2].

**Kerosene fuel and gas oil fuel comparison:**

Figure(10) and Figure(11) show that when increasing the amount of water flow inside the heat exchanger from 0 to 30 L/min, the corresponding increases in CO and UHC emissions increase are (25.96%,23.49%)respectively, at  $\Phi=1.15$  and fuel droplet size 80 $\mu\text{m}$  for gas oil fuel. But, for kerosene fuel the increasing in CO and UHC emissions are (25.33%,21.42%) respectively.

Figure(12) shows that when increasing the amount of water flow inside the heat exchanger from 0 to 30 L/min, the corresponding decrease in NO<sub>x</sub> emission is (10.81%), at  $\Phi=1.15$  and fuel droplet size 80  $\mu\text{m}$ , for gas oil fuel. But, for kerosene fuel the decrease in NO<sub>x</sub> emissions is (9.88%). Figure(13) shows that when increasing the amount of water flow inside the heat exchanger from 0 to 30 L/min, the corresponding increase in soot emission is (15.21%), at  $\Phi=1.15$  and fuel droplet size 80  $\mu\text{m}$ , for gas oil fuel. But, for kerosene fuel the increasing in soot emissions is (14.25%).

Figures (10) - (13) show that CO, UHC, NO<sub>x</sub> and soot result from kerosene fuel is lower than those obtained from gas oil fuel due to different fuel properties that influence CO, UHC, NO<sub>x</sub> and soot production in the manner described below:

**1. Viscosity and surface tension:**

Viscosity is an oil resistance to flow. Larger droplet size value for gas oil fuel droplets is due to the influence of higher viscosity and surface tension values compared to kerosene fuel (despite of the difference is slightly with respect to surface tension (as shown in the Appendix (B)), which then affect the evaporation rate, and thus CO, UHC, NO<sub>x</sub> and soot emissions for kerosene fuel are lower than for gas oil fuel.

**2. Volatility:**

Kerosene fuel is more volatile and has lower flash point value (as shown in the Appendix(C)) compared to gas oil fuel, hence, the droplet evaporation occurs in relatively

shorter time scale due to higher dispersion rate and smaller droplet size. Then, this decreases CO, UHC, NO<sub>x</sub> and soot emissions.

**3. Aromatic content:**

Aromatic content in the gas oil fuel is higher than kerosene fuel. Increasing aromatic content increases soot tendency. Thus, soot in gas oil fuel is higher than kerosene fuel.

**CONCLUSIONS**

According to the results obtained through the experiments, it was found that increasing the heat extract rate from the exhaust gases: CO, UHC and soot emissions will be increased. But the NO<sub>x</sub> emissions decrease. The emissions from gas oil generally are more than emissions from kerosene fuel. Increasing aromatic content increases soot, NO<sub>x</sub>, UHC and CO emissions. Decreasing H/C ratio increases soot and NO<sub>x</sub> emissions. Increasing viscosity and surface tension produces more (CO, UHC, NO<sub>x</sub> and soot) emissions.

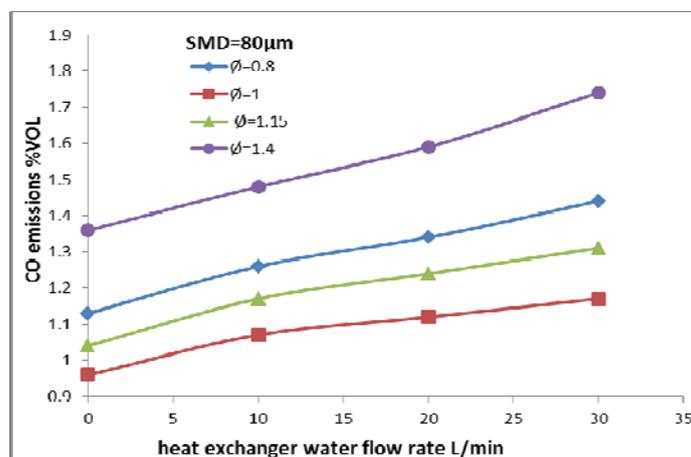


Figure.(6) CO emissions from gas oil fuel versus heat exchanger water flow rate .

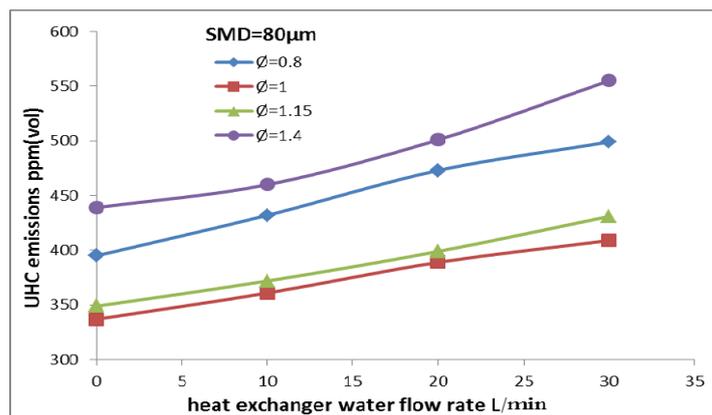
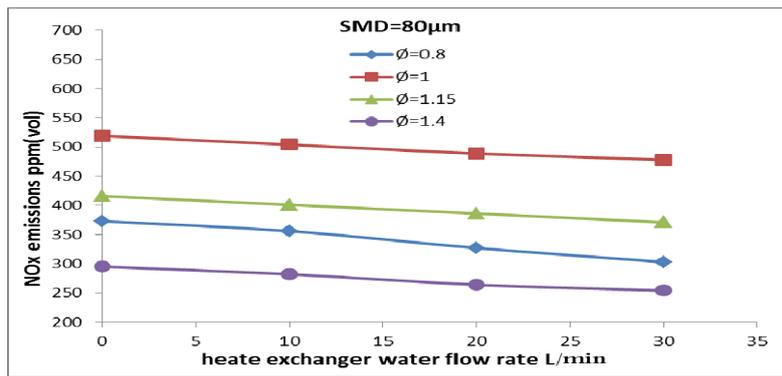
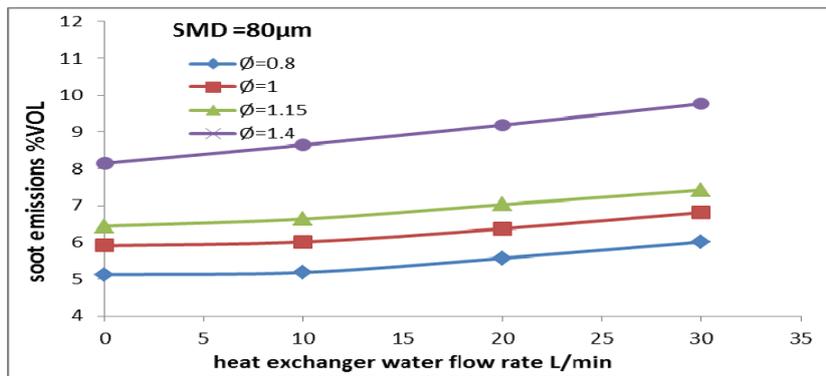


Figure.(7) UHC emissions from gas oil fuel versus heat exchanger water flow rate



Figure(8) NO<sub>x</sub> emissions from gas oil fuel versus heat exchanger water flow rate.



Figure(9) soot emissions from gas oil fuel versus heat exchanger

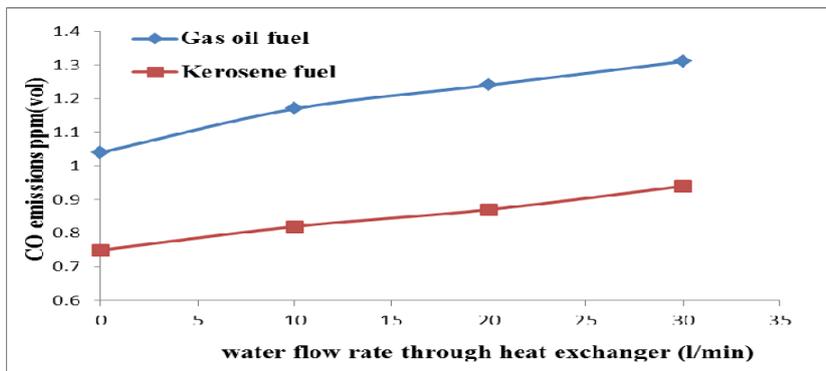


Figure.(10) CO emission versus water flow rate through heat exchanger

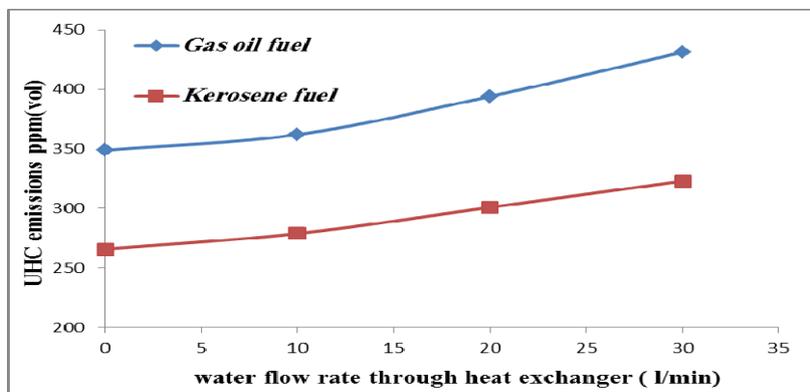


Figure.(11) UHC emission versus water flow rate through heat exchanger .

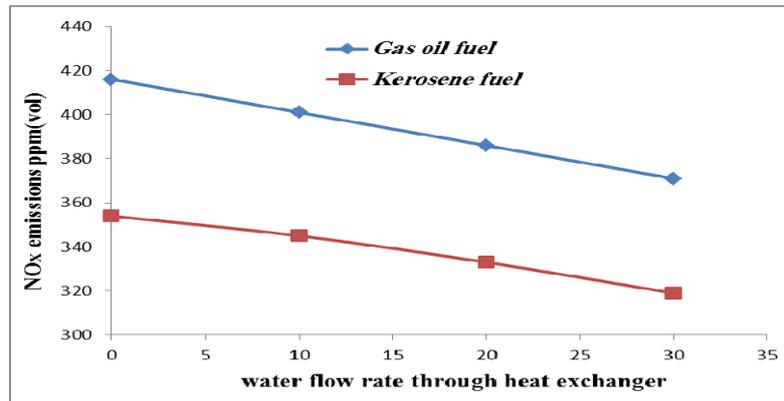


Figure.(12) NO<sub>x</sub> emission versus water flow rate through heat exchanger.

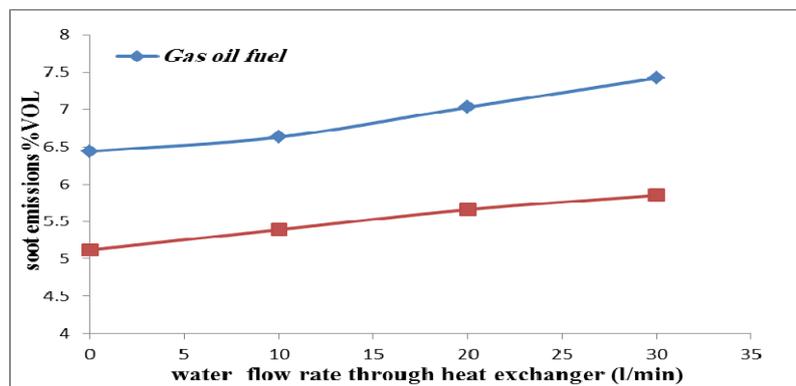


Figure.(13) soot emission versus water flow rate through heat exchanger

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[3]Mohammed Nazri Mohd .Jaafar, G.E. Andrews and M.C.Mkpadi, 'NO<sub>x</sub> emission reduction from gas burner system applying water cooling technique', Departement of Aeronautics and Automotive Mechanical Engineering Faculty University Technology Malaysia 81310 UTM Skudai and JOHOR MALAYSIA, Departement of Fuel and Energy University of Leeds, LS2 9JT, Engeland, 2000.

**Appendix(A)**

:Procedure of calculation of the equivalence ratio for gas oil and kerosene fuels

**1. A- Calculation of theoretical A/F for gas oil fuel.**

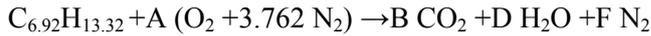


- Balance for carbon  
Hence, B=9.12
- Balance for hydrogen  
Hence, D=8.425

- Balance for oxygen  
Hence, A=13.3325
- Balance for N<sub>2</sub>  
Hence ,F=50.15

$$(A/F)_{stloch} = \frac{13.3325(32 + 3.762 * 28)}{12 * 9.12 + 16.85} = 14.4986$$

**B- Calculation of theoretical A/F for kerosene fuel.**



- Balance for carbon  
Hence, B=6.92
- Balance for hydrogen  
Hence, D =6.66
- Balance for oxygen  
Hence, A =6.92+3.33=10.25
- Balance for N<sub>2</sub>  
Hence, F=38.56

$$(A/F)_{stloch} = \frac{10.25(32+3.762*28)}{6.92*12+13.32*1} = 14.60$$

**1. Calculation of the amount of the main air :**

The amount of the main air is calculated from the following equation:

$$V = K\sqrt{h}$$

Where:

K=constant =  $21 \times 10^{-3}$ , and h=monometer reading in mmH<sub>2</sub>O

$$\text{At } h = 0.3 \text{ mm H}_2\text{O} \rightarrow V = 21 \times 10^{-3} \times \sqrt{0.3} = 0.0115 \frac{m^3}{sec}$$

Either with respect to the mass of air

$$m = \rho \times V$$

$$\text{At main air} = 0.3 \text{ mmH}_2\text{O} \rightarrow m = 1.19 \times 0.0115 = 0.013685 \frac{kg}{sec}$$

**2. Calculation of air which used in atomization:**

$$\text{At scale flow meter} = 1 \rightarrow m_{ab} = 1.19 \times 4 \times \frac{10^{-3}}{60} = 7.93 \times 10^{-5} \frac{kg}{sec}$$

**The table of the ratio of atomization air to the main air:**

Atomization air				
Main air		$7.93 \times 10^{-5}$	$1.19 \times 10^{-4}$	$1.58 \times 10^{-4}$
	0.013685	$5.8 \times 10^{-3}$	$8.695 \times 10^{-3}$	0.0116
	0.01666	$4.7599 \times 10^{-3}$	$7.14 \times 10^{-3}$	$9.53 \times 10^{-3}$
	0.019278	$4.11 \times 10^{-3}$	$6.172 \times 10^{-3}$	$8.24 \times 10^{-3}$

The maximum ratio of air used in the atomization to the main air is

$$\text{Air ratio} = \frac{1.985 \times 10^{-4}}{0.013685} = 0.0145$$

Hence, the air used in the atomization may be neglected

**3. Calculation of the amount of gas oil fuel :**

$$m_f = \rho \times V_f$$

$$\text{At fuel scale} = 2 \rightarrow m_f = 840 \times 0.042 \times 10^{-3} \times \frac{1}{60} = 5.8 \times 10^{-4} \frac{\text{kg}}{\text{sec}}$$

**4. Calculation the amount of kerosene fuel :**

$$m_f = \rho \times V_f$$

$$\text{At fuel scale} = 2 \rightarrow m_f = 800 \times 0.04 \times 0.001 \times \frac{1}{60} = 5.333 \times 10^{-4} \frac{\text{kg}}{\text{sec}}$$

**5. Calculation of equivalences ratio:**

$$\Phi_v = \frac{(A/F)_{stloch}}{A/F)_{actual}}$$

**A- Calculation of equivalence ratio for gas oil fuel :**

At  $m_f = 5.8 \times 10^{-4} \text{ kg/sec}$  and  $m_{air} = 0.013685 \text{ kg/sec}$

$$\Phi_v = \frac{14.4986}{\frac{0.013685}{5.8 \times 10^{-4}}} = 0.6144$$

$$\Phi = 1.9214 \times \Phi_v = 1.9214 \times 0.6144 \approx 0.79$$

**B- Calculation of equivalence ratio for kerosene fuel :**

At  $m_f = 5.333 \times 10^{-4} \text{ kg/sec}$  and  $m_{air} = 0.013685 \text{ kg/sec}$

$$\Phi_v = \frac{14.608}{\frac{0.013685}{5.333 \times 10^{-4}}} = 0.5675$$

$$\Phi = 1.9214 \times \Phi_v = 1.9214 \times 0.5675 \approx 1.0904$$

**Appendix (B)**

Properties of the fuels used in this study (marketing specification of Iraqi petroleum products and Al Dora Refinery).

Fuel properties	Fuel type Gas oil	Kerosene
Equivalent Chemical formula	C <sub>9,12</sub> H <sub>16,85</sub>	C <sub>6,92</sub> H <sub>13,32</sub>
Surface tension (σ) kg/s <sup>2</sup>	0.0267	0.026
H/C ratio	1.84	1.92
Specific gravity @15.4°C(max)	0.85	0.801
Flash point (abel) °C (min)	54	38
Viscosity Cst @40°C (max)	5.6	-
Calorific value Kcal/kg (gross)EST	10800	10900
Nitrogen content	-	-
Sulphur content	1%W(max)	0.2%V(max)