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Emissions of Local Heavy Fuel Oils

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Abstract: This work aims to measure the emission level of local heavy fuel oils used in boilers and furnaces. Two types of fuel oil are commonly used in the Sudan. These are heavy fuel oil (HFO) produced in Elobied refinery and heavy coker gas oil (HCGO) of Khartoum refinery. The experimental combustion set up consists of a combustion chamber, a burner, a stack and a forced draught fan. Besides measurement of temperature and concentrations of flue gas emissions (CO_2, H_2O, CO, SO_x, NO_x), combustion air and fuel flow rates were measured. A theoretical combustion model was developed to predict the combustion performance. The model employs material balance, energy balance and reaction kinetics. It was used to validate the experimental results. The elemental analysis of fuel oils revealed that they have low sulfur content. It was also found that HCGO has high concentrations of heavy metals (Fe, V, Ni, Ca, Zn). The rheological test revealed that HFO has a non-Newtonian behavior and high atomizing temperature. The combustion performance parameters of air fuel ratio, excess air, emissions were evaluated. The results revealed significant emissions of CO and NO_x in particular at low fuel air ratio ($\gamma<1.1$). The lowest emission level is found to be at 15 to 20 % excess air.

Keywords: *Combustion, heavy coker gas oil, NOx emission, CO emission*

1. INTRODUCTION

Two major categories of fuel oil burned in thermal power systems are distillate oils and residual oils. Distillate oils include kerosene and diesel fuels. They are more volatile and less viscous than residual oils. They have negligible nitrogen and ash contents and usually contain less than 0.3 percentage sulfur (by weight). Distillate oils are used mainly in domestic and small commercial applications. Residual oil is sometimes referred to as furnace or heavy fuel oil (HFO) or Bunker C or No. 6 fuel oil. Residual oil is more viscous and less volatile than distillate oil. Because residual oils are produced from the residue remaining after the lighter fractions have been removed from the crude oil, they contain significant quantities of ash, nitrogen, and sulfur. Residual oils are used in process steam and power production [1-3].

Pollutants or emissions of fuel oil include CO, NO, NO_2, NO_x, SO_2, SO_x and particulate matter (PM) such as soot [4-6]. The pollutants emit when the combustion is incomplete. Combustion is said complete if all carbon in the fuel burns to CO_2, all hydrogen burns to H_2O and all sulfur (if any) burns to SO_2. Conversely, combustion is incomplete if the combustion products contain any unburned fuel or components such as C, H_2, CO, OH. Insufficient oxygen is considered as the main reason of incomplete combustion. Combustion of lighter distillate oils results in significantly lower PM formation than does combustion of heavier residual oils. Other reasons include insufficient mixing and dissociation. The latter occurs at high temperatures. The magnitude of these emissions depends, in addition to incomplete combustion, on many factors such as (1) the grade and composition of the fuel (2) the type and size of the fire equipment (boiler) (3) the firing and loading practices used (4) equipment maintenance practice and management. With increasing environmental awareness and concern a number of controlling measures and technologies have been developed to minimize emissions from fuel oil. These equipment are called “add-on air pollution control” (APC) equipment [5].

The total thermal power generated in the Sudan is about 400 MW. There are mainly two brands of fuel oils used. These are heavy oils produced from local refineries (Elobied refinery and Khartoum refineries). HFO of Elobied is the residue of atmospheric distillation unit while HFO of Khartoum refinery is a product of coke; hereafter called heavy coker gas oil (HCGO). The crude for HFO is Nile blend while for HCGO is Fula blend, both are Sudanese oil brands.

The objective of this work is to determine the emission levels of HFO and HCGO.

2. MATERIALS AND METHODS

2.1 Experimental Setup

Figure 1 shows schematic representation of the experimental setup. Table 1 shows the key of items in Fig. 1. The experimental setup consists of a combustion chamber, a burner, a stack and a force draught fan and electric heater. The setup facilitates the measurements of temperature and concentration flue gas and flow rates and temperatures of air and fuel

2.2 Laboratory Analysis

Samples of HFO and HCGO were analyzed for physical, chemical and elemental properties. Element analysis is meant to analyze the main fuel elements (Carbon C, Hydrogen H_2, Sulfur S, Oxygen O_2, and Nitrogen N_2) and contaminants (Aluminum, Lead, Sodium, Barium, Manganese, Tin, Boron, Molybdenum, Titanium, Chromium, Nickel, Vanadium, Copper, Silicon, Iron, Silver and any other elements). Table 2 shows the analysed parameters and the standard test method used in the analysis. The samples were analyzed in a accredited laboratory. The flue gases concentration of CO_2, CO, O_2, NO, NO_2, NO_x and SO_2 are measured using the flue gas analyzer Model Testo 340.

Table 1. Key for experimental setup

Item	Descriptions
1	Combustion Chamber (0.5 m diameter, 1.5 m height)
2	Firing Set (Burner tip, Draught Fan, Air Control valve)
3	Orifice meter
4	Flue gas sampler duct.
5	Flue gas control valve
6	Chamber drain valve
7	Flue gas duct
8	Electrical fuel oil heater (thermostat controller up to 140 °C)
9	Fuel storage tank
10	fuel recirculation line
11	Fuel pump (up to 20 bar)
12	Fuel pump section line

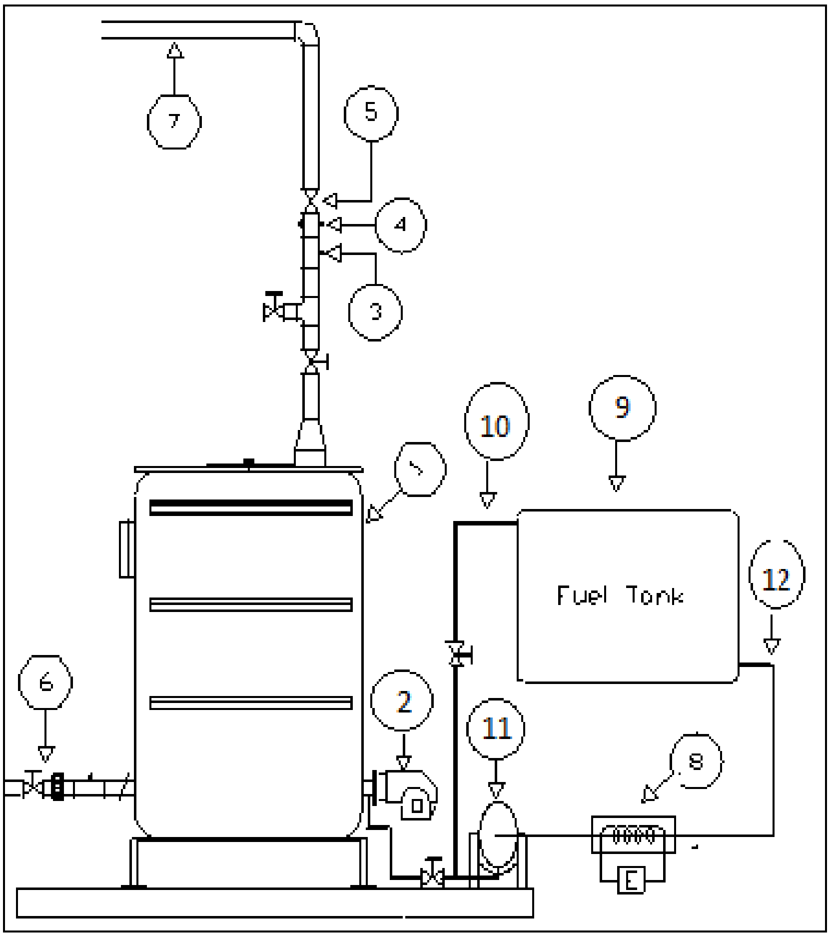

Fig. 1. Experimental setup

Table 2. Standard test methods

Test item		Unit	Method
Flash point		ºC	KS M2010:2004
Kinematic viscosity at 50 C		m^2/s	KS M2014:2004
Pour point		ºC	KS M2010:2004
Carbon residue		wt %	KS M ISO 1037:2006
Water and sediment		wt %	KS M ISO 3734:2003
Ash		wt %	KS M ISO 6245:2003
Sulphur		wt %	KS M ISO 8754:2003
Water		wt %	KS M ISO 9029:2003
Density at 15 °C		g/cm^3	KS M 2002:2001
Fuel Elemental analyser	C	wt %	ASTM 5291
	H	wt %	ASTM 5291
	N	wt %	ASTM 5782
Heat of Combustion		kJ/kg	KS M 2057:2006
Net heat of combustion		kJ/kg	KS M 2057:2006
Contaminants Elemental analyser Al, Pb, Na, Ba, Mg, Sn, B, Mo, Ti, Cr, Ni, V, Cu, Si, Fe, Ag		mg/kg (ppm)	ASTM-D 4951 ICP

3. COMBUSTION MODEL

Combustion is often studied as a complete combustion. For the sake of reminder the definition of complete combustion is repeated again in the following sentences. The combustion is said to be complete if all carbon in the fuel burns to CO_2, all hydrogen burns to H_2O and all sulfur (if any) burns to SO_2. Conversely, the combustion is incomplete if the combustion products contain any unburned fuel or components such as C, H_2, CO, OH. Insufficient oxygen is considered as the main reason of incomplete combustion. Other reasons include insufficient mixing and dissociation. The later occurs at high temperatures.

The minimum amount of air required for complete combustion also called stoichiometric or theoretical air is determined from the following combustion equation:

$$hH_2 + cC + nN_2 + oO_2 + sS + a_{th}\left(O_2 + 3.76N_2\right) \rightarrow xCO_2 + yN_2 + zH_2O + wSO_2 \qquad (1)$$

where, a_{th} is the stoichiometric coefficient for air. The values of the lower case letters h, c, o, s is obtained from elemental analysis directly. The flue gas (CO_2, H_2O and N_2, SO_2) coefficient x, y, z, w and a_{th} are obtained by balancing the coefficient of C, H_2, N_2, O_2 and S of Eq. (1). The fuel air ratio is determined by taking the ratio of the mass of air (m_{air}) to the mass of fuel (m_{fuel}) as:

$$AF = \frac{m_{\text{air}}}{m_{\text{fuel}}} \qquad (2)$$

The ratio of actual mass of air ($m_{air,actual}$) to stoichiometric or theoretical mass of air ($m_{air,\ theoretical}$) is called the stoichiometric ratio (γ) as

$$\gamma = \frac{m_{\text{air,actual}}}{m_{\text{air,theoretical}}} \qquad (3)$$

The excess air is defined as (γ-1).

4. RESULTS AND DISCUSSION

4.1 Fuel properties

Table 3 shows the analysis of HFO and HCGO fuels. Fuel elemntal analysis shows no significant difference between HFO and HCGO. Density and calorific values for both fuels are almost the same as well. However, the viscosity and pour point indicate that HFO is heaver than HCGO. Hence, HFO requires heating for better atomization and sufficient air-fuel mixing. HFO is a product of simple refinery and HCGO is a product of complex refinery. HFO is a residual product, and HCGO is considered as distillated product. Contaminants elemental analysis shows high concentration of Fe, V, Ni, Ca and Zn in HCGO than in HFO, inspite the fact that HFO is a residual product and HCGO is a distillated product (the metal content should be nill). In other words the level of heavy metal should be higher in residual oils than distillate oils. This is not surprising as the crude oil of Nile blend (the base of HFO) contains less heavy metals that Fula blend (the base of HCGO).

4.2 Emission Level

Figures 1 shows the stack composition of O_2 and CO_2 for HFO and HCGO respectively. The solid line indicates the theoretical level. It can be seen that the experimental results matches the theoretical results with no significant variation. This is attributed to the high level of accuracy in the elemental and physical analysis of the fuels and emissions.

4.3 Emission of carbon monoxide (CO)

Tables 4 and 5 show CO emission level for HFO and HCGO respectively. The presence of CO is inductive of incomplete combustion. Incomplete combustion may be due to many reasons [7-9]:

1. Insufficient oxygen (O_2). Clearly CO concentration is high at low values of fuel - air ratio. This is expected, as the air is just enough for complete combustion. If small amount of this air went off combustion for example due to poor fuel/air mixing and atomizing temperature the lack of air will occurs. Other factors of insufficient air include cold-wall flame quenching; reduced combustion temperature; decreased combustion gas residence time; to mention a few.

2. Combustion efficiency. The rate of emission in smaller boilers and furnaces is more than that of large equipment. This is due to the fact that smaller combustors have higher heat transfer area to flame volume ratio than larger one. Hence high heat losses and reduced flame temperature and combustion intensity and hence, lower combustion efficiency.

4.4 Emission of NO_x

Tables 4 and 5 show NO_x emission level for HFO and HCGO respectively. Clearly there is no clear trend with fuel - air ratio although previous studies reported exponential trend of NO_x with flame temperature, N_2 concentration in the flame, the square root of O_2 concentration in the flame and residence time [9]. Nevertheless, for both fuels the fuel air ratios of 1.15 to 1.20 yield the least emission.

5. CONCLUSIONS

This work provided information on the level of emission of local heavy fuels oil. This information is vital to industry and environmental engineers

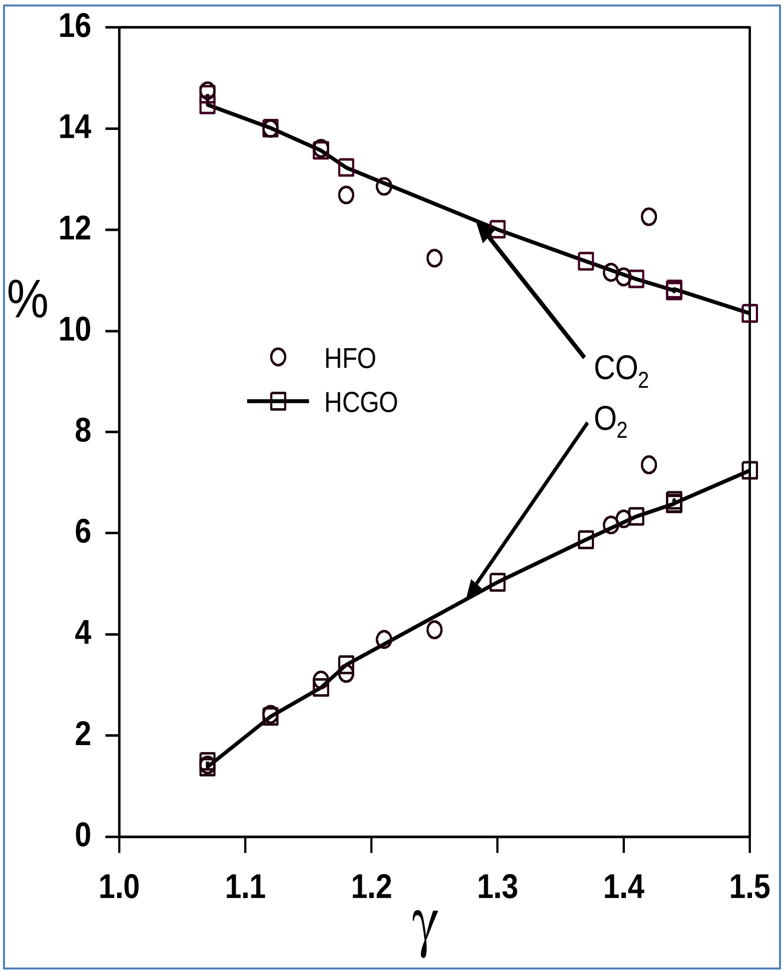

Fig. 2. CO_2 and O_2 in HFO and HCGO

Table 3. CO and NOx in HFO

Test Conditions: m_{fuel}=1.75 kg/h, $T_{ambient}$ =40±2°C, $AF_{stoichiometric}$=13.80777kg air/kg fuel

γ	$T_{adia.}$	CO_2	O_2	CO	NO_X
-	°C	%	%	ppm	ppm
1.42	1697	12.26	7.35	243	83.6
1.40	1719	11.07	6.28	151	99
1.39	1730	11.16	6.16	93	116.2
1.25	1876	11.44	4.09	87	118.7
1.21	1923	12.86	3.90	75	81.7
1.18	1965	12.69	3.23	78	112.8
1.16	1990	13.61	3.10	68	83.6
1.12	2043	14.00	2.42	109	88.5
1.07	2121	14.75	1.42	198	109.5

Table 4. CO and NO_x in HCGO

Test Conditions: m_{fuel}=1.75 kg/h, $T_{ambient}$ =40±2 °C, $AF_{stoichiometric}$=13.8617kg air/kg fuel

γ	$T_{adia.}$	CO_2	O_2	CO	NO_X
-	°C	%	%	ppm	ppm
1.50	1614	10.35	7.24	72	130.4
1.44	1666	10.79	6.65	98	120.2
1.44	1671	10.83	6.59	127	119.3
1.44	1671	10.80	6.58	771	97.9
1.41	1694	11.03	6.33	87	122.3
1.37	1735	11.38	5.87	128	112.7
1.30	1807	12.01	5.03	49	129.5
1.18	1943	13.23	3.40	106	94.9
1.16	1980	13.57	2.95	50	119.7
1.12	2026	14.01	2.38	77	107.4
1.07	2089	14.47	1.49	3035	82.1
1.07	2102	14.68	1.38	1217	87.1

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