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The Efficiency Improvement by Combining HHO Gas, Coal and Oil in Boiler for Electricity Generation

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Academic Editors: Paul Stewart and Chris Bingham
Received: 29 October 2016; Accepted: 10 February 2017; Published: 20 February 2017

Abstract: Electricity is an essential energy that can benefit our daily lives. There are many sources available for electricity generation, such as coal, natural gas and nuclear. Among these sources, coal has been widely used in thermal power plants that account for about 41% of the worldwide electricity supply. However, these thermal power plants are also found to be a big pollution source to our environment. There is a need to explore alternative electricity sources and improve the efficiency of electricity generation. This research focuses on improving the efficiency of electricity generation through the use of hydrogen and oxygen mixture (HHO) gas. In this research, experiments have been conducted to investigate the combined effects of HHO gas with other fuels, including coal and oil. The results show that the combinations of HHO with coal and oil can improve the efficiency of electricity generation while reducing the pollution to our environment.

Keywords: efficiency; pollution control; reducing fuel; performance improvement

1. Introduction

Electricity demands have increased dramatically. To satisfy these increasing demands, many developing countries have installed thermal power plants that mainly use coal as the raw material for electricity generation because it is a cheap and abundant material. However, it has also been found that coal material is one of the big sources of pollution to our environment.

For electricity generation, there are many available sources, including coal, natural gas, nuclear, oil, etc. Among these sources, the coal material accounts for about 41% of current worldwide electricity supply; natural gas 21%; nuclear 13%; oil 5%; and others 3% [1]. However, it is noted that the widespread use of coal is one of the factors leading to problems such as the emission of greenhouse gases, the demolition of the ozone layer, pollution and acid rain, etc.

To deal with these problems, many developed countries have changed from using fossil fuels to renewable energies, such as wind, biomass, solar, and hydro power. The aim was to reduce CO_2 emission that have been found to have contributed a lot to global climate warming [2]. However, many countries have set up plans to phase out fossil fuels. As a result, the use of coal is expected to continue for many years. In addition, it is noted that an abrupt stop in the use of fossil fuels may lead to concerns such as the disruption to the global economy. These concerns highlight the importance of seeking solutions that can improve the efficiency of electricity generation in the face of increasing electricity demand and depleting fossil fuels storage.

As a kind of clean and efficient energy, hydrogen energy has attracted increasing attention for electricity generation. Relevant studies started in the 1970s and some approaches have been developed for generating hydrogen and oxygen (HHO) gas. Available approaches include electrolysis, the thermos chemical method, photo dialysis and the thermal decomposition of water. Among them, the electrolysis approach, which obtains hydrogen by splitting water into hydrogen and oxygen, is found to be relatively efficient and cheap [3]. In the past, HHO gas has been mainly used for internal combustion engines as this kind of gas has a high gross calorific value (GCV) that can lead to lower carbon content in the outlet and lower fuel consumption. However, somewhat differently, in this research, HHO gas was used in combination with coal and oil in a boiler, with the aim to improve electricity generation efficiency. Due to its high GCV, HHO gas is expected to reduce fuel consumption while improving combustion inside a furnace. In addition, due to the complete combustion of hydrocarbon in fossil fuels, the HHO is expected to reduce air pollution. In a real thermal power plant, HHO gas can be added into a furnace to improve the efficiency of electricity generation. However, detailed efficiency data about the use of HHO has rarely been revealed in past studies. This has prompted us to conduct intensive experiments to understand the effects of combining HHO with other energy sources, such as coal and oil, for electricity generation. Our experiments reveled detailed information about the improvements of boiler efficiency by combining HHO with coal, the coal consumption rate, the oil consumption rate, the increases of steam production and the reductions of the emissions of various particles when combining coal and oil with various amounts of HHO. These experiments were conducted in an oil-fired boiler. Our experimental results showed that the combinations of HHO gas with coal or oil can improve the electricity generation efficiency and reduce pollution.

The remainder of this paper is organized as follows. Section 2 includes a literature review about HHO gas and the improvement of boiler operating characteristics. Section 3 details the methodology. Section 4 covers the testing arrangement and procedure of mixing HHO gas with heavy oil (HO) and light diesel oil (LDO). The theoretical calculation results and test results are depicted. Section 5 draws a conclusion and suggests future research directions.

2. Literature Review

2.1. HHO Gas

HHO is also known as "Brown gas" which is derived from the name of Professor Yull Brown who found some unique properties of HHO [4]. The main usage of HHO was to empower automobile engines. The unique properties found for HHO include the following: it does not have a predefined burning temperature and it reacts to the substances when being burned; it will start imploding rather than exploding when it contains 66.67% of hydrogen with the remainder being oxygen. This can have four times the vacuum energy compared with the combination of HHO with air. In addition, when combining HHO with diesel or petrol, it can also improve the burning efficiency considerably. As hydrogen burns quicker than the refined oil products, the flame propagation of HHO gas is faster than oil products [4].

2.2. The Derivation of HHO Gas

There are various approaches for electricity generation, including electrolysis, the thermos chemical method, photo biolysis and the thermal decomposition of water [5]. Electrolysis is an easy way to obtain hydrogen energy by separating the hydrogen and oxygen from water. Due to its higher energy, the mixture of oxygen and hydrogen can be used as an alternative to fossil fuels. Such a mixture can lead to advantages such as eco-friendly, rapid firing and great flame propagation. Under the normal combustion temperature and pressure, HHO gas will burn from 4% to 94% with the temperature of 2000 °C. The HHO will start combusting when it reaches the auto-ignition temperature which is about 570 °C under the normal atmospheric pressure. The minimum energy required to combust the HHO is about 0.02 mJ. According to Julius Thomsen, the quantity of heat produced is about 34,000 calories when the mixture burns. This heat-disturbance is independent to the mode in which the process is conducted; but the temperature of the flame is dependent on the circumstances in which the process takes place [6]. If the hydrogen and oxygen are in equal quantities, then its flames can reach a higher temperature This temperature is lower when the mixture has an excess of one or the other and if it is mixed with nitrogen or another inert gas.

Though different techniques are available for separating hydrogen and oxygen, this research maintained the traditional techniques of hydrogen and oxygen separation.

2.3. Oxygen Combustion in the Coal-Fired Boiler

There are some studies about coal-fired boilers [7–10]. Figure 1 shows a schematic of a coal-fired oxy-fuel boiler [11], in which oxygen is first separated from the air and then mixed with a stream of recycled flue gases from the boiler. Fuel is burned in the boiler. The resulting water vapor is condensed from the flue gases to produce a stream of purified CO_2.

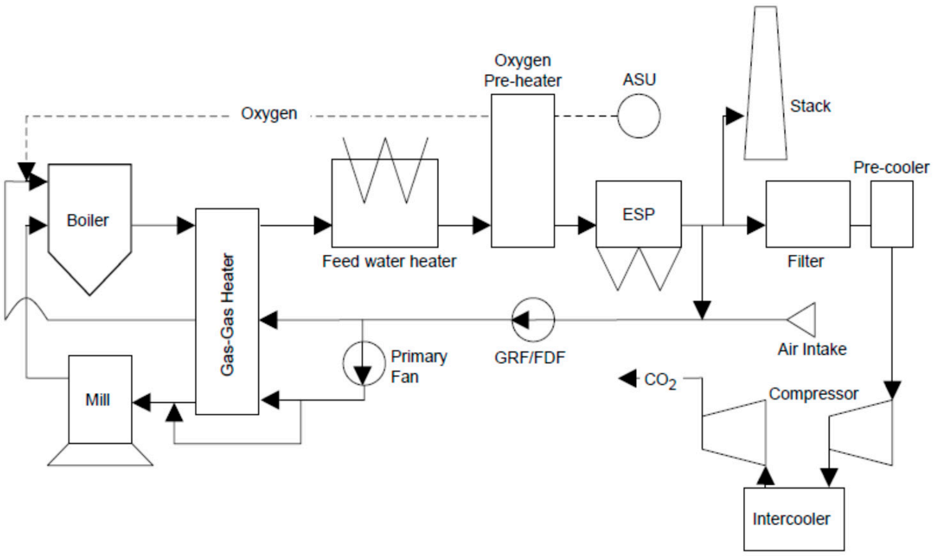

Figure 1. Oxy fuel firing in the coal-fired power plant [11].

For both new and existing pulverized coal-fired power stations, near-zero emission technology can be applied to capture CO_2 from flue gases. In the flue gases, the CO_2 can concentrate from approximately 17% to 70% in mass, and they can be captured by a cooling process and compressed for further transport and storage.

2.4. Removal of Nitrogen before Combustion and CO_2 before Exhaust in the Coal-Fired Power Plant

Figure 2 shows the configuration of a coal-fired power plant with pre-combustion nitrogen removed and CO_2 removed before flue gas exhaust [12]. In the process, the air from the atmosphere is first processed by an Air Admission Unit (ASU) that aims to remove nitrogen so that pure oxygen will enter the boiler for combustion. During combusting, the NO_x particles will be reduced and CO_2 and water vapor (H_2O) will be generated in the flue gas. The output flue gas will be further processed by a Selective Catalytic Reduction Reactor (SCR) that aims to remove the NO_x content. Following this, the Electrostatic Precipitator (ESP) will remove the solid particles in the flue gas. Finally, the Flue Gas Desulphurization (FGD) will remove the Sulphur content in the flue gas. Having completed the three processes, the flue gas is composed of CO_2 and water vapor. After removing the CO_2 and water vapor through an external cleaning method, the flue gas is then recycled into the boiler.

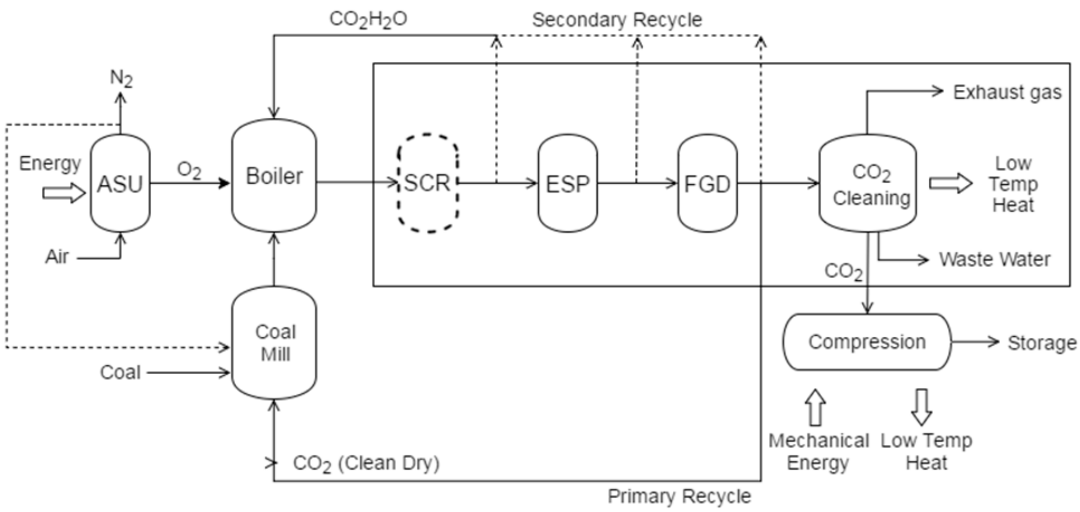

Figure 2. The configuration of a coal-fired power plant [12].

The pure oxygen can improve the combustion of hydrocarbon, thereby improving the boiler efficiency. This can reduce contaminants in the gas due to a complete combustion, which helps reduce the pollution to our environment.

2.5. Flue Gas Recycling to the Boiler

Figure 3 shows the process of flue gas recycling [13]. The exhaust gas enters a stack through a flue gas cooler, a tubular air heater, a multi-cyclone dust collector, and a bag filter. Part of the exhaust gas is taken from downstream of the bag filter and recycled as the primary gas for the transportation of pulverized coal for combustion. On the other hand, oxygen is supplied using an evaporator system and a liquid oxygen tank. Part of the oxygen is mixed with the secondary gas and another part is directly injected into the burning area through the center of the pulverized-coal burner. Part of the secondary gas is taken out and injected into the furnace through staging air ports to obtain staged combustion.

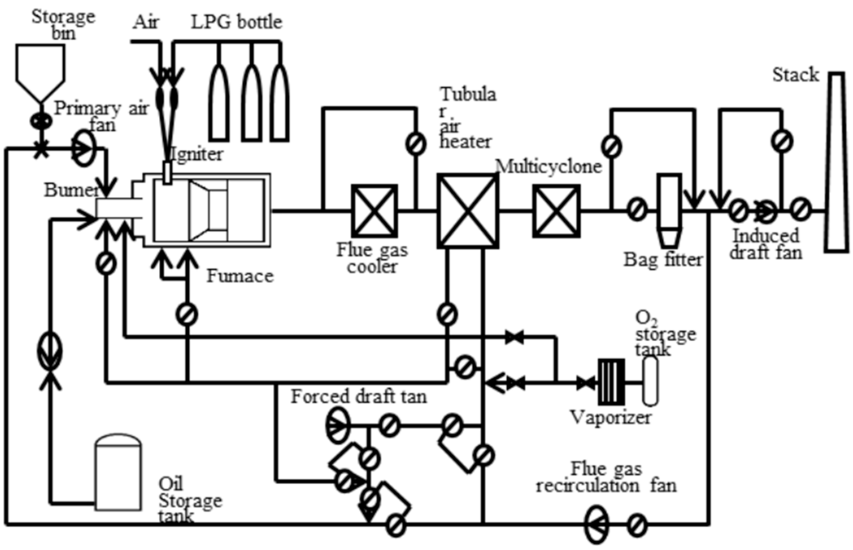

Figure 3. The process of flue gas recycling [13].

3. Methodology

3.1. Testing Arrangements for HHO Gas in an Oil-Fired Boiler

To assess efficiency improvement, the boiler efficiency needs to be measured. In this research, the direct method is used to measure the boiler efficiency. The direct method is also known as the "input–output method" as it only uses the output (steam) and the heat input (i.e., fuel) for efficiency assessment.

Figure 4 shows the test facility required for HHO experiments. It includes the following components: oil-fired boiler (capacity of 156 L water), oil tank, water tank, HHO generator (with the capacity of 7200 L/h), stack (emission measurement port), and oil feed pump. Details of each component are described below.

(1) Oil-fired boiler: Table 1 lists the details of the boiler for experiments. In this boiler, some modifications have been made in the burner to receive HHO gas into the boiler.
(2) Oil tank: In this research, the oil tank is placed at the height of 2 m above the ground. In addition, to ensure the purity of oil, a filter is placed in the pump suction side to avoid the oil flowing back to the tank.
(3) Water tank: Similar to the oil tank, the water tank is also maintained at a height above the ground during the whole testing process.
(4) HHO generator: The HHO generator is the device used to generate HHO gas. Table 2 shows the specifications of the HHO generator. It has the capacity of producing 7200 L/h by consuming 7 liters of water. The generator produces HHO gas using the principle of electrolysis, using a NaOH electrolyte.
(5) Stack: This is the inbuilt part of the boiler where the emission analyzer is used to measure the outlet gas.
(6) Oil feed pump: This is the pump for feeding the oil fuel into the oil-fired boiler.

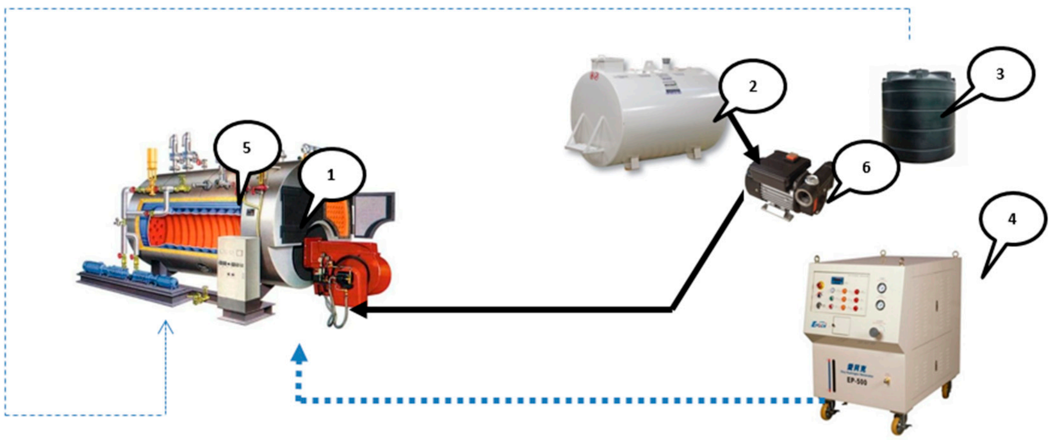

Figure 4. Test facility

Table 1. Oil-fired boiler specification.

Description	Unit	Value
Evaporation capacity	kg/h	1500
Heat transfer area	m^2	9.9
Pressure	kg/cm^2	10
Water capacity	L	156
Type of fuel	L	Diesel/Heavy oil
Power	KW	11.5
Weight	kg	1950

Table 2. The specifications of the HHO generator.

Description	Values
Voltage	440 V
Phase	Three phase
Current	60 A
Power	29 KW/h
Pressure	1.5 kg/cm^2
Water consumption	7 L/h
Max gas output	7200 L/h

3.2. Testing Procedure

The following steps explain how to carry out the tests properly. The burner of the boiler needed to be modified as the original boiler provided by the manufacturer can only supply one fuel at a time. In our testing, it needs to combine HHO gas with other fuels in the boiler. Keep enough water in the boiler in order to avoid the tests being interrupted and to avoid damages to the tubes in the boiler due to excessive operating heat. Adjust the amount of air supplied to the burner to one-third, and set the heating temperature to 70–110 °C for diesel oil; 120–150 °C for heavy oil (HO). Excessively hot fuel will cause unstable pumping pressure while excessively cold fuel will cause incomplete burning, explosion and even abnormal fire. Ensure the operating conditions, such as the current circuit, burner switches, and oil leakages, required by the boiler manual. Increase the pressure to feed oil into the burner. A low oil pressure will usually cause imperfect spray. Thus, maintain the pressure for oil feeding more than 15 kg/cm^2. Start the boiler and maintain the operating characteristics. First, test the HO and collect the data, and then test the light diesel oil (LDO) and collect the data. The emission characteristics are measured using an emission analyzer in the stack of the boiler. Having completed the tests without HHO, conduct the combinations of HHO gas. Ensure that there is not any leakage. Carefully handle the HHO gas to avoid exposure to the flame.

4. Experimental Results

4.1. The Efficiency Measurement of the Boiler When Only Coal Is Used

The efficiency measurement was carried out on the 40THP Fluidized bed combustion boiler at L&T Industries, Surat, India. A performance test is carried out with sub-bituminous coal and then simulated with Indian lignite coal for comparisons. The operating data of the boiler is listed in Table 3 [14].

Table 3. The operating data of the boiler.

Fuel Type	Indian Lignite Coal	Sub-Bituminous Coal
Steam generation rate	40,000 kg/h	40,000 kg/h
Operation hours	7200 h/year	7200 h/year
Steam pressure	32 kg/cm^2	32 kg/cm^2
Steam temperature	380 °C	380 °C
Coal firing rate	5846 kg/h	4300 kg/h
Gross Calorific Value (GCV) of fuel	4300 kcal/kg	5800 kcal/kg
Total surface area	150 m^2	150 m^2
Surface temperature	210 °C	210 °C
Wind velocity	3.9 m/s	3.9 m/s
Ambient temperature	33 °C	33 °C
Humidity factor	0.021 kg/kg of dry air	0.021 kg/kg of dry air

Table 4 shows the data of water used in this experiment. The total dissolved solids (TDS) is controlled at 200 parts per million (ppm) and pH is controlled at 7.1 for the experiment water.

This experiment also executes the ultimate analysis of coal; in total, coal has six components. The percentages of those six components are detailed in Table 5. Table 6 shows the ingredients of exhaust gas in percentages obtained from a flue gas analyzer.

Table 4. Feed water analysis data.

A. Feed Water Analysis from Laboratory		
Feed water temperature	160 °C	160 °C
Total Dissolved Solids (TDS)	200 ppm	200 ppm
pH	7.1	7.1

Table 5. Ultimate analysis data.

B. Ultimate Analysis of Coal		
C	37%	59%
H_2	2.9%	3.1%
N_2	1.1%	1.1%
O_2	4.5%	10.4%
Ash	36%	12.1%
Moisture	17%	12.9%
Sulphur	1.5%	1.4%

Table 6. Flue gas analysis data (Chetan et al., 2013).

C. Flue Gas Analysis with Flue Gas Analyzer		
Flue gas temperature	600 °C	600 °C
% O_2 in flue gas	8.12%	8.12%
% CO_2 in flue gas	11.6%	11.6%
% CO in flue gas	0.42%	0.42%

4.2. Coal Consumption without HHO Gas Added

Based on the coal consumption data, as shown in Table 3, the total yearly consumptions of the coals—Indian Lignite and sub-bituminous—can be estimated as follows. The calculations are based on the plant operation time without considering the losses during handling.

(1) The total Indian Lignite consumption per year is 7200 h × 5846 kg/h = 42,091,200 kg.

(2) The total sub-bituminous consumption per year is 7200 h × 4300 kg/h = 30,960,000 kg.

4.3. Coal Consumption with HHO Gas Added

To find the efficiency improvement of combining HHO with coal, we have conducted experiments in a boiler and measured the boiler efficiency using the direct method. Referring to Table 3, the following calculation is based on the addition of 1 kg of HHO gas per hour to coal [15].

(1) The total GCV required per year if Indian lignite is used = Coal consumption per hour × GCV × Total operating hour in one year = 5846 kg/h × 4300 kcal/kg × 7200 h/year = 180,992,160,000 kcal/Year.

(2) The total GCV available per year if 1 kg of HHO is used per hour = HHO consumption per hour × GCV × Total operating hour in one year = 1 kg/h × 34,000 kcal/kg × 7200 h/year = 244,800,000 kcal/year.

(3) The reduction in Indian Lignite consumption = {total Indian lignite consumption per year without HHO} − {(total GCV required per year if Indian lignite used − total GCV available per year if HHO used 1 kg per hour)/GCV of Indian lignite} = 42,091.2 − {(180,992,160,000 kcal/Year − 244,800,000 kcal/year)/4300 kcal/h} = 42091.2 − 42,034.26 tons/year = 57 tons/year if 1 kg of HHO per hour is used.

(4) The total GCV required per year if sub-bituminous coal is used = Coal consumption per hour × GCV × Total operating hour in one year = 4300 kg/h × 5800 kcal/kg × 7200 h/year = 179,568,000,000 kcal/Year.

(5) The total GCV available per year if 1 kg of HHO per hour is used = HHO consumption per hour × GCV × Total operating hour in one year = 1 kg/h × 34,000 kcal/kg × 7200 h/year = 244,800,000 kcal/year.

(6) The reduction in sub-bituminous coal consumption = {Total sub-bituminous coal consumption per year without HHO} − {(Total GCV required per year if sub-bituminous coal used − Total GCV available per year if 1 kg of HHO per hour is used)/GCV of sub-bituminous coal} = 30,960 − {(179,323,200,000 kcal/Year − 244,800,000 kcal/year)/5800 kcal/h} = 30,960 − 30,917 tons/year = 43 tons/year if 1 kg of HHO per hour is used.

The above results show that HHO gas can reduce yearly coal consumption by up to 57 tons of Indian lignite and 43 tons of sub-bituminous when 1 kg of HHO per hour is added. Though the generation of HHO gas will incur some costs, they will be nullified by benefits such as prolonged availability of coal and reduced environmental pollution.

4.4. Oil Consumption vs. Steam Production

4.4.1. Heavy Oil

Table 7 shows the average Heavy Oil (HO) consumptions and steam productions when combining HO with various amounts of HHO. The denotation of HHO (1800) indicates that 1800 L of HHO is added per hour (L/h). In this research, four amounts, i.e., 1800, 3600, 5400 and 7200 L, of HHO were tested for each kind of fuel. In total, there are five conditions in the same oil consumption, but with different HHO amounts. The results demonstrate that when HHO increased, the steam production increased. The amount of 1800 L of HHO led to the highest percentage increase and 7200 L of HHO led to the highest increase in steam.

Table 7. Average HO consumptions and steam productions when combining hydrogen and oxygen mixture (HHO).

Item	HO Consumption (L)	Steam Temperature (°C)	Steam Temperature Increase (%)	Steam Pressure (kg/cm^2)	Steam Production (L)
HO	27.67	129.67	0.00	5.47	363.67
HO + HHO (1800)	27.33	143.00	10.29%	5.47	377.67
HO + HHO (3600)	27.33	143.67	10.80%	5.57	408.67
HO + HHO (5400)	27.67	144.33	11.3%	5.53	434.67
HO + HHO (7200)	27.67	145.00	11.84%	5.53	460.33

Table 8 shows the average increases (%) of HO consumption and steam production when combining HO with various amounts of HHO. The results demonstrate that when HHO increased, the steam production increased also.

Table 8. Average increases (%) of HO consumption and steam production when combining HO with various amounts of HHO.

Item	HO Consumption (L)	Steam Production (L)	HO Consumption Increase (%)	Steam Production Increase (%)
HO	27.67	363.67	0%	0%
HO + HHO (1800)	27.33	377.67	−1%	4%
HO + HHO (3600)	27.33	408.67	−1%	12%
HO + HHO (5400)	27.67	434.67	0%	20%
HO + HHO (7200)	27.67	460.33	0%	27%

4.4.2. Light Diesel Oil

Table 9 shows the average LDO consumptions and steam productions when combining LDO (Light Diesel Oil) with various amounts of HHO. The results demonstrate that when HHO increased, the steam production increased during the same LDO consumption.

Table 9. Average increases (%) of LDO consumption and steam production when combining LDO with various amounts of HHO.

Item	LDO Consumption (L)	Steam Temperature (°C)	Steam Temperature Increase (%)	Steam Pressure (kg/cm^2)	Steam Production (L)
LDO	28.00	133.00	0.00	5.50	382.67
LDO + HHO (1800)	27.67	143.00	7.52%	5.50	398.00
LDO + HHO (3600)	27.67	143.33	7.78%	5.43	424.67
LDO + HHO (5400)	27.67	143.67	8.0%	5.50	442.00
LDO + HHO (7200)	27.33	144.67	8.78%	5.55	464.00

LDO: Light Diesel Oil.

Table 10 shows the average increases (%) of LDO consumption and steam production when combining LDO with various amounts of HHO. The results demonstrate that when HHO increased, the steam dramatically increased during the same LDO consumption.

Table 10. Average increases (%) of LDO consumption and steam production when combining LDO with various amounts of HHO.

Item	Oil Consumption (L)	Steam Production (L)	Increase in Oil Consumption (%)	Increase in Steam (%)
LDO	28.00	382.67	0%	0%
LDO + HHO (1800)	27.67	398.00	−1%	4%
LDO + HHO (3600)	27.67	424.67	−1%	11%
LDO + HHO (5400)	27.67	442.00	−1%	16%
LDO + HHO (7200)	27.33	464.00	−2%	21%

4.5. Emissions Measurement

4.5.1. Emissions from Heavy Oil

Table 11 shows the average amounts of various particles in the exhaust gas when combining HO with various amounts of HHO.

Table 11. Amounts of various particles in the exhaust gas when combining HO with various amounts of HHO.

Item	O_2 (%)	CO	CO_2	NO	NO_2	SO_2	HC
HO	3.68	98.3	14.18	153.6	8.15	185.2	10.76
HO + HHO (1800)	5.55	47.89	12.50	151.47	5.90	185.17	3.17
HO + HHO (3600)	5.74	28.77	12.18	148.62	7.00	179.97	1.60
HO + HHO (5400)	5.69	27.95	12.42	147.17	7.50	175.03	1.35
HO + HHO (7200)	5.88	24.93	11.68	145.73	5.50	155.62	0.68

Unit: ppm.

Table 12 shows the average reductions (%) of various particles in the exhaust gas when combining HO with various amounts of HHO. They show that HHO can reduce the amounts of various particles in the exhaust gas.

Table 12. The reduction amounts (%) of various particles when combining HO with various amounts of HHO.

Item	O_2 (%)	CO	CO_2	NO	NO_2	SO_2	HC
HO	0	0	0	0	0	0	0
HO + HHO (1800)	51%	−51%	−12%	−1%	−28%	−0.018%	−71%
HO + HHO (3600)	56%	−71%	−14%	−3%	−14%	−3%	−85%
HO + HHO (5400)	55%	−72%	−12%	−4%	−8%	−5%	−87%
HO + HHO (7200)	60%	−75%	−18%	−5%	−33%	−16%	−94%

4.5.2. Emissions from Diesel Oil

Table 13 shows the average amounts of various particles in the exhaust gas when combining DO with various amounts of HHO.

Table 13. The amounts of various particles when combining DO with various amounts of HHO.

Item	O_2 (%)	CO	CO_2	NO	NO_2	SO_2	HC
DO	2.40	180.43	14.59	78.20	6.57	3.73	2.77
DO + HHO (1800)	5.53	49.50	11.90	65.77	5.75	0.61	1.58
DO + HHO (3600)	5.93	38.95	11.55	65.73	4.07	1.48	1.00
DO + HHO (5400)	5.87	36.07	11.99	66.63	3.63	1.08	0.61
DO + HHO (7200)	5.70	34.10	11.48	65.90	3.87	0.34	0.70

DO: Diesel Oil.

Table 14 shows the average reductions (%) of various particles in the exhaust gas when combining DO with various amounts of HHO.

Table 14. Average reductions (%) of various particles when combining DO with various amounts of HHO.

Item	O_2	CO	CO_2	NO	NO_2	SO_2	HC
DO	0	0	0	0	0	0	0
DO + HHO (1800)	130%	−73%	−18%	−16%	−12%	−84%	−43%
DO + HHO (3600)	147%	−78%	−21%	−16%	−38%	−60%	−64%
DO + HHO (5400)	144%	−80%	−18%	−15%	−45%	−71%	−78%
DO + HHO (7200)	137%	−81%	−21%	−16%	−41%	−91%	−75%

4.6. Discussion

This study concentrates on the overall performance of the boiler, which does not consider the other factors that influence the boiler efficiency, such as heat loss, load factor etc., which can be calculated, if the test is carried out in the real power plant with the required modifications. However, the results suggest that adding HHO gas to the coal will improve the efficiency of the boiler.

Coal plays a major role in the sustainable development of countries such as India. The demand for coal is increasing substantially to generate a large portion of electricity in India. Even though India has abundant coal reserves, it still needs to import coal from other countries. Furthermore, to prolong the availability of the coal advanced technologies, the consumption of coal needs to be reduced and the existing plants need to be optimized. By using HHO, this change will ensure that the coal based power plants will have better respond to reduce contaminations.

As for emission characteristics, the reduced emission shows that the combustion of the oil-fired boiler is more complete than using only the fuel oil; this is achieved due to the high calorific value of the HHO gas mixture. The result shows the straight forward information that the use of HHO gas will help to maintain a clean environment as well prolonging the availability of coal for the future with the improved operating characteristics of the boiler. Thus, this breakthrough method will, without any doubt, be an efficient contribution to the world.

5. Conclusions

The increasing demands on electricity necessitate the improvement of electricity-generation efficiency. The increased number of thermal power plants installed by many developing countries can help to meet the electricity demands, however, they also intensify the problems of air pollution and global warming due to the use of coal material for electricity generation. In the face of the increasing electricity demand and depleting coal resources, improving the efficiency of electricity generation is definitely required.

In this research, we have proposed combining HHO with coal or oil to improve the efficiency of electricity generation. To investigate their effects, we have conducted intensive experiments, and the results showed concrete improvements. It is found that the combination of HHO with coal can reduce the coal consumption and emissions of various particles (CO, CO_2, NO, NO_2, SO_2, and HC) as HHO enables a complete combustion in a boiler due to its high GCV. Though the combination of HHO with oil has little effect in reducing the consumption of oil, it can reduce the emissions of various particles, which helps to maintain a cleaner environment. In this research, we have generated detailed information when combining HHO with coal and oil. These experimental data can be referenced by engineers to improve their boiler efficiency.

Based on the aforementioned experiments, we discuss the findings as follows.

(1) Our experiment shows that the combination of HHO with coal can reduce coal consumption. Specifically, the addition of 1 kg of HHO can lead to the saving of 7.9 kg for Indian lignite and 5.4 kg for sub-bituminous. These benefits mainly come from the high GCV of HHO that enables more efficient combustion in the boiler.

(2) The combination HHO with coal can also improve the boiler efficiency. Specifically, the addition of 1 kg HHO gas with Indian lignite can improve efficiency by 0.2%; the addition of 1kg HHO gas with sub-bituminous can improve the efficiency by 0.14%.

(3) From Table 8, it is noted that the combinations of HHO with heavy oil (HO) have little effect in reducing HO consumption. However, these combinations can significantly increase the steam production (4%–27%). The more HHO, the higher the steam production.

(4) From Table 10, it is noted that the combinations of HHO with light diesel oil (LDO) have little effect in reducing LDO consumption. However, these combinations can significantly increase the steam production (4%–21%). The more HHO, the higher the steam production.

(5) The additions of HHO to HO or LDO can lead to fewer emissions of various particles in the exhaust gas. In general, the more HHO, the fewer the emissions of various particles in the exhaust gas. From Table 12, it is noted that the combinations of HO with various amounts of HHO can significantly reduce the amount of emissions of various particles, including CO, CO_2, NO_2, and HC. For the CO especially, it can reduce from 51% up to 71% of emissions. From Table 14, it is noted that the combinations of LDO with various amounts of HHO can reduce a significant amount of emissions of various particles of CO, CO_2, NO, NO_2, SO_2, and HC.

In this research, the effects of combining HHO with coal and oil were investigated and evaluated by using a direct method that does not take heat loss and load factor into account. In addition, all experiments were conducted in a compact oil-fired boiler. In future studies, one can conduct experiments in a real plant using the indirect method to investigate various losses that can impact the boiler efficiency. This would help us to better understand the operating characteristics, such as air requirement for combustion and heat loss, etc., during combustion. Specific research topics of further studies could include the combustion flame characteristic after adding HHO gas, or the possibility of water formation during the HHO combustion. Moreover, the effect of radiation and heat transfer after the addition of HHO is a valuable research topic. Real power plant testing can also be explored more deeply.

Acknowledgments: This research was supported in part by MOST 105-2221-E-151-039 and MOST 105-2622-E-151-006-CC3 from the ministry of Sciences and Technology. The authors also appreciate the support from National Kaohsiung University of Applied Sciences in Taiwan.

Author Contributions: Chia-Nan Wang guided the research direction and found the solutions; Min-Tsong Chou conducted the hardware, software and designed the experiments; Hsien-Pin Hsu summarized the data and edited the paper; Jing-Wein Wang contributed to software coding; Sridhar Selvaraj conducted the experiments and analyzed the results. All authors have contributions to the research.

Conflicts of Interest: The authors declare no conflict of interest.

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