

## Article

# Co-Firing of Fast Pyrolysis Bio-Oil and Heavy Fuel Oil in a 300-kW<sub>th</sub> Furnace

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**Abstract:** Combustion characteristics and pollutant emissions of burning fast pyrolysis bio-oil/heavy fuel oil (HFO) blends in a 300-kW<sub>th</sub> furnace are investigated. Lauan (shorea) wood is used as biomass feedstock for making bio-oil via a fast pyrolysis process. The bio-oil has high viscosity, high water and oxygen content, as well as a low heating value. A furnace test is conducted for pure HFO and bio-oil/HFO blends with various mixing ratios. The results show that instability occurs during the test for cases with more than 5% bio-oil in the emulsion. Notably, it is verified that burning a bio-oil/HFO blend with a 2.5% bio-oil and a 97.5% HFO exhibits similar furnace performance and has lower NO and SO<sub>2</sub> emission levels as compared to burning pure HFO. The reductions of NO and SO<sub>2</sub> emissions are 2.6% and 7.9% for this blend, respectively.

**Keywords:** bio-oil; fast pyrolysis; furnace; combustion characteristics; emissions

## 1. Introduction

Bio-oil, a renewable liquid product produced via the fast pyrolysis process, has a lower sulfur and nitrogen content compared with that in fossil fuels. Fast pyrolysis of biomass thermally cracks solid biopolymers to generate a bio-oil, which can be used as a fuel directly or can be upgraded to form a higher-energy-content transportable liquid for power, heating, or the generation of electricity [1–4]. The decoupling nature of the plant is the most significant advantage of biomass pyrolysis liquid bio-oils [5]. The use of pyrolysis bio-oil has spread around the world. Bio-oil derived from pyrolysis processes has great potential to replace conventional fossil fuels (such as diesel, heavy fuel oil, and natural gas) for on-site power generation and heating, as well as to be a fuel source for medium- or large-scale combustion systems such as furnaces, boilers, and turbines [6].

There are two methods for the pyrolysis process, namely slow and fast pyrolysis [7]. The heating rate, the maximum reaction temperature, and the residence time (biomass heating time) are the main parameters controlled in the pyrolysis process. Heating rates for slow pyrolysis are typically below 100 °C/min, whereas those for fast pyrolysis can exceed 500 °C/min. The reaction temperature for slow pyrolysis is about 300 °C, and that for fast pyrolysis is around 500 °C. The residence time for slow pyrolysis is several minutes or even hours, while that for fast pyrolysis is short (less than two seconds). This difference in the residence time leads to substantial differences in pyrolysis product distributions; slow pyrolysis generates primarily bio-gas (syngas), while fast pyrolysis produces primarily bio-oil [8]. Biochar, as the by-product of biomass pyrolysis, is the second highest yield product for both slow and

fast pyrolysis systems. On a weight basis of the biomass feedstock, typical biochar yield is in a range between 15% and 40%. It is not suitable for upgrading condensable liquids from slow pyrolysis to transportation fuels [8]. Nevertheless, fast pyrolysis is an advanced process, and has gained great interest in recent years due to the high yield (about 70%) of raw bio-oil that can be directly produced from biomass [9,10].

Zheng et al. [6] investigated the spray combustion characteristics of bio-oil that was fast pyrolyzed from rice husk. After attaining steady state combustion, the temperature in the center of the combustion chamber was found to exceed 1400 °C. The CO concentration dropped, with an increase in the equivalence ratio, indicating that complete combustion was improved under operating conditions with higher oxygen concentrations. Meanwhile, the NO<sub>x</sub> concentration was slightly increased at a higher equivalence ratio due to the higher temperature and the increased O<sub>2</sub> concentration. Furthermore, the measured SO<sub>x</sub> concentration was very low (smaller than 30 ppm), since bio-oils contain insignificant amounts of sulfur.

Fast pyrolysis bioliquids have good potential for the replacement of conventional fuel oils such as heavy fuel oil and diesel. Using fast pyrolysis liquids (bio-oils) as fuel offers many advantages, including a clearly positive CO<sub>2</sub> balance, high-energy density, and a possibility of utilization in both small-scale power generation systems and large power stations [3,11]. As an alternative fuel, bio-oil can be co-fired in fuel oil, natural gas, or coal plants. In addition to the advantages of higher overall efficiencies and lower investment costs in comparison with 100% biomass fired in existing power plants, co-firing bio-oil with conventional fossil fuels has several environmental benefits, such as reduced emissions of CO<sub>2</sub>, NO<sub>x</sub>, and SO<sub>x</sub> [3,12]. Moreover, bio-oil can be utilized as either a start-up or back-up fuel for industrial facilities [13].

Biofuels as a renewable green energy can be used alone or blended with common fossil fuels as alternative fuels in diesel engines, furnaces, and boilers. Many researchers have reported that biodiesel can be blended with diesel from 5% to 30%, and there are no big problems running a diesel engine with B20 (20% biodiesel blend with 80% diesel by volume) [14,15]. Moreover, co-firing bio-oil with fossil fuels like coal [16,17] and natural gas [18] has been investigated, particularly at large power plants. The Red Arrow Products Company in the USA has co-fired bio-oil (produced by Rapid Thermal Processing) with coal in a boiler equipped with a 20-MWe Stoker burner with a five percent share of thermal input by bio-oil. It was found that the power plant operated with no notable problems after cost-efficient boiler modifications to allow for co-firing bio-oil with coal, and no negative impacts were noticed in emission levels, operation and maintenance programs, or ash handling [16]. Waagenar et al. [17] also reported co-firing fast pyrolysis bio-oils in a coal-fired power plant. Additionally, pyrolysis bio-oil has also been co-fired with natural gas in a combined cycle power station of 350 MWe in Harculo in the Netherlands [18].

Bio-oil can be used as a replacement for conventional fossil fuels in existing industrial boilers. However, some modifications to the combustion system and operating conditions are required in order to improve combustion for co-firing bio-oil with fossil fuels, since some problems might take place during the usage of standard equipment constructed for firing fossil fuels [19]. For instance, the existing burner must be replaced with a modified oil burner or a newly designed bio-oil burner (such as a burner head configuration) for firing bio-oil. In addition, the pumping, piping, oil preheating, and valve systems must also be specially designed for bio-oil.

The usage of bio-oil to completely replace fossil fuels has some limitations, since bio-oil has bad properties, such as high viscosity, poor volatility, coking, and corrosiveness. These limitations cause the primary challenge in the combustion process and industrial applications. However, a low blend ratio of bio-oil to petroleum-derived oil (low bio-oil content) has advantages, such as the fact that it can occur without modification of the burner and boiler sections, and can be easily combusted in existing industrial boilers and furnaces. Moreover, biofuels like biodiesel, ethanol, and butanol are made from agricultural crops, leading to food security issues and an increase in energy costs. On the

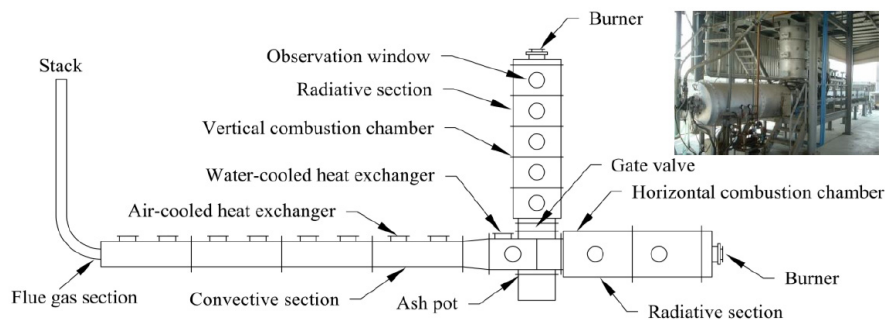
other hand, bio-oil derived from fast pyrolysis of woody biomass (such as wood waste and other non-edible feedstocks) does not cause the problem of food security or the increase in energy prices.

In a recent study, we performed heating experiments for suspended droplets of bio-oil/diesel blends and bio-oil/heavy fuel oil (HFO) blends to examine microexplosion and ignition behaviors [20]. Bio-oil used in the experiments was produced from fast pyrolysis processing of lauan wood. The results showed that ignition did not occur when the bio-oil/HFO blends had lower mixing ratios of bio-oil below 50%. However, with high blending ratios (not less than 60%), ignition could occur. Moreover, the bio-oil/HFO blends were observed to take a longer time than the bio-oil/diesel blends to finish burning. Considering the practical applications of fast pyrolysis bio-oil in industrial furnaces and boilers, further study is required to achieve a better understanding of the combustion characteristics and pollutant emissions when co-firing bio-oil with HFO. In the present study, therefore, an existing 300-kW<sub>th</sub> multi-fuel combustion test furnace was utilized without any modifications to explore the combustion and emissions characteristics of bio-oil/HFO blends. We aim to examine the feasibility of using these blends as a replacement for HFO in industrial applications.

## 2. Experimental

### 2.1. Furnace

Figure 1 shows a schematic of the experimental setup [21]. The overall structure and design of the 300-kW<sub>th</sub> multi-fuel combustion test furnace is divided into three parts: radiative, convective, and flue gas zones. There are two combustion chambers: a horizontal (for gaseous/liquid fuel) and a vertical (for solid fuel) refractory-lined radiant chamber with a 0.56 m inner diameter. The length of the horizontal combustion chamber is 2.8 m, while the length of the vertical combustion chamber is 3.05 m. These two combustion chambers are separated by a moveable gate, and can be used alternatively in conjunction with the horizontal convective section. Both are closely connected to the radiative zone, and are equipped with an observation window in order to facilitate observation of flame appearance and combustion stability.

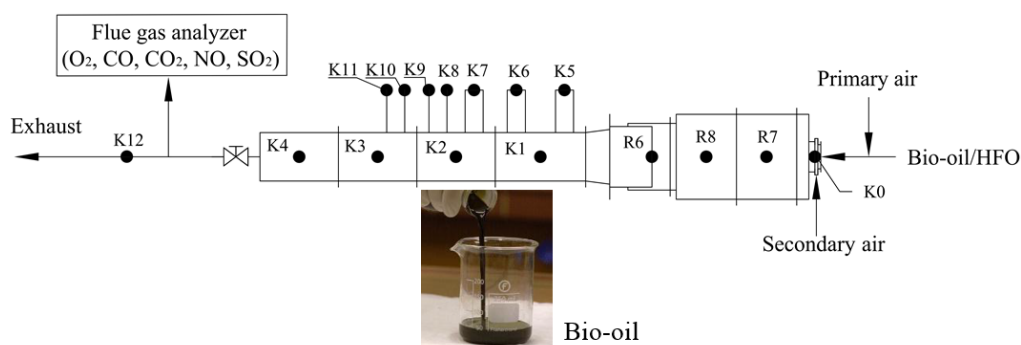


**Figure 1.** Schematic diagram of the 300-kW<sub>th</sub> multi-fuel test furnace.

In this study, a horizontal combustion chamber was utilized to run the experiments. Figure 2 shows a schematic diagram of the horizontal combustion test furnace. It is equipped with a low-pressure oil burner (LPB) with an air blast nozzle, which uses compressed air for atomization. The primary air (atomizing air) and the secondary air (combustion air) are supplied by a 7.5 hp blower. The fuel stream is injected from the center of the nozzle with primary air, and the annular secondary air stream is introduced by surrounding the centrally injected liquid-fuel jet flowing into the horizontal combustion chamber. With a pilot liquid petroleum gas flame as the heat source, after the oil sprays are ignited, stable spray flames are established.

There are two types of cooling systems, including water-cooled and air-cooled heat exchangers in the horizontal convective section. An 11 kW<sub>e</sub> pump is used to supply the cooling water, which exchanges heat with high temperature flue gas and then returns to a cooling tower to cool down

for recycling. Meanwhile, two 10 hp blowers are employed to supply the cooling air. Flue gases, which are induced by a 10 hp induced draft fan, run through the convective section and exit from the stack.



**Figure 2.** Schematic diagram of the horizontal combustion test furnace.

## 2.2. Experimental Procedures

All of the experiments were conducted in a horizontal furnace, whose schematic is shown in Figure 2. In the experiments, mixing equipment was installed for the mixing process, and the rotational speed of the mixer was about 80 rpm. The bio-oil was prepared from the fast pyrolysis of a woody biomass (lauan wood). The physical and chemical properties of the pyrolysis bio-oil are listed in Tables 1 and 2. Table 1 shows proximate and ultimate analysis results as well as heating values. Table 2 illustrates the physicochemical properties of the bio-oil, including gross calorific value, water content, pyrolysis solids content, kinematic viscosity, density, sulfur content, ash content, pH, pour point, and flash point, based on the test methods of ASTM D7544. Table 3 shows the physical and chemical properties of the heavy fuel oil.

**Table 1.** Properties of the pyrolysis bio-oil.

Proximate Analysis		Ultimate Analysis	
Water	26.99 wt %	Carbon	38.69 wt %
Ash	1.43 wt %	Hydrogen	4.36 wt %
Flammable substances	71.58 wt %	Oxygen	28.09 wt %
-	-	Nitrogen	0.24 wt %
-	-	Sulfur	0.13 wt %
-	-	Chlorine	0.07 wt %
Lower heating value (LHV)	17.11 MJ/kg	Higher heating value (HHV)	18.79 MJ/kg

**Table 2.** Physicochemical properties of the bio-oil based on the test methods of ASTM D7544.

Properties	Bio-Oil	Test Method
Gross heat of combustion (MJ/kg)	18.79	D240
Water content (wt %)	26.99	E203
Pyrolysis solids content (wt %)	1.21	D7579
Kinematic viscosity at 40 °C (cSt)	11.85	D445
Density at 20 °C (kg/dm <sup>3</sup> )	1.18	D4052
Sulfur content (wt %)	0.13	D4294
Ash content (wt %)	1.43	D482
pH	2.55	E70
Flash point (°C)	72	D93, Procedure B
Pour point (°C)	−7	D97

**Table 3.** Properties of heavy fuel oil.

Test Item	Test Results	Method
Density (@ 60 °F)	0.9533 g/mL	ASTM D-1298
Flow Point	12 °C	ASTM D-97
Water	0.32 vol %	ASTM D-95
Flash Point	110 °C	ASTM D-93
Viscosity (@ 50 °C)	130 cSt	ASTM D-445
LHV	40.63 MJ/kg	ASTM D-240
HHV	42.93 MJ/kg	ASTM D-240
Carbon	88.11 wt %	ASTM D-5291
Hydrogen	10.84 wt %	ASTM D-5291
Nitrogen	2.763 mg/g	ASTM D-4629
Sulfur	0.46%	ASTM D-4622

The mixing ratios of the heavy fuel oils and pyrolysis bio-oil were set at 2.5%, 5%, and 10% bio-oil in the emulsion, and 0.2% of surfactant was added to support the mixing stability. The liquid fuel was heated up to 80 °C inside the service tank, and then it was pumped from the tank. Before entering the combustion chamber, the liquid fuel was heated again to 90 °C. The air was divided into two streams: the primary air used for atomization, and the secondary air used for combustion.

R-type and K-type thermocouples (Omega Engineering, Inc., Norwalk, CT, US) were used to measure the temperature. As shown in Figure 2, three R-type thermocouples (R6, R7, and R8) were placed in the area around the combustion chamber, wherein R6 is employed to measure the flue gas temperature after cooling by the water cooling system. R7 and R8 were used to measure the wall temperature of the combustion chamber. Twelve K-type thermocouples (K0–K11) were used to measure the temperatures in the convective section. K0 was utilized to measure the outer surface temperature of the burner; the K1–K4 thermocouples were used to measure the flue gas temperature at different positions, and the K5–K11 thermocouples were used to measure the heat exchanger temperature for cooling the flue gas.

The emission of flue gas was analyzed using four Rosemount analyzers (Emerson Electric Co., St. Louis, MO, US): O<sub>2</sub> (Model 755, 0%–25%, ±0.1%), CO (Model 880, 0–1000 ppm, ±1 ppm), CO<sub>2</sub> (Model 880, 0%–100%, ±0.1%), and NO/NO<sub>2</sub>/SO<sub>2</sub> (Model NGA2000, 0–2000 ppm, ±1 ppm). The gas sample has to be conditioned through cooling, drying, and filtering before reaching the analyzers. Therefore, a dry, clean gas sample stream was created, and the emission results are shown as volume concentrations on a dry basis.

### 2.3. Furnace Preheating Process

An industrial multi-fuel combustion test furnace facility is lined with refractory bricks, which act as a source of heat absorption. The temperature rises with burning time. When the furnace wall temperature changes too much, combustion characteristics will change considerably. To avoid the influence of temperature variations on the combustion characteristics, before doing subsequent experiments, the furnace must be heated first until the wall temperature reaches a quasi-steady state.

Diesel was used to preheat the furnace. The preheating process was performed step by step. At the beginning, combustion under the operating condition of a diesel-oil flow rate of 12 L/h with an air flow rate of 140 Nm<sup>3</sup>/h was maintained for 4 h. Then, the oil flow rate was increased to 16 L/h, with an air flow rate of 170 Nm<sup>3</sup>/h for another 4 h. Finally, the oil flow rate was fixed at the maximum value of 20 L/h, with an air flow rate of 220 Nm<sup>3</sup>/h for the last warming period until the wall temperature did not change substantially over time, indicating achievement of a quasi-steady state. Warming-up took about 20 h prior to conducting the experiments.

### 3. Results and Discussion

Data retrieval was conducted once every 15 min by recording the temperature distributions in the furnace and the emission concentrations in the flue gas.

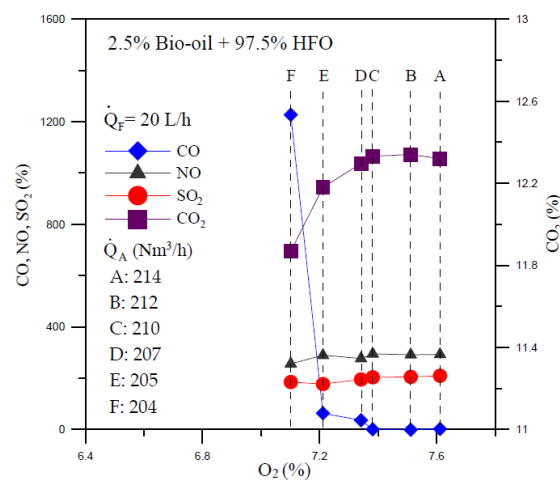
#### 3.1. Combustion Tuning

Before the subsequent experiments were conducted, the air flow rate in each case was tuned to meet the minimum amount of excess oxygen required for combustion, which is the so-called combustion tuning process. In each case, stable combustion was maintained for at least thirty minutes before taking data. The minimum amount of excess oxygen required for combustion was determined by the minimum CO emissions from the flue gases measured at the exhaust [22].

The formation of nitrogen oxides has a clear relevance with excess oxygen and temperature in combustion. NO concentration decreases with decreases in excess oxygen. However, CO formation increases rapidly when the excess oxygen is reduced below a critical point. For a complete combustion situation, the excess oxygen must be adjusted above this critical point. Below the critical point, the combustion situation is in an incomplete combustion condition. Then, there is smoke generation.

The emulsion of 2.5% of bio-oil in heavy fuel oil was chosen for testing to determine the oxygen requirement for complete combustion and to gradually adjust the amount of combustion air. The variations in the emissions in the flue gas with excess oxygen concentration are shown in Figure 3.

The fuel flow rate ( $\dot{Q}_F$ ) was fixed at 20 L/h in the combustion tuning and stable combustion processes. As shown in Figure 3, points A, B, C, D, E, and F correspond to the air flow rates ( $\dot{Q}_A$ ) of 214, 212, 210, 207, 205, and 204  $\text{Nm}^3/\text{h}$ , respectively. The excess oxygen concentration decreased with decreases in the flow rate of combustion air, from A (214  $\text{Nm}^3/\text{h}$ ) to F (204  $\text{Nm}^3/\text{h}$ ). For combustion air that was greater than the critical point for complete combustion (point C in the figure), the amount of CO formation was nearly 0 ppm. However, when the amount of combustion air was less than that of complete combustion air, a large amount of CO was generated (as shown at the F-point). Increasing the combustion air led to an increase in the excess oxygen concentration. As expected, NO formation increased with increases in the amount of excess oxygen (from F to A). Therefore, the NO emission decreased with decreases in the combustion air. Formation of  $\text{SO}_2$  depends on the sulfur content of the fuel oil itself. Hence, when using the same fuel, the  $\text{SO}_2$  emissions almost maintain a constant value. The results show a better adjustment of combustion air at point B. With an air flow rate of 212  $\text{Nm}^3/\text{h}$ , NO formation was not high, and CO was low. This condition was adopted for subsequent experiments, because it achieves the optimum operating condition that meets the minimum excess oxygen requirement with the least flue gas heat loss.



**Figure 3.** Combustion tuning process for burning the emulsion of 2.5% bio-oil + 97.5% heavy fuel oil (HFO).

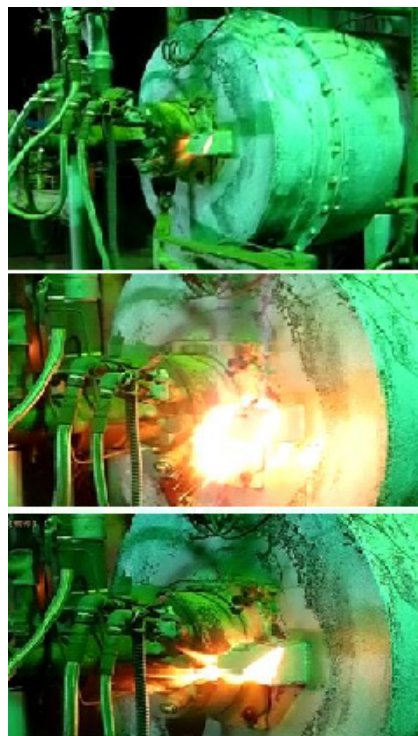


### 3.2. Temperature Distribution

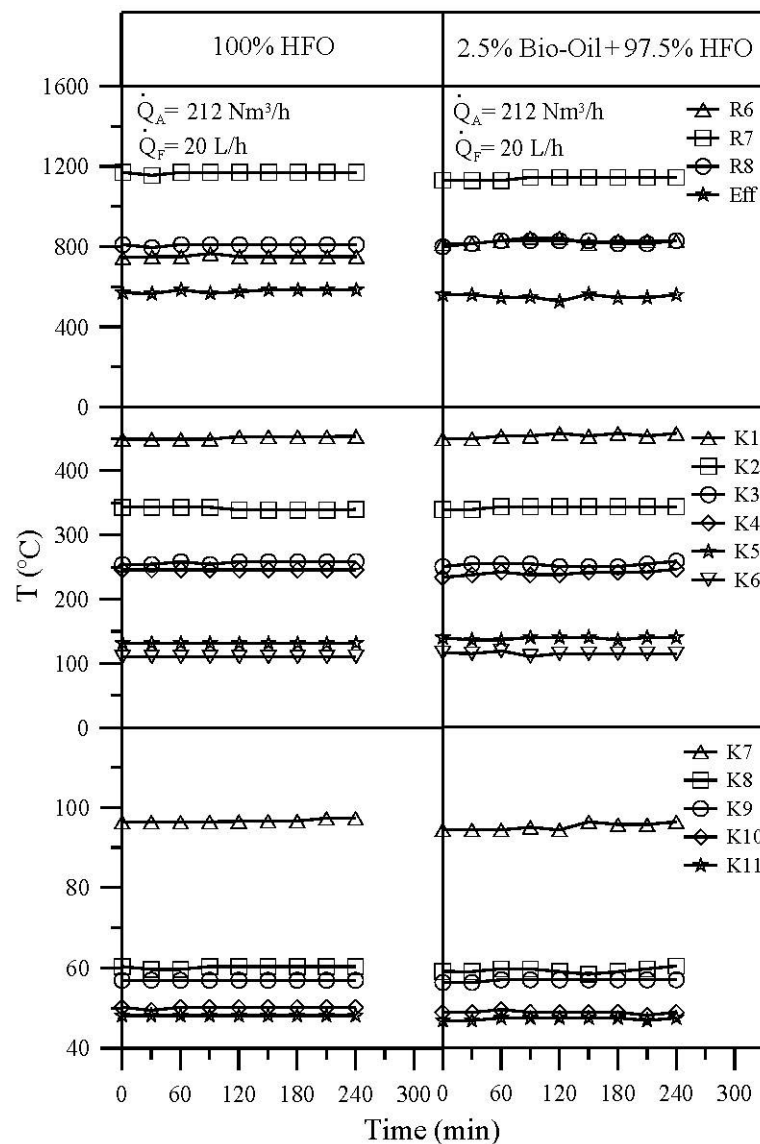
With the exception of the 2.5% bio-oil + 97.5% HFO emulsion, combustion instability occurred in the cases of blending ratios of 5% and 10% bio-oil. Instability was observed with the emergence of an explosion or burst of flame from the furnace (as shown in Figure 4). The instability was due to the emulsion preheating process. HFO must be heated up to 90 °C before being fed to the atomizer in order to reduce its viscosity. However, the preheating process greatly affects the characteristics of bio-oil, which is very susceptible to preheating because of its complex components. The emulsion of bio-oil and HFO with a blending ratio equal to or higher than 5% becomes sticky and difficult to pump. Therefore, only the results of pure HFO and the emulsion of 2.5% bio-oil + 97.5% HFO are shown in the following.

Figure 5 shows the temperature distributions with time for pure HFO and the emulsion of 2.5% bio-oil + 97.5% HFO at a fixed amount of liquid fuel supply rate of 20 L/h with an air flow rate of 212 Nm<sup>3</sup>/h. The bio-oil had a high water content of around 27% and a lower heating value than HFO, as shown in Table 1. Therefore, at a fixed fuel rate, with increases in the mixing ratio of bio-oil, the temperature was gradually reduced. In the primary combustion zone, the temperatures for R7 and R8 (furnace combustion chamber wall temperature) for firing HFO were only slightly higher than those for firing the 2.5% bio-oil + 97.5% HFO emulsion.

Figure 5 also shows that the flue gas temperature decreased gradually from K1 to K4. This is related to the measurement positions and the effects of cooling by using a heat exchanger. Additionally, the variations in the measured air temperatures at different positions (K5–K11) for cooling the flue gas with time shows that the temperature decreased from K5 to K11. This is due to the position of the heat exchanger itself. All the temperatures for K1–K11 show nearly constant values during the stable combustion processes. This is because of the stable combustion during the experiment.



**Figure 4.** Photographs of instability during the combustion test.



**Figure 5.** Temperature distributions for burning 100% HFO and the emulsion of 2.5% bio-oil and 97.5% HFO.

### 3.3. Emissions

Figure 6 shows the concentration of flue gas composition versus time for burning the pure HFO and the emulsion of 2.5% bio-oil + 97.5% HFO at constant supply rates of combustion air and fuel. It was found that  $O_2$  and  $CO_2$  concentrations in flue gas for these two liquid fuels are nearly the same.

As for the amount of CO emission, both experimental conditions are adjusted to the minimum oxygen required for complete combustion. Therefore, the CO concentrations in these two conditions are close to 0 ppm. Moreover, NO emissions decrease with an increase in the bio-oil content in the blends. The pyrolysis bio-oil had low calorific value and a high water content of up to 27%, and burning the 2.5% bio-oil + 97.5% HFO emulsion resulted in a slightly lower temperature in the combustion chamber as compared to burning pure HFO, leading to a reduction in NO emissions (about 2.6%).

The amount of  $SO_2$  emissions always depends on the sulfur content in the fuel. Bio-oil has a lower sulfur content than heavy oil; increasing bio-oil content therefore reduces  $SO_2$  emissions. As expected, the  $SO_2$  emission for burning the emulsion of 2.5% bio-oil + 97.5% HFO was slightly lower than that for



burning pure HFO. An  $\text{SO}_2$  emission reduction of around 7.9% was obtained for burning the emulsion of 2.5% bio-oil + 97.5% HFO compared with pure HFO.

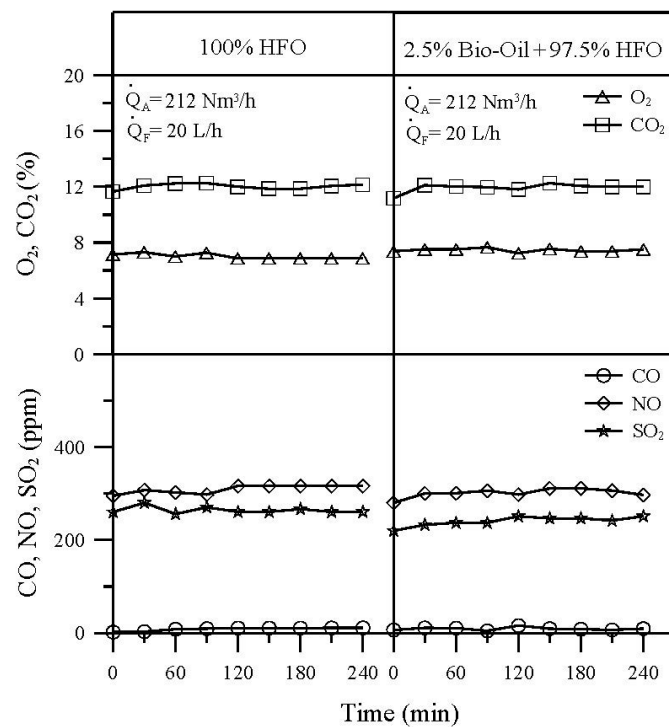


Figure 6. Emissions when burning 100% HFO and the emulsion of 2.5% bio-oil and 97.5% HFO.

#### 4. Conclusions

In this study, combustion characteristics and pollutant emissions of burning fast pyrolysis bio-oil/heavy fuel oil blends in a 300-kW<sub>th</sub> furnace were investigated. The conclusions are drawn as follows:

- (1) At fixed fuel and air flow rates, burning the emulsion of 2.5% bio-oil + 97.5% HFO resulted in a slightly lower temperature in the combustion chamber than burning pure HFO, since the pyrolysis bio-oil has a low calorific value and a high water content of as much as 27%.
- (2)  $\text{O}_2$  and  $\text{CO}_2$  concentrations in flue gas for burning the blend of 2.5% bio-oil + 97.5% HFO and pure HFO were nearly the same. Additionally, the CO concentrations in these two burning conditions are close to 0 ppm because of the low excess oxygen operating conditions.
- (3) Compared with burning pure HFO, an NO emission reduction of around 2.6% was obtained for burning the emulsion of 2.5% bio-oil + 97.5% HFO.
- (4)  $\text{SO}_2$  emission for burning the emulsion of 2.5% bio-oil + 97.5% HFO was slightly lower than that for burning pure HFO. An  $\text{SO}_2$  emission reduction of around 7.9% was obtained.

In view of the furnace tests, due to the complex composition of fast pyrolysis oil, preheating will lead to instability of the fuel supply system in the combustion test. Increasing the mixing ratio of fast pyrolysis bio-oil in HFO will make the combustion unstable during the preheating process. Closing the fuel preheating device will cause the deterioration of oil liquidity. When burning mixed fuel oils and pyrolysis bio-oil, it may be necessary to consider using two separate sets of oil pipeline rather than direct co-firing. Refined purification in the process of oil production is also needed to reduce unnecessary substances and the proportion of volatile substances for practical application.

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**Author Contributions:** Wei-Cheng Huang and Fakhrur M. Rizal performed the experiments and analyzed results. Shuhn-Shyurng Hou generated ideas, designed experiments, analyzed results, and wrote the manuscript. Ta-Hui Lin generated ideas, designed experiments, analyzed results, and helped editing the manuscript.

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

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