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Emissions and energy/exergy efficiency in an industrial boiler with biodiesel and other fuels

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A R T I C L E   I N F O

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A B S T R A C T

Industrial boilers are significant equipment in industrial operations used to provide steam or heat for production. More than 80% of fire-tube boilers use heavy oil in small and middle industries in Taiwan. Due to biodiesel as a sustainable fuel, the objective of this study is to measure experimentally and evaluated energy and exergy analysis of the fire-tube boiler using biodiesel (BD), undistilled biodiesel (UB), low sulfur oil (LSO), and ultra-low sulfur diesel (ULSD), and the various mixing ratios of undistilled biodiesel and low sulfur oil (UB90, UB70, and UB50) to reduce emissions from fire-tube boilers. Results from BD and UB are comparable, and UB exhibited a high NOx reduction rate of 68.9% and a high SO_2 reduction rate of 99.5% compared to LSO. The boiler that employed UB decreased CO_2 emissions, NOx, and SO_2 emissions. NOx emission increases with increasing LSO content. The boiler's maximum energy efficiency when using BD is 86.6%, and the overall exergy efficiency is 44.8%. The boiler with UB70 had the lowest energy efficiency of 73.5% and the lowest exergy efficiency of 38.7% because of the increased heat loss. The Benefits of this study are not only for boiler applications but also for government policy references.

Nomenclature

AFF	air-fuel ratio
BD	biodiesel
C	correction emission concentration (ppm or mg/Nm)
C_p	specific heat capacity (J/kg•K)
d	Relative density at 15 °C
E_x	Exergy
FGR	flue gas recirculation (%)
GCV	gross calorific value of the fuel (kJ/kg)
HHV	High heating value (kJ/kg)
h	Enthalpy (kJ/kg)
LNB	low NOx burner
LHV	low heating value (kJ/kg)

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LSO	low sulfur oil
M	quantity of steam generated (kg)
$\dot{m}$	Mass flow rate (kg/s)
R	gas constant (kJ/kg •K)
s	Entropy (kJ/kg •K)
S	standard deviation
T	Temperature (^{o}C)
UB	undistilled biodiesel
ULSD	ultra-low sulfur diesel

Subscript

0	reference state
a	Air
c	combustion
en	Energy efficiency
ex	Exergy efficiency
f	fuel
fg	Flue gas
i	Mole fraction
$loss$	Heat loss
p	product
s	steam
w	Feed water
χ	exergy
xd	Exergy destruction
xs	Steam exergy

Superscript

ph	physical
ch	chemical
po	Potential
ke	kinetic
0	reference state
H	Steam generation
B	Boiler

Greek letters

η	efficiency
δ	measurement error
γ	precision error

1. Introduction

Energy consumption and its impacts on the environment have become major global concerns. Environmental effects such as air pollution are affecting people's lives at increasingly high levels, where haze occurs in most areas in both developed and developing countries. According to a World Health Organization report, air pollution has been to more than 6.5 million deaths [1]. As a result, many countries have taken steps to combat it. Air quality control policies, for example, have been developed to limit emissions from stationary and mobile sources. Stationary sources include coal-fired power plants and various industrial-emitting pollutants devices. Boilers and heating furnaces, for example, contribute to air pollution. Among the various stationary sources of pollution, boilers play a crucial role in providing water or steam for many different chemical processes. Boilers provide water vapor as a power source for the electric generator and a source of heat in daily life, and their fuel consumption and emissions are enormous. These industrial boilers can have several categories: water-tube, fire-tube, and coal-fired boilers. The most popular types of boilers in Taiwan are water-tube and fire-tube boilers. The water-tube boiler is water in the boiler tube with high-temperature flue gas outside the tube surface, providing heat to water. Water-tube boilers used in factories require high pressure and high evaporation capacity. However, the fire-tube boiler is a fire tube or flue pipe in which the flue gas produced by the burned fuel with air flows through and heats the water, vapor, or vapor-water mixture outside the fire tube or flue pipe. Fire-tube boilers are mainly available in small factories with low pressure and evaporation capacity. According to the Environmental Protection Administration (EPA), there are approximately 114, 988 boilers in Taiwan. Fire-tube boilers accounted for 80% of the total.

All these boilers emit around 14,845 tons of NOx and about 11,246 tons of SOx annually [2]. To improve air quality and reduce boiler emissions, Taiwan's EPA also revealed standards to limit boiler NOx emissions to less than 100 ppm and SOx emissions to less than 50 ppm by 2020 [3]. In addition, the EPA has announced alternative regulations to encourage industries to replace old heavy-oil boilers with natural gas boilers or to use clean, sustainable fuels [4]. Traditional oil-fired boilers can operate with liquid fuels like diesel and biofuels without modifying parts. It is the most cost-effective way to reduce emissions immediately.

In industrial boilers, three primary ways of forming NOx are thermal, fuel, and prompt NOx [5]. Many developed techniques, such as flue gas recirculation (FGR), low NOx burners (LNBs), air staged combustion technology, re-burning technology, flue gas denitrification technology [6], and gas and coal co-firing technology [7,8] can decrease boiler NOx emissions. Another option is to use clean fuels such as ultra-low sulfur diesel (ULSD), biomass, and biodiesel to reduce boiler emissions. The combustion temperature is critical in producing NOx emissions [9]. FGR technologies employed in industrial burners, boilers, gas turbines, internal combustion engines, and Stirling engines can reduce the combustion temperature and NOx emissions while increasing combustion efficiency. FGR is a method that uses flue gas mixed with fresh air to inhibit combustion and lower the combustion temperature, thereby reducing NOx emissions. By adding relatively inert gases, such as N_2, H_2O, and CO_2, to the fuel-air mixture to dilute it and lower flame temperature, FGR lowers thermal NOx because the lower temperature prevents the reaction of diatomic nitrogen and oxygen in the fuel-air mixture [10,11]. However, FGR is ineffective in reducing fuel NOx. LNBs are to produce more branched flames by controlling air and fuel. It lowers the flame temperature resulting in less NOx in the combustion process [12]. These technologies necessitate boiler modifications such as replacing exhaust pipes and installing a blower or replacing an LNB burner with an oil burner. Changing boiler fuels is another option for lowering emissions without requiring boiler modifications, as previously discussed in the literature [13], which indicates that using biomass as fuel could reduce CO_2, SOx, and NOx emissions.

In addition to emissions, energy consumption is the primary consideration in all fields involving using energy. Similarly, the most cost in the boiler operation process is the use of fuel in the boiler. In the previous two decades, energy and exergy exploration were widely applied to both power plants and air conditioners, and heat pumps [14–16]. Boilers are a subject in power plant research to evaluate exergy and energy efficiencies [17].

Exergy is relevant to the second law of thermodynamics as the amount of available energy derived from each unit in a system. Exergy is related not only to the amount of heat emitted by the system but also to the temperature of the surrounding environment. The available energy of each unit can be calculated using an exergy analysis and used as a reference for system design or operation. However, regarding boiler systems, little literature compared the exergy efficiency of boilers that used different fuels. Song et al. [18] evaluated and created a chemical exergy database for biomass 86, but out of biodiesel. Li et al. [19] calculated the exergy of a boiler fed by biomass. Their findings could help evaluate and improve the design of biomass boilers. Costa et al. [20] investigated the exergy and energy efficiency of a 50 MW power station fed by residual forest biomass. They pointed out that residual biomass with a lower moisture content had higher energy efficiency.

Biodiesel, a low-sulfur and nitrogen content liquid fuel, has been used in road transportation. It can reduce atmospheric and greenhouse gas emissions [21,22]. Conventional biodiesel is created by transesterifying vegetable or animal fats, such as soybean, rapeseed, or pig fat [23]. A search of the literature revealed some studies on biodiesel boilers as well. Some researchers have measured and investigated the emissions of biodiesel and heating oil-fueled boilers [24]. Their findings showed that using biodiesel reduces CO and PM emissions significantly. Bazooyar [25] has also studied the emissions of a semi-industrial boiler fed with Petro diesel and various biodiesel feedstock fuels, including grape seed, corn, sunflower, and soybean. Some studies have found that biodiesel has higher combustion efficiency and lower emissions than diesel [26]. The CO, SO_2, and CO_2 emissions decreased with increasing biodiesel blending ratios, except for B10 [27]. The process of biodiesel production includes transesterification, esterification, recovery, biodiesel separation, purification with conventional water washing, and distillation (see Fig. 1). Because diesel engine vehicles have very accurate fuel injection systems, biodiesel should be purified using a distillation process to reduce impurities and monoglycerides in the biodiesel and make it suitable for diesel engine applications [28]. The distillation process needs to heat the crude biodiesel and pass it through the distillation tower to purify biodiesel, which means higher costs and more energy consumption. A boiler burner does not have the same severe criteria as a diesel engine due to using the heavy oil burner, so biodiesel without a distillation process is also appropriate for a boiler burner. It only needs to filter the impurities in the fuel. As a result, industries use biodiesel without a distillation

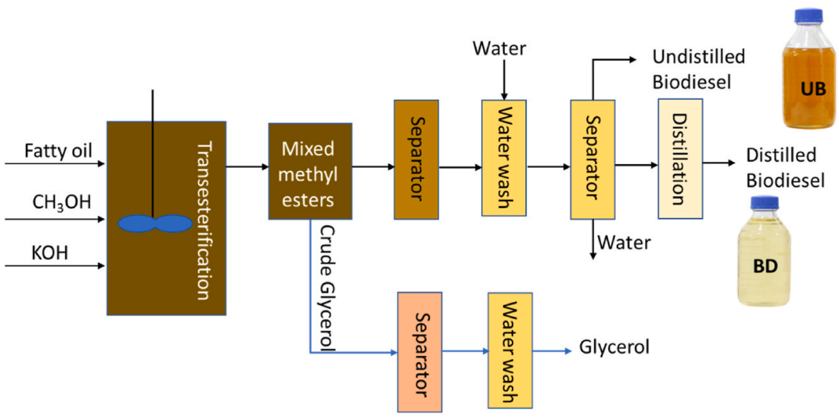

Fig. 1. Biodiesel production process schematics.

process (also known as undistilled biodiesel, defined as UB in this paper) in boilers to save money. Against biodiesel, UB contains the most acids, diglycerides, triglycerides, and fatty acids (defined as BD in this paper). It is less expensive and suitable for boiler applications.

According to the previous review, there are few studies on boiler emissions when using UB in conjunction with FGR on the exergy of boilers when using BD and other commercial fuels. The cost of an industrial boiler experiment is high, and there has never been a similar study. The novelty and goal of this study is to use BD, UB, LSO, ULSD, and mixing fuels of UB blended with LSO to realize how to decrease emissions from fire-tube boilers and increase energy/exergy efficiency. This study evaluated the operating parameters and emissions of industrial fired-tube boilers using these fuels and determined the emissions and energy efficiency of boilers. The impact of FGR on NOx emissions has also been investigated and discussed. Employing the information can determine the value of biofuels in boilers. The results of the experiment and exergy evaluation are beneficial for industry applications and research development.

2. Experimental arrangement and approach

2.1. Experimental arrangement

Fig. 2 depicts a horizontal fire-tube steam boiler with measurement devices such as a fuel flow meter, an airflow meter, an FGR meter, a NO_X meter, and an emissions analyzer. The fire-tube boiler is a higher outer shell of a pressure vessel that houses the combustion chamber and numerous straight tubes. The combustion gas exits the combustion chamber via straight pipes, while water and steam circulate outside these pipes [29]. Because the transfer surface is limited, this type of boiler cannot operate under high-pressure conditions not used for high steam generation capacity. The steam generation capacity in this study was 3 tons per hour, the heat transfer surface was 54 m^2, and the maximum operating pressure was 10 kg/cm^2. Small and medium enterprises in Taiwan have used the most low-cost boilers and burners that feed heavy oil in their factories. The most traditional type of burner was a low-pressure air-atomizing oil burner used in this study, as shown in Fig. 3. The fuel injection pressure was 2 kg/cm^2. Fuel consumption ranged from 70 to 240 L per hour, with the maximum fuel flow rate determined by the size of the boiler. In this case, the maximum fuel consumption rate was 140 L per hour. This work placed a tee tube at the exhaust pipe that extended into the air inlet of the burner to assess the impact of FGR. A blower was installed in the burner's air inlet to force the flue gas out. When the viscosity and impurity of the tested oil, particularly the low sulfur oil, were taken into account, the maximum fuel consumption of the tested boiler was 140 L per hour. This study employed a Piusi K400 fuel flow meter. This fuel flow meter is an oval gear with high accuracy and low-pressure loss. The fuel flow meter had an accuracy of 0.5% through the scale range. The maximum flow rate was 1800 L per hour and was suitable for diesel, BD, and other types of liquid oil. The flow meter appeared upstream of the burner, and no returned oil occurred.

2.2. Tested fuels

The fuels tested in the boiler are biodiesel (BD), undistilled biodiesel (UB), low sulfur oil (LSO), and ultra-low sulfur diesel (ULSD). The specifications of all of these fuels are in Table 1. LSO has a much higher water content, viscosity, and sulfur content than the other three fuels. Because BD and UB are from animal or vegetable fats, their sulfur content is similar to ultra-low sulfur diesel, which is less than five ppm. The BD and UB have sulfur content much lower than LSO.

2.3. Gaseous emissions measurement equipment

Use the MRU Optima 7 to measure CO, NO, NO_2, O_2, and SO_2 emissions from a boiler [30]. Measure the exhaust gas temperature and measure CO_2 and efficiency using the exhaust gas composition. As shown in Table 2, the measurement module principle was according to electrochemistry methods and the type of measured gases, measurement range, and accuracy. Measure the air pump sucking the flue gas from the exhaust pipe in the measurement procedure. The sampling gases are cooled and filtered before being

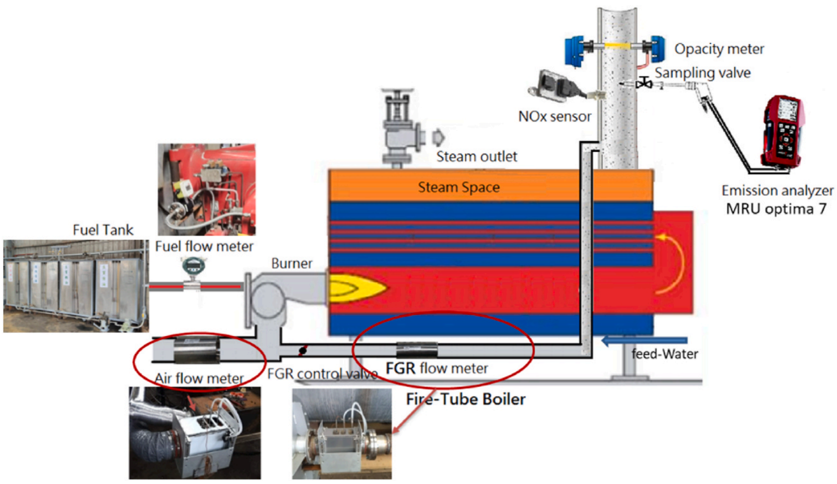

Fig. 2. Experimental setup.

Fig. 3. Picture of Experimental boiler and apparatus.

Table 1
Specifications of the tested fuel.

Fuel Type	BD	UB	ULSD	LSO
Acid Number (mg KOH/g)	0.31	0.26	–	–
Water (mg/kg)	210	248	71	−1900
Ester Content (wt%)	98.08	94.0	–	–
Oxidation Stability (hr)	13.8	11	–	–
Density @15 °C (g/ml)	0.8811	0.8824	0.8294	0.9434
Viscosity @40 °C (cSt)	4.262	4.612	3.103	108.6
Iodine Number	107	87.8	–	–
Free Glycerol (wt%)	0.009	0.01	–	–
Monoglycerides (wt%)	0.1008	0.9016	–	–
Diglycerides (wt%)	ND	0.5464	–	–
Triglycerides (wt%)	ND	0.3232	–	–
Total Glycerol (wt%)	0.0351	0.2894	–	–
Sulfur (ppmw)	2	2	3.7	3950
Hydrogen (wt%)	12.34	11.8	13.4	11.8
Carbon (wt%)	76.43	76.3	86.6	87.4
Oxygen (wt%)	11.23	12.0	<0.2	<0.2
Low Heating Value (kJ/kg)	39881	39931	42907	43739
High Heating Value (kJ/kg)	40881	40931	45482	46364

Table 2
The specifications for MRU Optima 7.

Gas	Range	principle	accuracy	resolution
O_2	0–21% vol	electrochemistry	0.2% abs.	0.1% vol.
CO	0-4000 ppm	electrochemistry	±5% of reading	1 ppm
NO	0-1000 ppm	electrochemistry	±5% of reading	1 ppm
NO_2	0–200 ppm	electrochemistry	±5% of reading	1 ppm
SO_2	0-2000 ppm	electrochemistry	±5% of reading	1 ppm

analyzed by each type of electrochemistry gaseous device. Use a measurement module at a height eight times according to the testing regulations.

2.4. *Testing procedure and calculation formula*

The first part of the experiment involves measuring emissions from the control group, which uses LSO and ULSD but no FGR. Measure the boiler operation parameters, including the steam temperature, pressure, and inlet air flow rate. The second stage entails feeding BD and UB into the boiler burner. Finally, investigate the effect of FGR with flue emissions measured compared to the non-FGR condition. The emissions and other data are then analyzed.

2.5. *Emission correction formula*

The EPA regulatory authority in Taiwan requires that the boiler's emission readings have a 6% correctness within the reference oxygen content. The use of reference oxygen ensures that emissions measurements appear consistently. The emission correction formula occurs in Eq. (1).

$$C = (21 - O_n) / (21 - O_s) \times C_s \tag{1}$$

where C denotes the correction or unnecessary correction emissions concentration (ppm or mg/Nm); C_s is the emissions concentration (ppm or mg/Nm) measured using the regular testing method; O_n denotes the oxygen reference value (%) from the exhaust gas, where 6% is used under normal conditions, and O_s is the measured exhaust gas oxygen concentration (%).

2.6. Flue gas recirculation rate and boiler efficiency formula

The formula shown in Eq. (2) calculate the flue gas recirculation rate (FGR).

$$FGR(\%) = (\text{Recycled flue gas})/(\text{Total flue gas}) \times 100 \tag{2}$$

The "input-output method" is a formula used to determine the boiler's efficiency. The unit of recycle and total flue gas is kg/h. Using the available energy output and heat input can calculate energy efficiency with Eq. (3).

$$\text{Boiler efficiency } \eta(\%) = (\text{Energy output})/(\text{Energy input}) \times 100 = [M(h_s - h_w) / q \times GCV] \times 100 \tag{3}$$

where M denotes the amount of steam produced (kg/hr); h_s represents the enthalpy of steam (kJ/kg); h_{sw} stands for the enthalpy of water (kJ/kg); q denotes the fuel consumption (kg/h), and GCV represents the gross calorific value of the fuel. In this study, boiler thermal efficiency refers to the Chinese National Standard (CNS 2141) [31] and uses LHV as the parameter for calculation. Employing data from the water and fuel flow meters calculates water and fuel consumption.

2.7. Measurement error analysis

According to Ref. [32], the measurement error (δ_k) consists of a bias error (β) and a precision error (γ_k), as shown in Eq. (4).

$$\delta_k = \beta + \gamma_k \tag{4}$$

The precision error is calculated by repeating n measurements, as shown in Eq. (5), where S is the standard deviation.

$$S_{\bar{x}} = \frac{S}{\sqrt{n}} \tag{5}$$

Eq. (6) can be used to calculate the measurement uncertainty (U) with 95% confidence, in which URSS is the measurement uncertainty calculated using the root sum square (RSS) method; B is the bias limit of emissions on the emission analyzer, which is equal to 0.01, and t is set to 2 for great samples. As shown in Table 3, the measurement uncertainties are estimated.

$$U_{Rss} = \left[\beta^2 + (tS_{\bar{x}})^2\right]^{1/2} \tag{6}$$

3. Exergy analysis methodology

3.1. Methodology

Assess the exergy and energy efficiency of the boiler with BD and various fuels by employing energy and exergy performance analysis. The energy performance analysis is based on the first law of thermodynamics, a method used to assess energy conversion or transfer in a process. Furthermore, the exergy performance analysis is based on the second law of thermodynamics and the entropy generation is an irreversible process. Exergy includes physical exergy, known as thermomechanical flow, chemical, potential, and kinetic exergy. It can appear in Eq. (7) [33].

$$E_x = E_x^{ph} + E_x^{ch} + E_x^{po} + E_x^{ke} \tag{7}$$

When the potential and kinetic exergy are ignored in this study's boiler exergy evaluation, E_x^{po} and E_x^{ke} are both zero. Eq. (8) shows how to rewrite physical exergy.

$$E_x^{ph} = \dot{m}[h - h_0 - T_0(S - S_0)] \tag{8}$$

in which h_0 denotes the enthalpy; T_0 is the temperature, and S_0 signifies the entropy in the reference state. The authors measured and referred to previous references or thermodynamic tables to get properties such as enthalpy and entropy to estimate the boiler exergy. For exergy calculations, the boiler can be separated into a combustion unit and a steam-generating unit, as shown in Fig. 4. In the combustion unit, fuel and air were introduced, which subsequently underwent a chemical reaction, with the generated high-

Table 3
Measurement uncertainties of emissions.

	bias error	Measurement uncertainties
CO:	1 ppm	±1.00 ppm
O_2:	0.1%	±0.102%
NOx:	1 ppm	±1.07 ppm
SO_2:	1 ppm	±1.00 ppm
Temp.	1.1 °C	±1.23 °C

temperature products flowing into the steam generating unit. The steam generating unit received high-temperature products and water to heat the water, which became saturated steam, flue gases, and heat. Then acquire the exergy efficiency and exergy destruction for each unit. Eq (9) expresses the total energy of the boiler.

$$E_{in}(kJ/s) = \dot{m}_f h_f + \dot{m}_a h_a \tag{9}$$

in which $\dot{m}_f$ denotes the fuel mass flow rate, and $\dot{m}_a$ represents the air mass flow rate introduced into the burner for combustion. As stated in Table 4, these flow rates were measured during the emission testing process. Furthermore, h_f and h_a denote the enthalpies of fuel and air. h_f is the lower heating value of various fuels delivered into the burner, and h_a can be computed using Eq. (10).

$$h_a(kJ/kg) = 1.005 \bullet T_a + a_w \bullet (1.88 \bullet T_a + 2501) \tag{10}$$

T_a = the temperature of air fed into the combustion, and a_w = the weight fraction of water in the air, which is equal to 0.0303.

The following equation can be used to determine energy destruction in the combustion unit:

$$E_{xd}^{c} = \dot{m}_a\left[E_{xa}^{ph} + E_{xa}^{ch}\right] - \dot{m}_p E_{xp}^{ph} + \dot{m}_f\left[E_{xf}^{ph} + E_{xf}^{ch} - E_{xfp}^{ch}\right] \tag{11}$$

When Eq. (8) is substituted in to Eq. (11), the exergy destruction is reformulated as follows:

$$E_{xd}^{c} = \dot{m}_a\left[(h_a - T_0 S_a) + E_{xa}^{ch}\right] - \dot{m}_p\left(h_p - T_0 S_p\right)$$

$$+\dot{m}_f\left[\left(h_f - T_0 S_f\right) + E_{xf}^{ch} - E_{xfp}^{ch}\right] \tag{12}$$

where the E_{xa}^{ch} is the chemical exergy of air. The E_{xa}^{ch} can be expressed in the standard environment by Eq. (13).

$$E_{xa}^{ch} = \sum_{i=1}^{n} x_i e_{xi}^{ch} \tag{13}$$

where x_i is the mole fraction of elements in the air, and e_{xi}^{ch} is the exergy of elements such as nitrogen, oxygen, and other gases; h_p is the enthalpy of heat products; S_a is the entropy of air; S_p is the entropy of heat products, and S_f is the entropy of fuel. The entropy of air, S_a, refers to the thermodynamics table. According to the law of mass conservation, $\dot{m}_p = \dot{m}_a + \dot{m}_f = \dot{m}_{fg}$, where $\dot{m}_p$ denotes the mass flow rate of products after combustion, and $\dot{m}_{fg}$ represents the mass flow rate of flue gases. Eqs.(14)–(16) can be used to calculate all entropies.

$$h_p = \left(\dot{m}_f h_f + \dot{m}_a h_a\right) / \dot{m}_p = \left(\dot{m}_f h_f + \dot{m}_a h_a\right) / \left(\dot{m}_f + \dot{m}_a\right) \tag{14}$$

$$S_p = h_p / \left(T_{fg} + 273.15\right) \tag{15}$$

$$S_f = h_p / (T_c + 273.15) \tag{16}$$

where T_{fg} is the temperature of flue gases derived from the experiment. T_c is the combustion temperature derived using Eq. (17).

$$T_c = T_{ca} + \left[LHV / C_p \times (1 + AFF)\right] \tag{17}$$

where C_p is the determined specific heat capacity using Eq. (18). AFF is the air-fuel ratio, which is computed employing the measured fuel and air mass flow rates during the test.

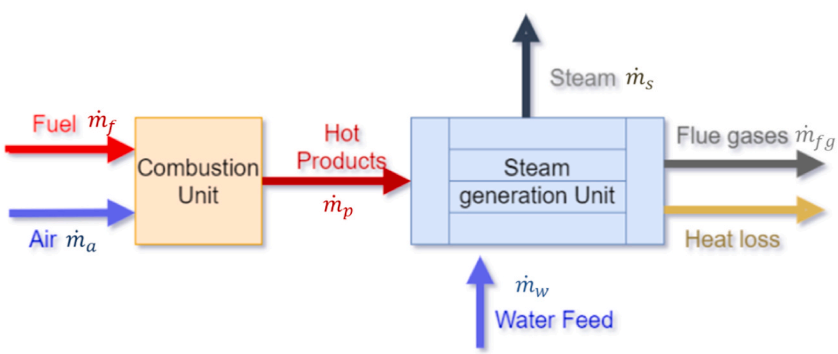

Fig. 4. Schematic diagram of exergy analysis on the boiler unit.

Table 4
Measurement parameters of the boiler for the exergy analysis.

Items	Mass flow rate (kg/s)			Flue gas Temp. (°C)	Air Temp. (°C)	Feed water Temp. (°C)
	$\dot{m}_a$	$\dot{m}_f$	$\dot{m}_w$	T_{fg}	T_a	T_w
BD	0.560	0.0337	0.460	208	30	45
UB	0.585	0.0326	0.483	209	31	45
UB90	0.480	0.0340	0.442	213	31	45
UB70	0.430	0.0326	0.419	216	31	45
UB50	0.410	0.0314	0.422	214	31	45
LSO	0.392	0.0222	0.322	204	31	45
ULSD	0.540	0.0300	0.472	206	32	45

$$C_p = \left[1.6831 + 3.3913 \times 10^{-3} \times T_{ar}\right] \Big/ \sqrt{d} \tag{18}$$

where T_{ar} is the room temperature of boilers during operations, as observed during the experiment, and d is the relative density of testing fuels at 15 °C.

E_{xf}^{ch} is the exergy of fuel, which is equivalent to the higher heating value (HHV), and can be found in the fuel analysis report presented in Table 1. E_{xfp}^{ch} is the exergy of the flue gases and is computed employing Eq. (13). The emissions test yielded the flue gas constituents. As a result, the exergy efficiency is defined as Eq. (19).

$$\eta_{ex}^{c} = \dot{m}_p\left(h_p - T_0S_p\right) \Big/ \dot{m}_f\left[\left(h_f - T_0S_f\right) + E_{xf}^{ch} - E_{xfp}^{ch}\right] \tag{19}$$

A heat exchanger in a steam production unit transfers heat from combustion to feedwater and heats the water into a saturated vapor with some heat loss. Radiation, convection, and stack losses are all the boiler's energy losses. Poor fuel and water quality will contribute to higher energy losses, lower efficiency, and inefficient operations. The heat loss Q_{loss}^{H} can also be calculated using Eq. (20) as follows:

$$Q_{loss}^{H} = \dot{m}_p\left(h_p - h_g\right) - \dot{m}_w(h_s - h_w) \tag{20}$$

where h_g denotes the enthalpy of flue gases; h_s represents the enthalpy of saturated steam, and the h_w is the enthalpy of feed water, all of which are cited in the thermodynamics textbook [34]. The ratio of heat input to energy production from the steam is the energy efficiency of a steam production unit. As a result, the energy efficiency of the steam generation unit is defined in Eq. (21) as follows:

$$\eta_{en}^{H} = \dot{m}_w(h_s - h_w) \,/\, \dot{m}_p\left(h_p - h_g\right) \tag{21}$$

Eq. (22) is also used to determine the exergy destruction of a steam generating unit, and it can be rewritten as indicated in Eq (23).

$$E_{xd}^{H} = \dot{m}_pE_{xp}^{ph} + \dot{m}_w\left[E_{xw}^{ph} + E_{xw}^{ch}\right] - \dot{m}_s\left[E_{xs}^{ph} + E_{xs}^{ch}\right] - \dot{m}_{fg}\left[E_{xfg}^{ph} + E_{xfg}^{ch}\right] \tag{22}$$

$$E_{xd}^{H} = \dot{m}_p\left(h_p - T_0S_p\right) + \dot{m}_w\left[(h_w - T_0S_w) + E_{xw}^{ch}\right] - \dot{m}_s\left[(h_s - T_0S_s) + E_{xs}^{ch}\right] - \dot{m}_{fg}\left[\left(h_{fg} - T_0S_{fg}\right) + E_{xfg}^{ch}\right] \tag{23}$$

where S_p is the entropy of the heated product; S_w is the entropy of the feed water, and E_{xw}^{ch} is the chemical exergy of water. $\dot{m}_s$ signifies the mass flow rate of steam, which is equal to the $\dot{m}_w$; S_s denotes the entropy of steam, and E_{xs}^{ch} is the chemical exergy of steam. $\dot{m}_{fg}$ denotes the mass flow rate of flue gas, which is equal to the value of $\dot{m}_p$. h_{fg} signifies the enthalpy of flue gas; S_{fg} denotes the entropy of flue gas, and E_{xfg}^{ch} represents the chemical exergy of the flue gas. The steam generation unit exergy is given in Eq. (25).

$$\eta_{ex}^{H} = \left\{\dot{m}_s\left[(h_s - T_0S_s) + E_{xs}^{ch}\right] - \dot{m}_w\left[(h_w - T_0S_w) + E_{xw}^{ch}\right]\right\} \Big/ \left\{\dot{m}_p\left(h_p - T_0S_p\right) - \dot{m}_{fg}\left[\left(h_{fg} - T_0S_{fg}\right) + E_{xfg}^{ch}\right]\right\} \tag{25}$$

After evaluating the exergy and energy efficiency of individual boiler units, Eq. (26) may be used to compute the energy efficiency of the boiler. Eq. (27) depicts the exergy destruction of combustion and the steam generation unit. Then use Eq. (28) to calculate the boiler exergy efficiency.

$$\eta_{en}^{B} = \dot{m}_s(h_s - h_w) \,/\, \dot{m}_fh_f \tag{26}$$

$$E_{xd}^{B} = E_{xd}^{c} + E_{xd}^{H} \tag{27}$$

$$\eta_{ex}^{B} = \left\{\dot{m}_s[(h_s - T_0S_s) - (h_w - T_0S_w)] + E_{xs}^{ch} - E_{xw}^{ch}\right\} \Big/ \left\{\dot{m}_f\left[\left(h_f - T_0S_f\right) + E_{xf}^{ch} - E_{xfp}^{ch}\right]\right\} \tag{28}$$

4. Results and discussion

4.1. Undistilled biodiesel (UB)

Fig. 5 shows that the FGR ranges from 0% to 26.3% when testing UB. Under FGR, which is equal to 0%, all emissions were very stable. The oxygen concentration in the exhaust was 3.23% under boiler operating circumstances; after emissions correction, CO emissions were approximately 4.13 ppm; NOx emissions were about 58.19 ppm; and SO_2 emissions were around 0.82 ppm. The ideal operating condition for the boiler was an oxygen concentration in the exhaust gas of roughly 2%–3% at a high load, according to Ref. [35]. When the oxygen content exceeds 5% in the air, the surplus air diverts heat away from the fuel burning, lowering boiler efficiency. As a result, the boiler operation in this study had the best operating conditions. The results showed that when UB appeared in the boiler, NOx emissions were substantially smaller than the regulatory requirement of 40 ppm. However, because the sulfur concentration of UB was less than five ppm, SO_2 emissions were nearly 0 ppm, much below the 50 ppm emission standards.

Fig. 5 also depicts the influence of FGR, ranging from 13% to 26.3%, on emissions when using UB in the boiler. When the FGR reaches 13%, the flue gas flows into the boiler's combustion chamber. Simultaneously, as the fresh air mass falls, the oxygen concentration decreases in the exhaust gas. The average CO emissions were 3.34 ppm, the O_2 concentration in the exhaust gas was 2.65%, the NOx concentration was 37.62 ppm, and the SO_2 was 0 ppm. When the FGR reached 17.1%, the O_2 fell to 2.36%, the CO was 3.54 ppm, and the NOx was 35.72 ppm. When the FGR was 20.5%, the O_2 concentration dropped to 2.09%, and CO was 4.52 ppm, higher than without the FGR. It was because the oxygen content diluted as the amount of flue gas increased, resulting in incomplete combustion. On the other hand, the average NOx emissions were 31.75 ppm, which decreased as the FGR increased. It can be attributable to incomplete combustion, which lowers the peak combustion temperature and inhibits thermal NOx. When the FGR reached 23.3%, the O_2 concentration in the exhaust gas decreased to 1.64%, while CO emissions increased to 8.59 ppm. When the FGR increased to 26.3%, the O_2 concentration in the exhaust gas decreased to 1.01%, while CO emissions increased to 29.24 ppm. Therefore, as the FGR gradually rose from 13% to 26%, less air and fresh oxygen entered the boiler. As a result, the measured oxygen concentration in the exhaust gas decreased from 2.65% to 1.01%. A higher FGR led to higher CO emissions, especially when the FGR was equal to 26.3%. NOx emissions decreased with increasing FGR, with results of 27.08 ppm and 21.15 ppm; flue gas quantities inhibited the formation of thermal NOx.

4.2. Biodiesel (BD)

Because the properties of BD and UB are so similar, the emission results were also very close. Fig. 6 demonstrates that when using BD, FGR was equal to 0%, the O_2 concentration in the exhaust gas was 2.84%, the correction to CO emissions was 5.68 ppm, NOx was 52.2 ppm, and SO_2 was 0 ppm. Since the degree of purification was greater in BD than in UB, NOx emissions were fewer than six ppm. Fig. 6 also indicates that when the FGR was equal to 7.7%, the emissions did not differ significantly because the flue gas was not high enough to make a difference. The O_2 concentration in the exhaust gas was approximately 2.56%; CO averaged 5.32 ppm, and NOx was 42.76 ppm. Because BD contains almost no sulfur, regardless of the FGR condition, SO_2 was 0 ppm. Only NOx emissions decreased to 39.72 ppm when the FGR rose to 13%, and the other emissions were not significantly different. In the same situation, BD had a NOx emission difference of only about two ppm compared to UB. The findings revealed that UB and BD had a minor impact on emissions. The flue gas affected combustion significantly when the FGR was equal to 20.5%. At the same time, CO emissions were affected by the flue gas and averaged about 13.8 ppm as the O_2 concentration declined to around 1.6%. NOx emissions have steadily decreased to 30.47 ppm. When the FGR increased to 24.3%, the combustion was significantly impacted by the flue gas when O_2 decreased to 1.2%, and CO increased by about 25.56 ppm because of incomplete combustion. Table 5 shows the power of the burner and the O_2 concentration under the constant fuel input operating condition. When using BD as the boiler fuel, the O_2 and NOx concentrations decreased as the FGR increased, just as they did with UB. CO emissions increased when the FGR exceeded 12%. They also increased when the FGR exceeded 23%. Regardless of FGR, the sulfur content of the fuel affected SO_2 emissions. Controlling the oxygen concentration in the exhaust gas between 2 and 3% would be the best operating condition. Therefore, the FGR rate should operate at about 7.7%. Under this condition, NOx emissions of the boiler decline by 18.0% compared to no FGR.

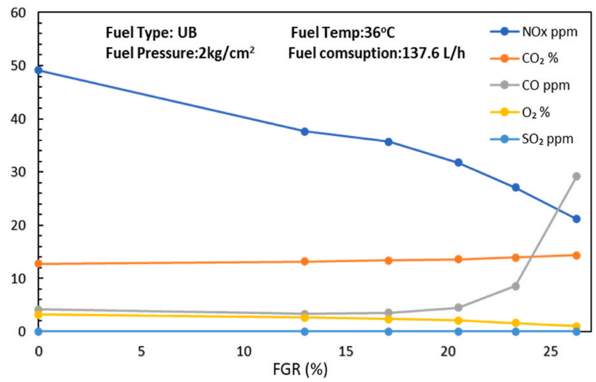

Fig. 5. Emissions of the boiler using UB with different FGR levels.

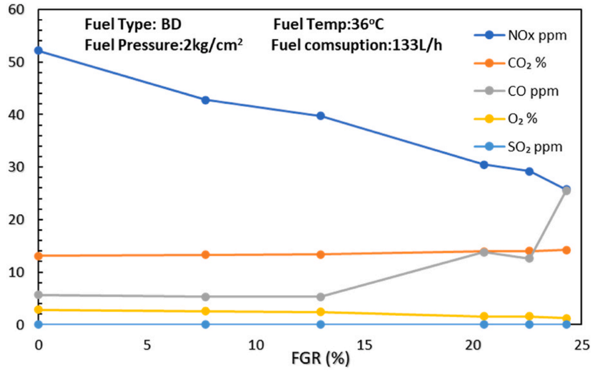

Fig. 6. Emissions of the boiler using BD with different FGR levels.

Table 5
FGR experiment operating condition and power of burner.

FGR(%)	*Air (kg/s)*	*Fuel input (kg/s)*	*Power of Burner (kW)*	*Flue gas Temp. (°C)*	*O_2 conc. (%)*
0	0.585	0.0326	1298	211	2.2
7.7	0.516	0.0326	1298	208	2.5
13.0	0.496	0.0326	1298	208	1.7
20.5	0.482	0.0326	1298	209	1.7
22.6	0.465	0.0326	1298	207	1.8

4.3. Ultra-low sulfur diesel (ULSD) and low sulfur oil (LSO)

ULSD was used as a control group to compare with UB. As a result, the comparison of ULSD and UB was without FGR. Fig. 7 shows that when ULSD flows into the boiler, the emissions are stable. Under an O_2 concentration of 3.48%, CO gaseous emissions were 5.28 ppm, and NOx concentration was 45.5 ppm. SO_2 emissions were 0 ppm since ULSD fuel has a low sulfur level of 3.7 ppm. Without FGR, the O_2 concentration was 3.38%; CO emissions were 9.34 ppm, NOx emissions were 158.09 ppm, and SO_2 emissions were 58.8 ppm.

LSO is the fuel for a conventional boiler, although boiler emissions are extremely high. The EPA issued regulations to phase them out. The test oil must pass through an electric heater to 60°C–80 °C with a controllable oil supply pressure, and the burner can run smoothly. Fig. 7 illustrates that when a low-sulfur oil flows into the boiler, the emissions are more unstable than when the other three fuels are in the boiler. Without FGR, the O_2 concentration was 3.38%; CO emissions were 9.34 ppm; NOx emissions were 158.09 ppm, and SO_2 emissions were 58.8 ppm. The NOx and SO_2 emissions exceeded the regulatory limitations. According to Ref. [36], NOx emissions form through two mechanisms: thermal NOx and fuel NOx, and the nitrogen content in the fuel determines the latter. The only way to reduce NOx emissions is with low nitrogen content. NOx emissions form primarily from combustion, occurring at a high combustion temperature. As previously stated, SO_2 emissions are exclusively dependent on the sulfur level of the fuel.

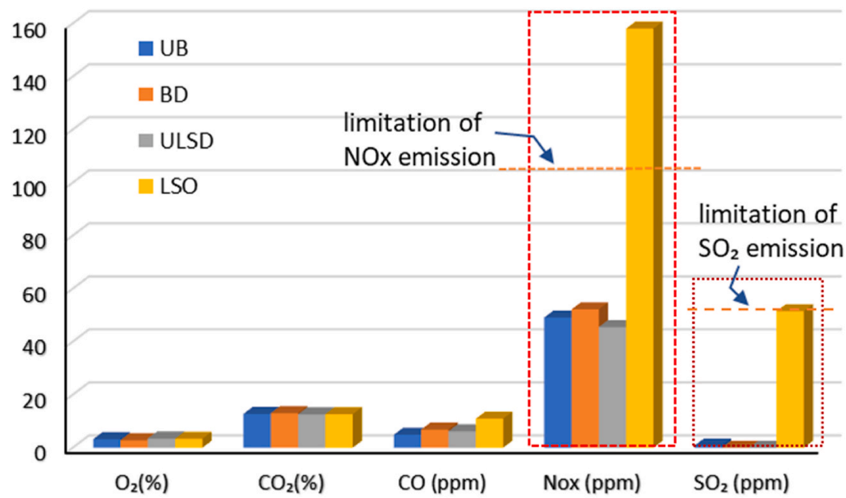

Fig. 7. Comparison of boiler emission concentrations without FGR using various fuels.

4.4. Emission comparison of various fuels

Fig. 8 also illustrates the boiler emissions with the various fuels of interest. The results show that regardless of whether using UB, BD, or ULSD, the emissions will meet Taiwan's 2020 emission standards. The results also demonstrate that LSO generates more emissions than the legal limit. Using the UB, BD, and ULSD reduces emissions significantly. Furthermore, UB has the benefit of carbon neutralization for promotion in the future. The exhaust gas for the boiler used in this study was approximately 1350 m^3/h, and the NOx emissions were 211 g/h when using LSO, resulting in 1.85 tons of NOx emissions per year. SO_2 emissions were 4.23 tons per year. However, if using UB, NOx emissions will decline to 0.58 tons per year, and SO_2 emissions will decrease to 0.02 tons per year. In terms of CO_2 reduction, the fuel consumption of this boiler is 130 L/h, equal to 1002.1 tons per year. According to Ref. [37], using UB reduces CO_2 emissions by an average of 80% compared to fossil fuels. As a result, CO_2 emissions will be approximately 2178.4 tons per year with LSO and only 1742.7 tons per year with UB. The BD and UB would be the best for emission and CO_2 reduction.

4.5. Emission comparison of UB mixing LSO

Using UB can lower NOx and SO_2 emissions, as demonstrated in Section 4.3, but since the cost of UB fuel was still significantly greater than that of LSO. For reducing fuel expenses, this study explores the emissions when mixing UB and LSO to see if they can stick to the emission requirement. UB90 is a blend of UB 90% and LSO 10%; UB70 is a blend of UB 70% and LSO 30%; and UB50 is a blend of UB and LSO 50% each. Fig. 8 shows that all the fuels used in the experimental boiler, including UB90, UB70, and UB50, have NOx emissions below the legal 100 ppm level. Increases in NOx emissions were significantly dependent on increases in the LSO ratio. SO_2 also presents the same trend. The usage of UB50, however, indicates that NOx is already extremely close to the legal limit and may cause NOx emissions to exceed the legal limit due to various operating conditions, such as combustion temperature rises. Other CO and CO_2 emissions did not increase with increasing the LSO ratio, which was the same as utilizing other oils, and there was no significant trend.

5. Energy and exergy analysis

5.1. Exergy analysis of BD with various FGR rates

The FGR is a critical approach to lowering NOx emissions in a boiler during the combustion process because non-inflammable flue gas dilutes the volume of fresh air. In Section 4.2, the boiler fed with UB at various FGR rates led to a decrease in NOx emissions; additionally, the boiler's exergy efficiency in the combustion and steam generation units also decreased. Fig. 9 depicts the boiler's exergy efficiency at various FGR rates when using BD as fuel. Increasing FGR not only reduces the exergy efficiency of the combustion unit but also raises the exergy efficiency of the steam generation unit by diluting the air more, resulting in increased heat loss and exergy destruction. When the FGR rate was 0%, the combustion in the boiler had the highest exergy efficiency at 43.5%, and the boiler's overall exergy efficiency was 45.9%. Furthermore, as the fuel input keeps constant with flue gases recirculated into the boiler, the combustion temperature decreases to reduce NOx formation. According to FRG, as the FGR rate increases, the enthalpy of the heat product decreases due to the reduction of fresh air. As a result, total exergy destruction increases to lower the boiler's exergy efficiency to 40.3% with a 22.6% FGR rate. Under the best FGR operating condition, which is about 7.7%, the boiler exergy efficiency decreases by 2.1% compared to no FGR.

5.2. Exergy destruction and exergy analysis of various fuels

Exergy refers to the maximum available part of the input energy in a system. Energy decreases during the energy transfer process. Employing exergy destruction assesses the energy quality in a system, with higher exergy destruction indicating a poor energy system

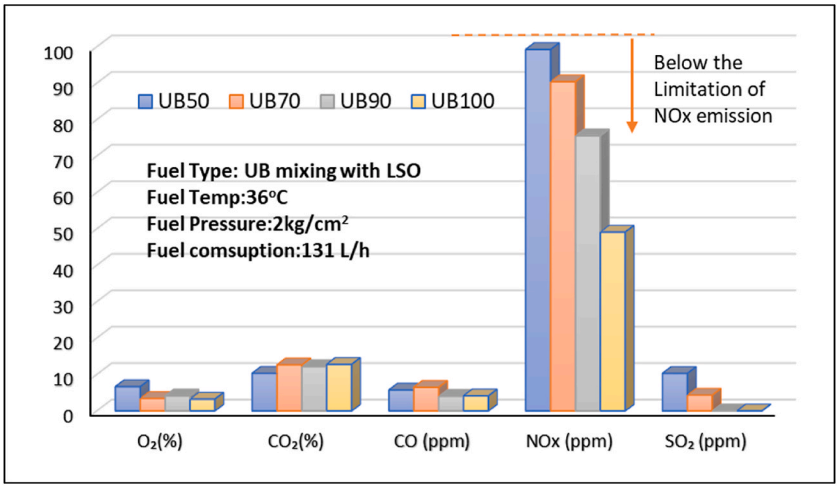

Fig. 8. Comparison of boiler emission concentrations using UB mixing with LSO.

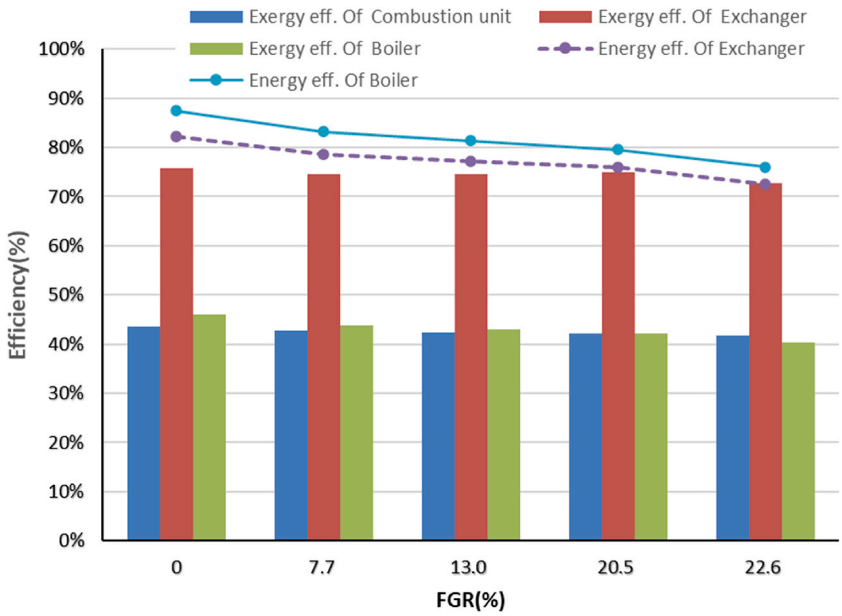

Fig. 9. Exergy efficiency for different FGR rates of the boiler with BD.

design. In other words, this will lead to lower energy efficiency and higher fuel consumption. The boiler can divide into a combustion unit and a steam generation unit, with the overall exergy destruction being the sum of the combustion and steam generation units. Using different fuels under the same testing conditions leads to varying exergy destruction of the various devices in the boiler. Fig. 10 shows the exergy destruction at different FGR ratios when using BD. According to Fig. 10, the steam generation unit loses more heat as the FGR ratio rises. The combustion unit is primarily responsible for the energy loss since its exergy destruction is about twice as great as the steam generating unit. Utilizing FGR to reduce NOx while suffering an energy efficiency loss is not the best strategy for reducing emissions and saving energy. Fig. 11 displays the exergy destruction of each unit in the boiler, with the combustion unit producing the highest exergy destruction. It is because the irreversibility process of the boiler is caused not only by the chemical reaction of the burner products but also by temperature differences between the burner products and the water in the boiler. In the case of a fixed fuel, the combustion unit had higher exergy destruction than the steam generation unit. In the exergy destruction of different oils, the UB and LSO blends have the opposite trend in NOx emissions. The higher the LSO blend, the lower the exergy destruction of the combustion and the steam generator unit. The current trend is consistent with that of the reference [38]. The combustion unit is the main contributor to exergy destruction, and the available energy gets the smallest in this unit; therefore, enhancing the exergy efficiency of the combustion unit can further increase efficiency gains.

As shown in Fig. 12, in terms of the steam generation unit, ULSD had the highest exergy efficiency at 77.1%, while UB70 had the lowest exergy efficiency at 68.2%. In the boiler system, BD had the highest exergy efficiency at 45.9%, while LSO had the lowest exergy efficiency at 35.3%. It was because LSO had the highest HHV in the denominator of Eq. (28) and the lowest exergy output due to non-flammable elements like water.

5.3. Energy efficiency

This study also evaluated the energy efficiency of the combustion and steam generation units using various bio-based fuels and commercial diesel fuels. Fig. 13 shows the energy efficiency of the steam generation unit and boiler. The heat transfer in the combustion unit was supposed to be in an adiabatic state, so the energy efficiency was 100%. The feed water in the steam generation unit received heat from the combustion byproduct. When using BD, the steam generation unit had the highest energy efficiency of 82.0%. When employing ULSD, the steam generation unit had an energy efficiency of 81.7%. The use of UB70 resulted in the lowest energy efficiency of the steam generation unit, which was 70.4%. The use of BD led to the best energy efficiency of 86.6%. While the UB50 and UB90 had close energy efficiency ratings of 75.8% and 75.5%, the UB70 had the lowest energy efficiency of 73.5%. Although BD has a lower LHV than ULSD, it releases more combustion heat because of the higher oxygen content, which leads to higher energy efficiency.

6. Conclusions

The objective is to use BD to reduce emissions and get efficiency improvements in the boiler for significant benefits of government policy references. In this study, the emissions of a fire-tube boiler using UB, BD, ULSD, LSO, and UB blended with LSO, including UB90, UB70, and UB50, were measured and analyzed. Performing an exergy analysis determined the exergy and energy efficiency of the boiler when fed with various fuels. The following are the findings of this study:

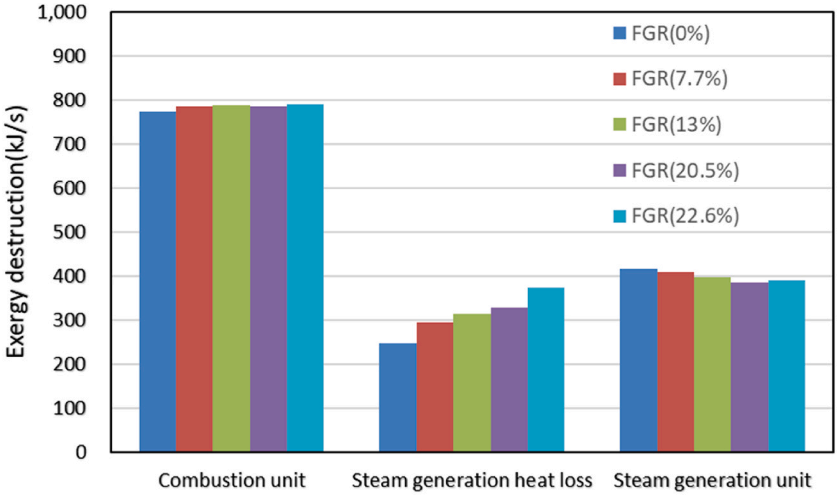

Fig. 10. Exergy destruction for different FGR rates of the boiler with BD.

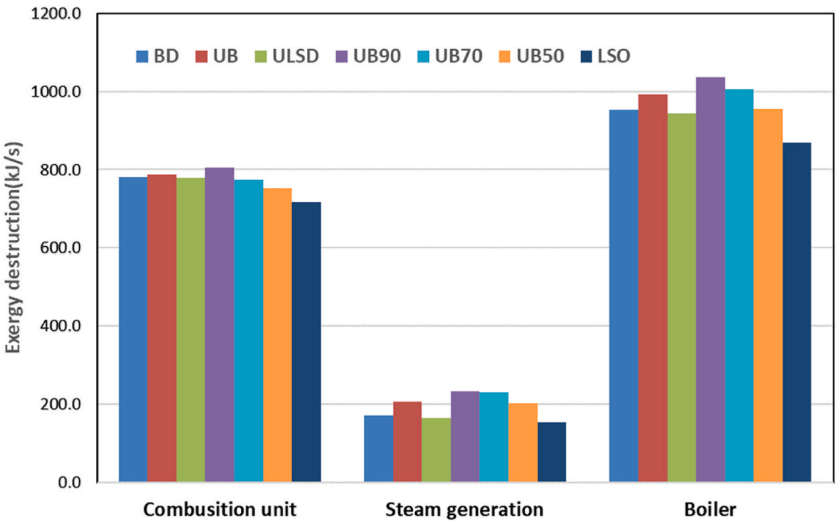

Fig. 11. Exergy destruction of the combustion unit, steam generation, and boiler without FGR for the various fuels.

1. The boiler energy efficiency is BD, ULSD, UB, LSO, UB90, UB50, and UB70, in that order, from high to low. The order of the exergy efficiency of the boiler from high to low is BD, ULSD, UB, UB50, UB90, UB70, and LSO.
2. According to the energy and exergy analysis, higher FGR rates lead to lower energy output and decreased energy efficiency. For the entire boiler system without FGR, BD has the highest energy efficiency as well as the highest exergy efficiency. In addition, the LSO resulted in the lowest exergy efficiency at 35.3%, and UB70 the lowest energy efficiency of the boiler at 73.5%.
3. The combustion unit is the main contributor to exergy destruction, and the available energy has the smallest in this unit. The exergy destruction of the steam generation unit loses more heat as the FGR ratio rises. Based on BD, the overall exergy destruction of the boiler is 8.9% higher than BD for UB90 and about 8.7% lower than BD for LSO.
4. When using UB and LSO blended fuels (UB90, UB70, and UB50), all can meet the NOx emission regulation requirements, and their NOx pollutants rise with the proportion of LSO. Because UB50 is very close to the regulatory limitation, there is a possibility of exceeding the regulations.
5. In the FGR experiment, the FGR rate should be operated at about 11.8%, to control the oxygen concentration between 2 and 3% and it was the best operation condition. In the various fuel experiments, the utilization of BD and UB would be the best choice for emission reduction.
6. UB and BD can apply not only to fire-tube boilers but also to water-tube boilers. Since water-tube boilers are always larger than fire-tube boilers, the reduced emissions will be higher. When comparing boiler operating costs, UB provides carbon-neutral benefits while costing less than BD and ULSD.

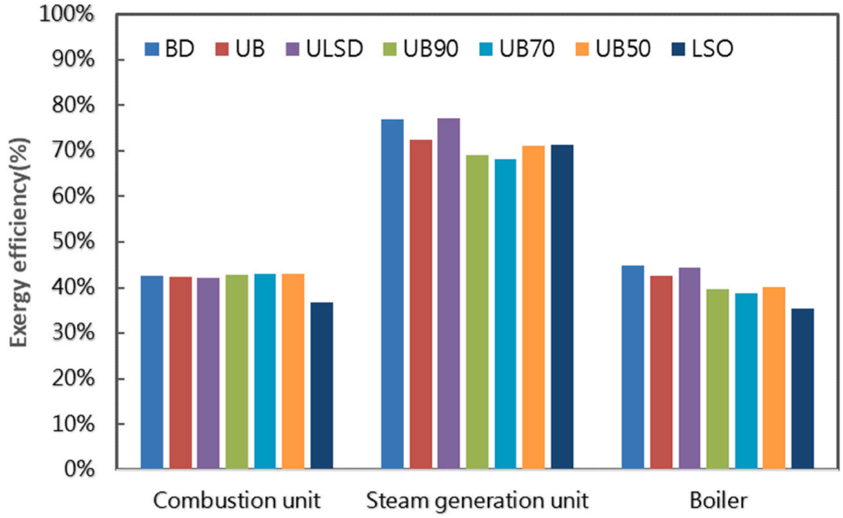

Fig. 12. Exergy efficiency of the combustion unit, steam generation, and boiler without FGR for the various fuels.

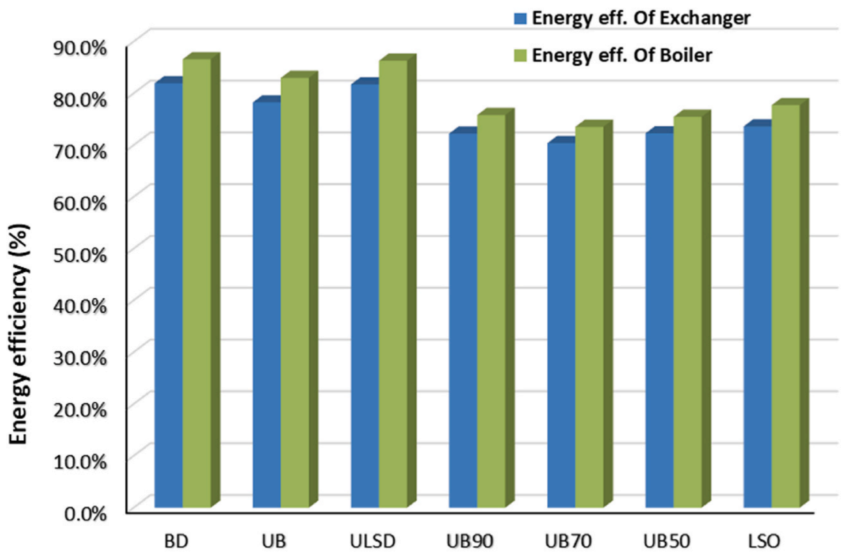

Fig. 13. Energy efficiency of the boiler without FGR for the various fuels.

Author starement

Ke-Wei Lin: Methodology, Formal analysis, and Writing – Original Draft; Horng-Wen Wu: Conceptualization, Resources, Writing – Review & Editing and Supervision.

Declaration of competing interest

We have no conflicts of interest to disclose.

Data availability

The authors do not have permission to share data.

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