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RESEARCH ARTICLE

Combustion of Scrap Waste Tires of a Cogeneration Plant

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Abstract

Various fuels can be used in circulating fluidized bed (CFB) boilers. In this study, the thermal and economic performance was investigated for three CFB fuels—heavy fuel oil, coal, and waste tire scraps—used in a cogeneration plant. The plant comprised a CFB boiler, a single-cylinder steam-extraction turbine, and a generator. Tire scrap combustion generated the most power per ton during peak hours: approximately 27.5% more than that generated using heavy oil and 42.3% more than when coal was employed; it also resulted in higher boiler efficiency during peak operation than coal (1.2% higher) or heavy oil (12.6% higher). The net plant efficiency during peak hours was highest for coal (25.09%), followed by tire scraps (23.82%) and heavy oil (18.11%). On the basis of international spot fuel prices, tire scraps were determined to have the lowest cost per kilowatt-hour generated, followed by coal and heavy oil. Using waste tire scraps as fuel can not only reduce pollution but also help hedge against international crises, which can affect energy imports.

Keywords: Circulating fluidized bed boiler, Heavy fuel oil, Coal, Scrap waste tire, Boiler efficiency, Net plant efficiency

1. Introduction

Approximately 1.5 billion tires are produced worldwide annually—equivalent to approximately 17 million tons of used tires. In 2013, EU countries were estimated to generate 3.6 million tons of used tires [1]; 4 million tons were produced in the United States in 2015 [2]. China, EU countries, the United States, Japan, and India generate approximately 88% of all tire scraps [3]. Most of these tires are recycled or recovered; however, waste tire treatment methods, such as gasification and pyrolysis, are underutilized. However, due to stricter EU environmental regulations, the energy crisis, and the expense of conventional fuel consumption, investment in pyrolysis oil plants has increased. Thus, pyrolysis may become an effective method of waste tire disposal. Unfortunately, tire scraps are still improperly discarded in some countries, resulting in negative impacts on both the environment and human health. Therefore, developing effective methods for appropriately disposing of waste tires is an urgent task.

Tires must be resistant to mechanical damage, long-lasting, and safe for use with vehicles; handling materials that meet these requirements is challenging. Rubber is not only durable and waterproof but also resistant to heat, current, many chemicals, and bacteria. All microorganisms that have been developed for use in experimental tire decomposition would still require over 100 years to completely break a tire down [4]. Moreover, tires are difficult to handle due to their large size. Dumped tires can become habitats for mosquitoes and rodents and are also a fire risk. Accidental or unregulated tire combustion produces toxic substances that contaminate the atmosphere, soil, surface water, and groundwater [5–7]. Despite these challenges, waste tires offer substantial opportunities for resource conservation because they are a large potential source of valuable materials and fuel [8].

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The number of global car drivers has been increasing rapidly in recent years. The numbers of drivers in Europe, China, and India were 322, 107, and 28 million in 2014, respectively, and are expected to reach 347, 332, and 69 million by 2025, collectively meaning nearly 750 million drivers. The increase in China and India represents more than a doubling of drivers within a single decade [9]. Moreover, the number of trucks is also increasing rapidly due to rising global demand for freight transportation, especially in developing countries. Truck tires must be more durable than car tires and can be substantially more difficult to handle.

The management of waste tires should follow generally accepted waste management principles: prevention, reduction, reuse, recycling, energy recovery, and ultimately landfill. This strategy can minimize the negative environmental impact of waste tires. The 1999 Waste Landfill Directive introduced a law prohibiting the landfilling of tires in EU countries [10], and the results of this directive have been impressive. In 1996, approximately 50% of waste tires were put in landfill; this proportion was reduced to 4% by 2010 [11]. Eleven states in the United States also prohibit the landfilling of tires; in some states, waste tires are employed as a supplemental fuel. The state of Arizona and some countries have begun to recycle waste tires for use in asphalt [12].

Inexpensive diesel fuels have low cetane numbers and cause knocking unless used in an engine with a high compression ratio, cetane improvers are added, or an external energy source is incorporated. Vihar et al. [13] used oil produced from waste tire pyrolysis in modern four-cylinder turbocharged and intercooled diesel engines to achieve better results at low load. Lopez et al. [14] pyrolyzed waste truck tires and reported that 475 °C is a suitable pyrolysis temperature because it ensures that no tire rubber is volatilized and yields up to 58.2 wt% pyrolysis oil. Furthermore, pyrolysis at this temperature produces oil of optimal quality and with high concentrations of valuable chemicals, such as limonene. Toledo et al. [15] investigated the use of a hybrid filtration reactor for the production of syngas, with the reactor being fueled by a mix of waste tire particles and alumina spheres. The hydrogen and carbon monoxide concentrations were found to be directly related to the thermal behavior of the reactor. These concentrations were highest when pure air was used as the gasifying agent, and higher reactor temperature was associated with higher syngas yield. Song et al. [16] used a waste tire microwave pyrolysis test system to investigate the effects of various factors on the production of limonene in waste tire pyrolysis oil. The optimal working parameters were a specific microwave power of 15 W/g and a particle size of 0.6 mm for steel-free tires. A recent study by Farooq et al. [17] explored the quality and quantity of pyrolysis oil produced through pyrolysis of wheat straw with a tire waste additive. Adding tire waste increased the calorific value from 23.3 MJ/kg for wheat straw alone to up to 40.7 MJ/kg. Adding tire waste also significantly increased the carbon content (58%–85%) but decreased the hydrogen and oxygen content of the resulting pyrolysis oil from 9.6% to 8.6% and 32.8% to 5.1%, respectively.

Taiwan's domestic energy production is limited; energy is a critical indicator of a nation's progress. In addition to actively developing alternative energy sources, increasing energy efficiency is critical to development. Since the industrial revolution, steam has been the main source of thermal power. The design and manufacture of boilers in the green era are focusing on increasing energy efficiency and reducing air pollution. In particular, circulating fluidized bed (CFB) boilers are highly efficient and can use diverse fuels [18–20]. However, substantial amounts of carbon dioxide and sulfur dioxide are emitted during combustion and may cause secondary pollution. After the Kyoto Protocol came into effect on March 6, 2005, many countries adopted strict measures for controlling carbon dioxide emissions [21]. Because CFB boilers can burn various fuels and be equipped with devices to reduce air pollution, the emissions of these facilities typically adhere to environmental protection regulations [22].

The fuels used in general boilers can be roughly classified as gas, liquid, and solid fuels. Gas fuels include natural gas, liquefied natural gas, and liquefied petroleum gas. If natural gas is pressurized above 47.4 kgf/cm^2, its volume can be reduced to 1/580 and 1/600 of its standard volume at liquefaction temperatures of −82.5 °C and −162 °C, respectively, facilitating its transportation [23]. Most liquid fuels are derived from petroleum, which is a reliable fuel with a mature production infrastructure. However, petroleum drilling disrupts wildlife habitats, and petroleum releases carbon dioxide and other air-polluting substances when burned. Coal, which is abundant and inexpensive, is a common solid fuel source, but its production and combustion also pollute the air, soil, and water [24]. Taiwan lacks natural resources; more than 98% of its energy is imported. Seeking reusable resources is the most appropriate and economical approach of developing alternative energy sources, and waste tires can be one such resource. The efficiency of waste tire recycling is high; in November 1987, the "Waste

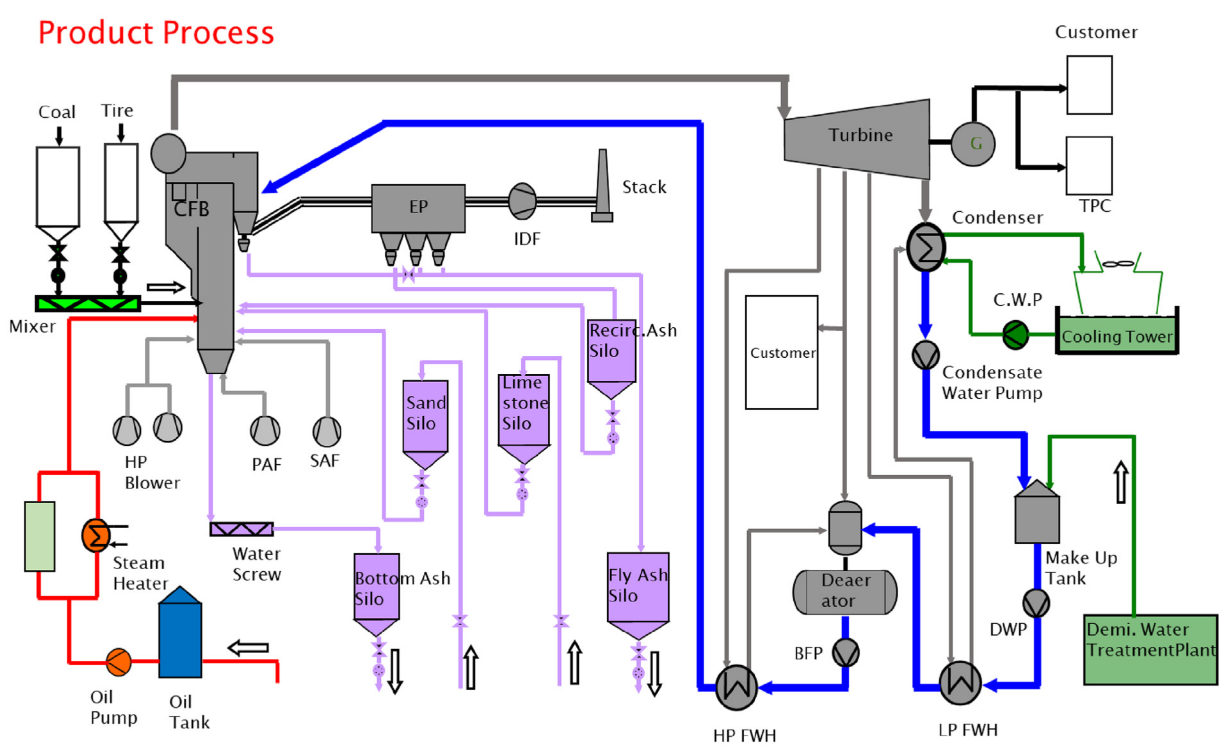
Disposal Law" of Taiwan was revised to stipulate that waste tires have recycling value. Tire scraps can be used as an auxiliary fuel and decrease fuel costs. This strategy would both reduce the consumption of conventional fuel and safely dispose of many waste tires.

Experiments were conducted in this study to investigate the performance of three fuels—heavy diesel oil, coal, and waste tires—used in CFB boilers in terms of boiler operating efficiency and the resulting environmental pollution, with the ultimate aim of reducing the number of waste tires sent to landfill in Taiwan. In addition, the power generation costs of individual fuels were obtained.

2. Experimental device

The CFB boiler used in this research was a compact model built by Foster Wheeler (Finland). Its steam output pressure is 125 kgf/cm^2, steam temperature is 541 °C, and maximum steam flow rate is 200 t/h. The boiler combustion chamber is 9.7 m wide, 4.8 m deep, and 29.1 m high, and the heat transfer area of the boiler is 8345 m^2 excluding the economizers.

Fig. 1 shows the operational sequence diagram of the whole system. The superheated steam produced by the boiler enters the steam turbine and drives the steam turbine to rotate. The single-cylinder extraction steam turbine built by Japan's FUJI company has a maximum output capacity of 48 MWh and turbine speed of 3600 rpm. The number of impeller stages is 36, and there are three stages of steam extraction. The maximum steam extraction volume is 100 t/h. The exhaust steam volume is 140 t/h. The generator (FUJI, Japan) has maximum power generation of 56,470 kVA, an output voltage of 11.4 kV, a current of 2860 A, a frequency of 60 Hz, and a power factor of 0.85. The generator is decelerated by a reduction gear synchronized with the steam turbine at 3600 rpm. The steam turbine drives the generator set to generate electricity at 11.4 kV. A small fraction of the produced electricity is stepped down through a transformer to 3.3 kV and 440 V for use on-site.



PAF: Primary air fan, SAF: Secondary air fan, IDF: Induced-draft fan, E(S)P: Electro-static precipitator, CWP: Cooling water pump, TPC: Taiwan power company, DWP: Demi-water pump, and BFP: Boiler feed pump, FWH：Feed water heater.

Fig. 1. Operational sequence diagram of the proposed system.

Another transformer boosts the voltage to 69 kV; it is then sold to Taiwan's power company (Taipower), which supplies electricity to end users. The gray line in Fig. 1 indicates the steam extraction process of the steam turbine. The steam is pumped into the high-pressure feedwater heater, where it heats the feedwater, and then enters a deaerator. Steam exiting the second stage of the steam turbine is extracted and sold to customers. A portion of the steam is sent to the deaerator to heat and pressurize it, ensuring that the feedwater is continuously saturated. The feedwater pump sends the feedwater to the boiler, and the steam remaining after the third-stage extraction is sent to the low-pressure feedwater heater to heat the feedwater. After being used for heating, this steam returns to the condenser. The recovered water is returned to the make-up tank to be recycled again.

The feedwater in this study was produced through treatment in a demineralization plant. Raw water is first treated through ion exchange, wherein anions and impurities are removed and ultrapure water is produced for power generation. This ultrapure water is then transported to the daily water tank, pumped through the low-pressure feedwater heater by a deaerator pump, and then fed to the deaerator to remove dissolved oxygen. Finally, the feedwater is pumped into the high-pressure feed water heater and enters the boiler after being heated [25].

The two main CFB boiler combustion elements are a hearth bed and a cyclone separator. Fuel and secondary air enter the hearth bed through its feed port. The primary air penetrates the hearth nozzle through a wind box, fully fluidizing the high-temperature bed material and fuel, which are then burned. During combustion, combustibles comprising small particles burn in the furnace and travel with the flue gas to the separation chamber.

During the cyclone separation process, the fine particles (less than 0.1 mm) with light specific gravity move upward with the flue gas through vortex finder. Then, the particles will go through the third superheater, the first superheater, the economizer, the air preheater, and finally the electrostatic precipitator [26], and are collected and sent to the fly ash silo. It is noted that the second superheater is placed in the furnace to absorb radiant heat. On the other side, the unburned pellets with heavier specific gravity will fall back into the re-feeder. Under the action of the high-pressure blower, these pellets will be returned to the furnace through the return leg and circulated again for combustion. The other part of the fuel in the furnace is burned into larger particles which appear as the bottom ash and are discharged from the bottom of the furnace under the control of the air pressure along with part of the bed material [27], as displayed in Fig. 2.

Recently enacted environmental protection regulations have made emission standards substantially stricter. CFB boiler flue gas pollutants are primarily nitrogen oxides, sulfur dioxide, carbon monoxide, carbon dioxide, and particulates. Higher temperature generally causes greater nitrogen oxide formation. Nitrogen oxide formation can be reduced by controlling the furnace temperature, through selective catalyst reduction, or through selective noncatalyst reduction. In a fluidized bed, sulfur dioxide can be effectively removed through dry desulfurization in which limestone is sprayed into the furnace. Carbon monoxide is mostly caused by incomplete combustion. Adjusting the boiler air volume and controlling the excess air volume can effectively prevent the production of carbon monoxide. The carbon dioxide emission has a great relationship with the fuel. The use of low-carbon alternative fuels can reduce carbon dioxide emissions. For the removal of fine particulate matter, an electrostatic precipitator (ESPs) is generally used in large power generation boilers. ESPs can effectively remove more than 99.8% of the particulate matter and make the boiler discharge meet environmental standards.

2.1. Data reduction

Boiler efficiency, η_b, is a measure of the goodness of the chosen process and equipment to transfer combustion heat to the heat in steam. Boiler efficiency, η_b, can be defined as the ratio of the rate of useful heat output, $\dot{Q}_{out}$, to the rate of total energy input, $\dot{Q}_{in}$. It can be written as

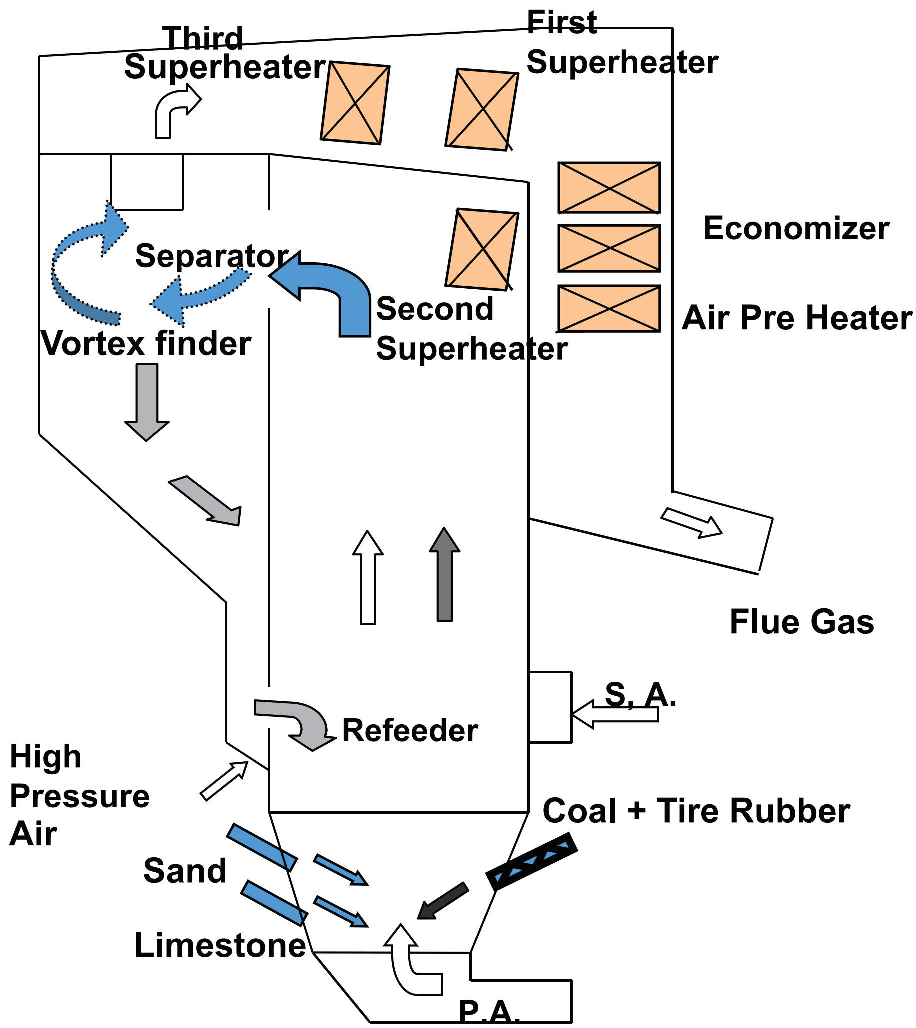
$$\eta_b = \frac{\dot{Q}_{out}}{\dot{Q}_{in}} \times 100\% \tag{1a}$$

$$= \frac{S \times m_s}{h_f \times m_f} \times 100\% \tag{1b}$$

where S represents enthalpy change of main steam, m_s indicates mass flow rate of main steam, h_f signifies calorific values (heating values) of fuels, and m_f stands for mass flow rate of fuel.

Net plant efficiency, η_n, is defined as the proportion of the total thermal energy input to the boiler actually converted into the electrical energy input to the power system.

Since approximately 860 kcal of thermal energy is required to generate 1 kWh of electricity, the following formula for calculating the net plant efficiency can be obtained.



P.A.: Primary air; S.A.: Secondary air

Fig. 2. Combustion process of the circulating-fluidized-bed boiler.

$$\eta_n = \frac{860\text{kcal} \times P_{net}}{\dot{Q}_{out}} \times 100\% \tag{2}$$

where P_{net} is net power produced.

Electricity generating efficiency is defined as electricity production measured at the point of outlet of the main generators divided by the fuel input used for heat produced.

It can be written in the form

$$\eta_e = \frac{860\text{kcal} \times P_{net}}{\dot{Q}_{in}} \times 100\% \tag{3}$$

It is noted that η_e can be immediately obtained by multiplying η_b by η_n. In this regard, this study mainly explores the effects of η_b and η_n of the cogeneration system on different fuels.

2.2. Uncertainty analysis

Before the experiment, all instruments were calibrated. Temperature was measured with K-type thermocouples to precision of ±0.5 °C. The flowmeters were an EJX910A multivariable transmitter (Yokogawa) with an accuracy of ±1% for steam readings and a 2507.9013 instrument (Hasler) with an accuracy of ±2% for fuel readings. Gas flow was measured using FLOWSIC100 sensors (SICK); the uncertainty in the measurements made by these devices depends on the exhaust velocity (Table 1). An analysis is performed to determine the uncertainty in each dependent variable calculated from measured variables. This analysis is applied to the boiler efficiency, net plant efficiency, and electricity generating efficiency in this work. The result

Table 1. Uncertainty analyses of the measured and calculated parameters.

Experimental parameters	Uncertainty of the measured data and calculated parameters
Gas-flow-measuring instrument (m^3/s)	$v < 2$ m/s: ±0.02 m/s $v > 2$ m/s: ±1%
Watt meter (W)	± 0.5%
Pressure gauge (MPa)	± 0.4%
K-type thermocouple (°C)	± 0.5 °C
Flowrate of steam (m^3/s)	± 1%
Mass flowrate of fuels (t/h)	± 2%
Boiler efficiency, η_b	± 4.5%
Net plant efficiency, η_n	± 3.8%
Electricity generating efficiency, η_e	± 5.2%

Note that v is velocity of exhaust. The density of steam with a pressure and a temperature of 125 kgf/cm^2 and 541 °C respectively is about 35.923 kg/m^3. In addition, the calorific values of the fuels are assumed to be constants. In this study, the calorific values of heavy diesel oil, coal and scrap waste tire are 10,000 kcal/kg [28], 7100 kcal/kg [28], and 9200 kcal/kg [29], respectively.

calculated from measured variables may be expressed as a function, $f(x, y, z, \ldots)$, of the physical variables $x, y, z, \ldots$ which have uncertainties σx, σy, σz, …, then the uncertainty in the value of the result σf is given by the formula

$$\sigma_f = \sqrt{\sigma_x^2\left(\frac{\partial f}{\partial x}\right)^2 + \sigma_y^2\left(\frac{\partial f}{\partial y}\right)^2 + \sigma_z^2\left(\frac{\partial f}{\partial z}\right)^2 + \cdots} \quad (4)$$

Consequently, the uncertainties of the parameters measured and calculated in the experiments are listed in Table 1.

3. Experimental method

3.1. Preparation of fuels

3.1.1. Heavy diesel oil

Heavy diesel oil is combusted in a CFB boiler to heat air; this hot air reheats the furnace wall and hearth. For furnace temperatures at or above 200 °C, silica sand can be used as the bed material. The separation chamber and other areas are uniformly heated by the circulating bed. If the silica sand particles are too large, the heating is uneven, stable heat storage is not achieved, and the fuel is not fully fluidized, resulting in low combustion efficiency. Moreover, the hearth nozzle refractory mud can be easily damaged by excessive friction. By contrast, if the silica sand particles are too small, the particles absorb the heat in the boiler, reducing boiler efficiency before the fuel is fluidized; moreover, the particles may be rapidly removed by the flue gas. Therefore, the silica used for bed material replenishment must be inspected and its particle size recorded to ensure that the requirements are met.

3.1.2. Coal

Coal is the primary fuel used in a CFB boiler. Its average particle size is between 2 mm and 250 μm; the particle size must not exceed 10.5 mm. Overall, coal particles that are >2 mm and between 250 μm and 1 mm in diameter cannot exceed 45% and 50% of the total coal weight, respectively; the remainder of the coal must have diameter <250 μm. An excess of large coal particles results in incomplete combustion and unburned carbon. However, if there is an excess of small coal particles, the coal cannot be fully fluidized, and these particles are also easily removed by the flue gas. Both outcomes result in poor combustion efficiency. Therefore, the coal crusher must be carefully selected and its gap adjusted to ensure acceptable coal crushing in both the forward and reverse directions. Fig. 3(a) presents an image of a standard coal sample.

3.1.3. Scrap waste tire

The combustion of tire waste is facilitated by co-combustion with coal. In typical co-combustion, approximately 70% coal and 30% tire scraps are used by weight. In analysis, the electricity generated

(a)

(b)

Fig. 3. Standard samples of (a) coal sand (b) scrap tires.

by the tire waste only can be obtained by subtracting the electricity expected to be generated by the coal from the total electricity generated. In a co-combustion plant, waste tires must be stored and stacked in compliance with fire and environmental protection regulations. Tire scraps should be shredded to pieces of length 1–3 cm before their combustion [30]. The US Environmental Protection Agency states that the optimal surface area of shredded tires being employed for combustion is approximately 6.45 cm^2 (1 in $\times$ 1 in) [31]. Excessively large shreds cannot be fully fluidized and burned with the bed material and coal, resulting in slag and difficulty discharging the bottom ash. Excessive slag production may result in the furnace having to be shut down for maintenance and slag having to be removed. By contrast, excessively small shreds can be carried away by the flue gas before being fluidized and burned; this is likely to cause combustion in the rear section of the boiler, resulting in slagging of the superheater and poor heat conduction. Consequently, the superheater will overheat locally, the boiler efficiency will decrease, and the superheater can easily be damaged, resulting in a crisis requiring an emergency shutdown. An image of a standard tire scrap sample is displayed in Fig. 3(b).

3.2. Experimental procedure

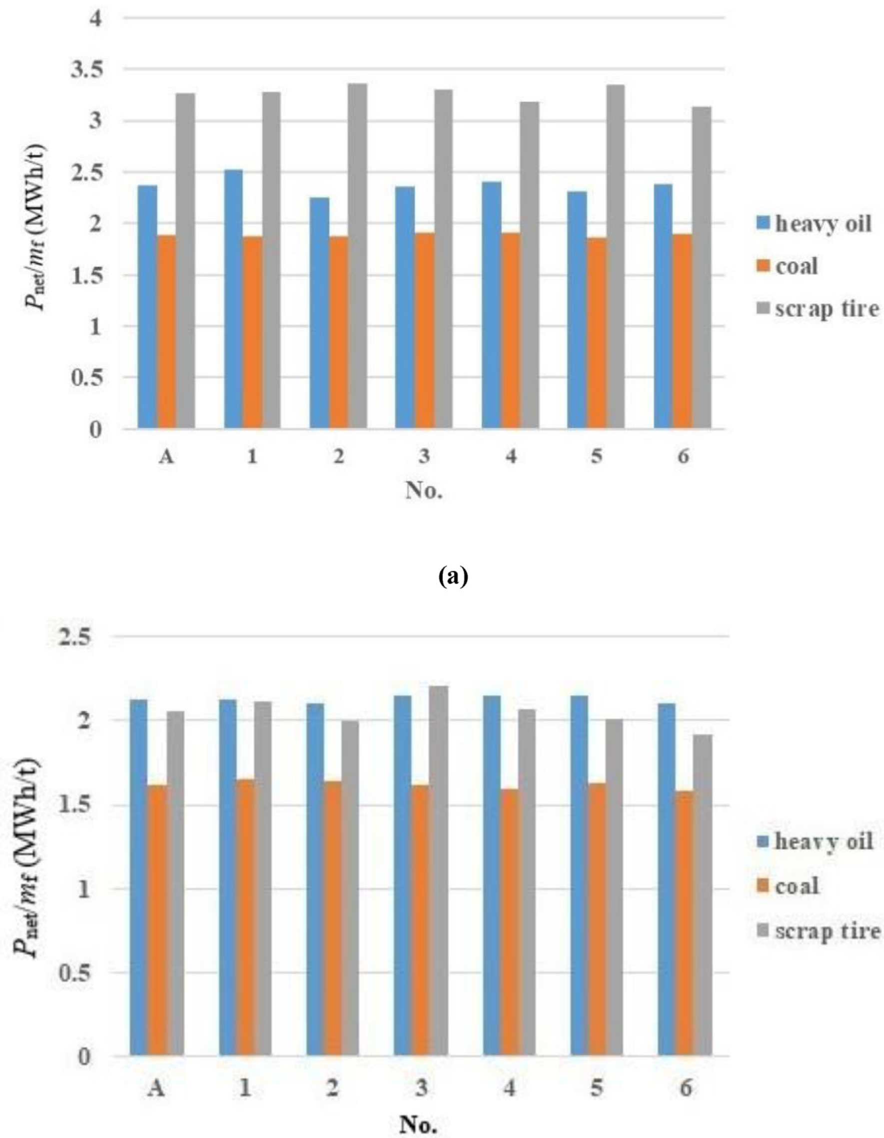
This research is based on a circulating fluidized bed boiler in a steam-electricity cogeneration plant located in southern Taiwan, using three kinds of fuels, such as heavy oil, coal and scrap waste tire, to study and analyze the electricity generating efficiency, boiler efficiency and net plant efficiency. Through the data acquisition system, electricity generating efficiency, boiler efficiency and net plant efficiency are obtained from a distributed control system. The boiler load indicates how many metric tons of superheated steam the boiler produces per hour. It is designed to collect and record the steady-state data for at least 12 hours in each experiment. In the experiment, the heavy oil is injected into the furnace for combustion, the temperature rise is controlled at 60–80 °C/h, the temperature rises from room temperature to 600 °C. When the furnace temperature reaches 200 °C, silica sand with standard particle size can be added as bed material. This process will take about 8 hours and then the coal is put in. The low combustion temperature limits the formation of NOx whilst the limestone absorbs SO_2 formed during the fuel combustion [18]. After the furnace temperature rises to 650 °C, the waste tire fragments are put in. Then, the produced high-energy steam can be used for heating or power generation. The volume flow rates of fuel, production steam, extraction steam and exhaust gas are measured after 45 min. Also, the temperatures of superheated steam and exhaust gas are recorded, and the data of the generated power is obtained.

4. Results and discussion

Fig. 4 presents comparisons of the power generated per ton of heavy oil, coal, and tire scraps during (a) peak and (b) off-peak hours. Six experiments were performed; data from each experiment is labelled with its corresponding number (1–6) in Fig. 4. "A" represents the average of the data obtained for all experiments. Net power, *P*net, is the total power produced, *P*tot, by the generator minus the power consumed by the system, *P*sc, during the generation process. Electricity generated per ton of heavy oil can be calculated by dividing *P*net by the mass flowrate of heavy oil, m_{fho}. It is noted that there are times when the fuel mass flow rate is smaller and the power generation is lower, the main reason being the experiments done during off-peak hours. Conversely, when the mass flow rate of the fuel is larger and the power generation is higher, which is measured during peak hours. It can be seen from the average data of peak hours in Fig. 4(a) that the most power was generated by tire scraps, followed by heavy oil and coal. Overall, approximately 27.5% and 42.3% more power per ton of fuel was produced by tire scrap combustion than by heavy oil and coal, respectively, despite heavy oil having the largest calorific value. This was attributable to the use of a fluidized bed, which is most efficient for solid fuels. Most of the heat from heavy oil combustion is carried away by the flue gas, resulting in higher exhaust temperature, heat loss, less steam production, and less power generation. From the observation of Fig. 4(a) and (b), scrap tires, heavy oil and coal generated much less electricity during off-peak hours than during peak hours.

Since the required steam is lower at this time, the rate of fuel consumption is also slower, resulting in a much lower heat loss for the heavy oil. Therefore, its power output is equivalent to or even more than that of scrap waste tires.

Boiler efficiency measures how much combustion energy is converted into steam energy. Next, the effects of using heavy oil, coal, and scrap tires on boiler efficiency are explored. Fig. 5(a) and (b) displays the experimental data measured by burning heavy oil, coal and scrap tires in a circulating fluidized bed boiler during (a) peak and (b) off-peak hours. To precisely calculate the enthalpy of the superheated steam, a FORTRAN program is coded



(b)

Fig. 4. Comparisons of the power generation per ton of heavy oil, coal, and scrap tire during (a) peak and (b) off-peak hours.

and linked to the subroutines of REFPROP [32]. Once the temperature and pressure of the steam in the boiler are entered, the enthalpy of steam is then calculated. It is noted that using heavy oil as boiler fuel, the average boiler efficiencies are 80.54% and 82.91% during peak and off-peak hours, respectively. When coal or scrap tire is used as boiler fuel, the average boiler efficiency is 91.12% or 92.18% during peak hours, whereas the average boiler efficiency is 91.09% or 88.48% during off-peak hours. From the above results, it can be known that the boiler efficiency is the highest when burning scrap waste tire, followed by coal, and the worst is heavy oil. The fluidized bed boiler burning heavy oil is the least efficient. This is due to the fact that the flow rate of heavy oil is fast, the high heat generated cannot stay in the furnace for a long time, and is quickly taken away from the flue by forced ventilation, resulting in excessive heat loss. As for the boiler efficiency of burning scrap tires and coal, the former is slightly higher because of its higher calorific value, but the difference between the two is not pronounced during peak hours. Although the calorific value of coal is lower than that of scrap tires, due to its slower flow characteristics, it exists longer in the circulating fluidized bed boiler for off-peak

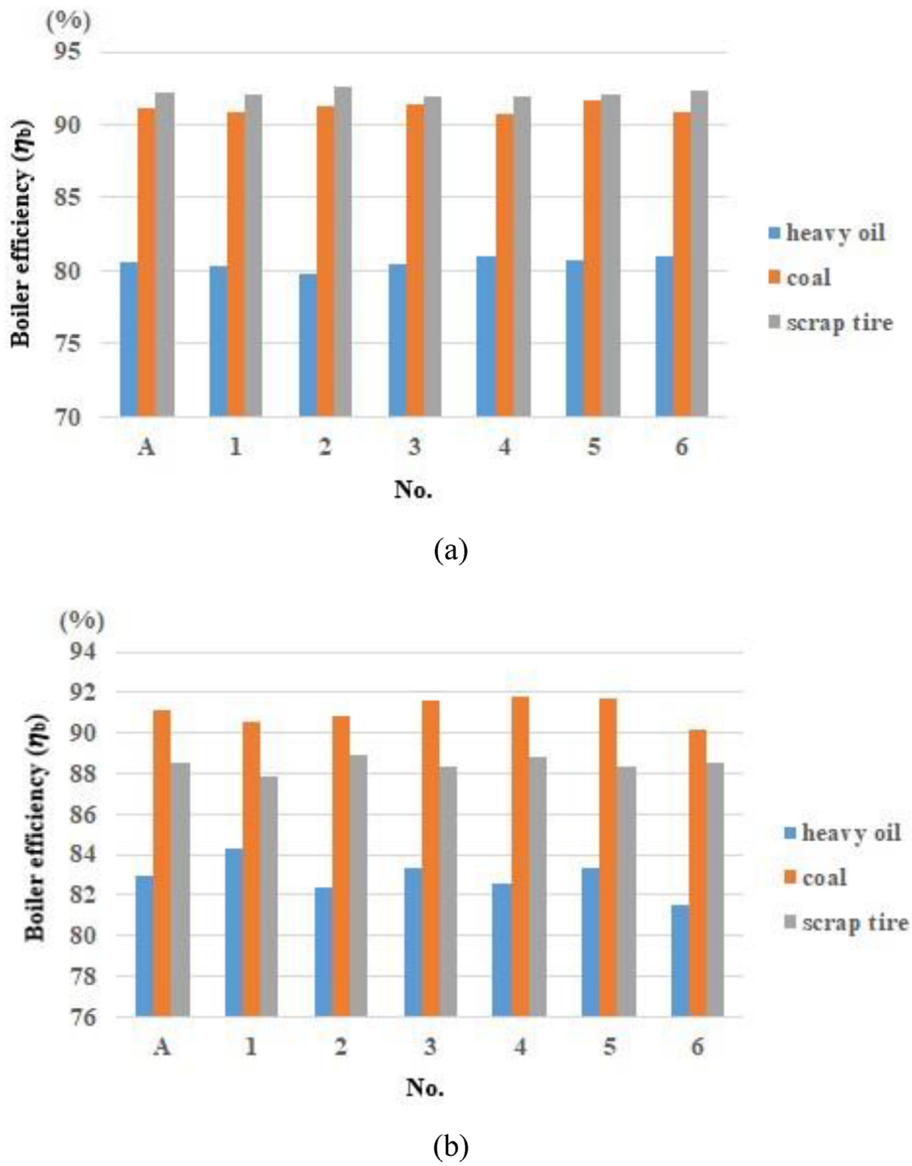
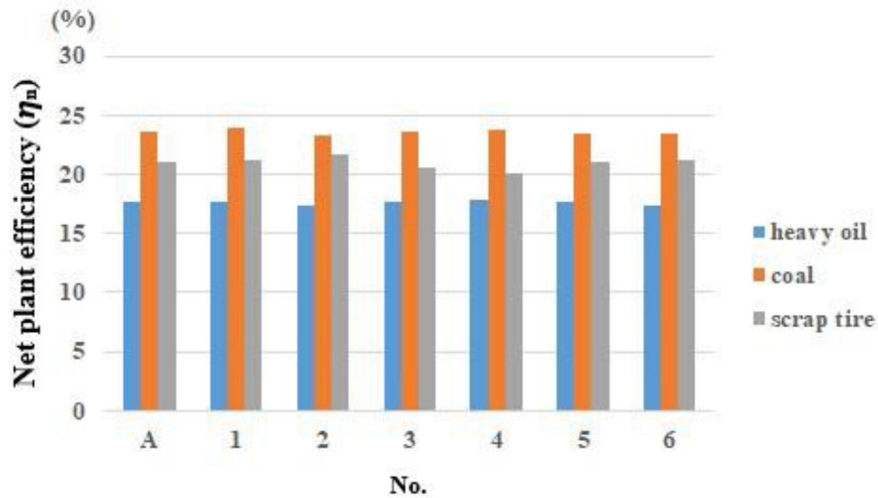


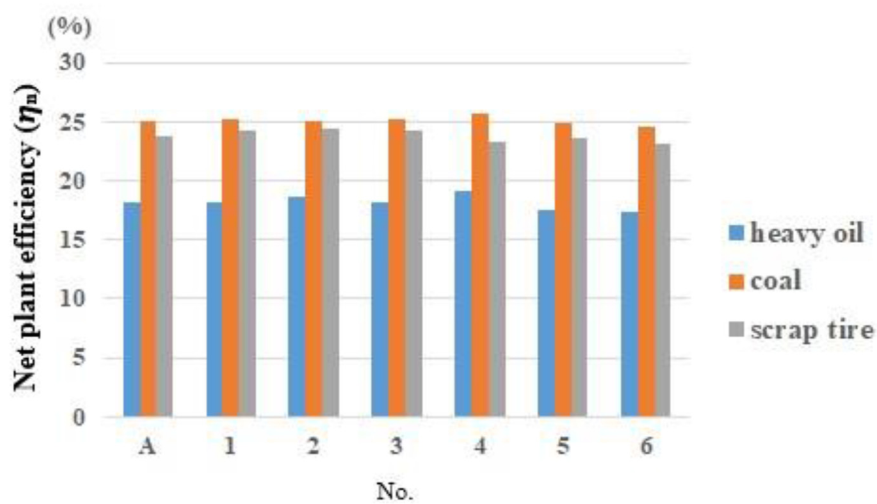
Fig. 5. Comparisons of the boiler efficiency for heavy oil, coal, and scrap tire during (a) peak and (b) off-peak hours.

loads, resulting in a longer heating time. Thus, its boiler efficiency is higher than that of scrap tires during off-peak hours.

The net plant efficiency is the net electrical power produced divided by the rate at which heat is supplied by the boiler. Fig. 6(a) and (b) illustrate comparisons of the net plant efficiency for heavy oil, coal, and scrap tire during peak and off-peak hours. From this figure, it can be observed that the net plant efficiencies of the proposed power plants with various fuels are mostly slightly low, and the net plant efficiencies are mostly not higher than 25%. This is because this plant is a cogeneration plant, and a part of the steam is extracted during the expansion process of the steam turbine for process heating. The average net plant efficiencies for the plant having circulating fluidized bed boiler with heavy oil, coal and scrap tire are 18.11%, 25.09%, and 23.82%, respectively, during peak hours and are 17.60%, 23.57%, and 20.99%, respectively, during off-peak hours. It should be pointed out that when the plant is operating in peak hours, the net plant efficiency is relatively high. On the contrary, when the operation of the plant is in the off-peak hours, the net plant efficiency is relatively low for all three fuels. This can be apprehended that as the fuel consumption rate is large, the temperature of the superheated steam heated in the boiler is also pretty high, and the electricity generated by the steam turbine is also very large. In this case, the highest



(a)



(b)

Fig. 6. Comparisons of the net plant efficiency for heavy oil, coal, and scrap tire during (a) peak and (b) off-peak hours.

Table 2. Prices of heavy diesel oil, coal and scrap waste tire fuel and electricity.

	heavy diesel oil	coal	scrap waste tire
NT$/t	25,209	9568	3200
NT$/kWh	9.4	5.2	1.3
NT$/kWh(TPC)[a]	6.4	2.9	–

[a] Extracted from Taipower's official website in June 2022 [33].

net plant efficiency is the cogeneration plant that uses coal as fuel, while the use of scrap tires and heavy oil as fuel ranks second and third respectively regardless of peak or off-peak hours.

The prices of various fuels and electricity in Taiwan are listed in Table 2. The fuel prices for the cogeneration plant are international spot prices. The price of low-sulfur fuel oil for power generation (sulfur content: 0.5%) per metric ton was NT$24,516 according to the China National Petroleum Corporation on August 12, 2022 [34]. The price adjusted on the basis of the fuel's specific gravity of 0.9725 was thus NT$25,209. Coal purchased from Australia cost approximately US$320 per ton on August 12, 2022 [35], equivalent to NT$9568 (US$1 ≈ NT$29.9). By contrast, waste tires cost approximately NT$3200 per ton [36]. These prices could be used to calculate the unit cost of electricity generated by the cogeneration plant; this unit cost was higher than that charged by Taipower for heavy diesel oil and coal. This higher cost was attributable to several factors. First, the Ukrainian–Russian war has triggered a global coal shortage, resulting in a sharp rise in fuel oil and coal prices, which has affected the spot prices used for calculations for the cogeneration plant. Taipower primarily procures coal through long-term contracts, however, and has thus been less strongly affected by the war. Second, the cogeneration plant produces not only power but also steam, which subsidizes the cost of power generation. Third, the cogeneration plant rarely uses heavy oil for power generation; heavy oil is only used if neither coal nor tire scraps can be fed to the reactor but steam generation is necessary.

Taipower does not use tire scraps for electricity generation, so no direct comparison is possible. However, the unit cost for electricity produced with tire scraps is far lower (NT$1.3/kWh) than Taipower's current price (NT$2.5/kWh). Thus, an increasing number of private power plant manufacturers and operators are investigating the use of tire scrap combustion for power generation. Despite the low cost of waste tires, however, substantial limestone must be used to desulfurize the high-sulfur rubber.

5. Conclusions

1. In the cogeneration plant's CFB, tire scrap combustion generated the most power per ton during peak hours: approximately 27.5% more than generated with heavy oil and 42.3% more than generated with coal.
2. The boiler efficiency was highest for tire scrap combustion during peak hours; it was 1.2% and 12.6% higher than that for coal and heavy oil combustion, respectively.
3. The net plant efficiency during peak hours was highest for coal (25.09%), followed by tire scraps (23.82%) and heavy oil (18.11%).
4. On the basis of international spot prices, this study determined that tire scraps have the lowest cost per kilowatt-hour, followed by coal and heavy oil. Costs for coal and heavy oil electricity generation are higher than the prices charged by Taipower.
5. Using tire scraps for electricity generation not only reduces pollution but also hedges against international crises that may affect energy imports. Tire sources are stable, and waste tires are inexpensive.

Declaration of competing interest

There is no conflict of interest.

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