

EFFECT OF REFUSE-DERIVED FUEL FEEDING RATIO ON PERFORMANCE AND STABILITY OF COMBUSTION TEMPERATURE CONTROL

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Abstract

In this study, the effect of Refuse-Derived Fuel type 3 (RDF-3) feeding ratio on a performance and a stability of combustion temperature control was examined. A new direct-combustion furnace was designed and constructed for co-combustion of RDF-3 and woodchip (WC) feedstock. In this work, four main ratios on wet basis of WC and RDF-3; 100 : 0, 90 : 10, 80 : 20, and 70 : 30 wt.% were tested at the combustion temperature of 970°C. The results showed that the complete combustion was achieved from all of feeding ratios. From an actual fuel feed rate, an increase in RDF mixing ratio could reduce the using of pure woodchip by 5.3 wt.%, 14.3 wt.% and 34.0 wt.% when mixing the RDF at 10 wt.%, 20 wt.% and 30 wt.%, respectively. At increasing of RDF mixing ratio, non-smoothly burning was also found to increase, however, a more rapid ignition behavior of was achieved

Keywords: Direct combustion, Refuse-Derived Fuel, Biomass, Pottery kiln

Introduction

In 2021, Thailand had 24.98 million tons of municipal solid waste (MSW) which decreased by 1.5% from the previous year. From those values, as high as 32% of improper disposal method was observed. Moreover, more than 93% improper disposal places were observed (Pollution Control Department, 2021). The reasons behind these values were due to a limited waste buyers which mostly are waste power plant, cement plant, and incinerator plant. Moreover, the long distance of

these buyers caused a high transportation cost. Many areas therefore choose to dispose to landfill or open dump which affects environment inevitably. Therefore, it is necessary to find the appropriate way to utilize MSW to reduce these problems.

So far, Refuse-Derived Fuel (RDF) has been widely used as an alternative fuel in the co-combustion process. (Kara 2012; Hemidat *et al.*, 2019; Karpan *et al.*, 2021) examined the

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combustion of RDF with coal in cement kilns. It was found that using co-fuels can reduce around 112.8, 486, and 94 USD h⁻¹ for petroleum coke costs respectively. Moreover, carbon dioxide emissions were also found to be less than those of using pure coal. At present, using of the co-combustion with RDF is found to conduct in the large industries as well as the small-medium enterprise (SMEs). Recently, Liplap *et al.* (2022) examined the combustion behaviors of RDF-2, RDF-3 and RDF-5 mixed with woody biomass in a small biomass power plant. From the mixing ratio 10, 20, and 30% of RDF-5, it was found that the higher combustion temperature combustion compared to those of pure biomass was observed. A similar obtained gas quality to those of pure wood combustion which was lower than the emission limitation was observed. However, the combustion of mixing of wood mixed with RDF-2 and RDF-3 was found some limitations. This was due to the relatively large size of RDF-2 and RDF-3 which resulted in a feeding difficulty of a screw conveyor system.

The use of RDF in SMEs business such as the pottery industry, wood baking factories are also rising of interest. Recently, Liplap *et al.* (2022) examined a combustion test of a pottery kiln with a direct combustion and downdraft kiln. It was found that to reach a complete combustion at the temperature of 970°C, around 3-4 tons of firewood was required. These results also agree with the report of The Pollution Control Department (The Pollution Control Department, 2018) that the efficient incinerator temperature should range from 850 to 1,050°C. In addition, Chen *et al.* (2019) found that the optimum conditions for RDF combustion were 900°C at oxygen concentration (O₂) of 14%.

Using RDF-2 and RDF-3 as co-fuels with firewood is, nowadays become one of the most interesting topics caused by the continuous rising of firwood price. However, there are several practical barriers for using these RDFs, such as the difficulty of RDF feeding system including the combustion performance of these mixed fuels. From the study of Phakphoom *et al.* (2022) it was found that the percentage of oxygen concentrations in flue gas was reduced by 82% compared to those of the pure wood when mixing RDF-3 with wood at a weight ratio of 17:83. A similar percentage of carbon monoxide emission as well as combustion performance was observed. However, the use of RDF-3 was found to maintain the combustion temperature much shorter time compared to the use of RDF-5. These results also agree with the work of Liplap *et al.* (2022) which conducted the combustion test in both the small biomass power

plant and pottery kiln. The cost of RDF-5, however, is generally higher than pure wood and RDF-3 by 61% and 59%, respectively. Then most businesses aim to use MSW, RDF-2 and RDF-3 as a fuel instead of RDF-5. Comparing RDF-2 and RDF-3, RDF-3 was found to be preferable than RDF-2 due to the relatively smaller size and lower moisture content. However, in practical terms, feeding the RDF-3 is quite difficult because of its physical characteristic. Practically, RDF-3 must be prepared in cylindrical shape before injecting into a fuel inlet chamber. From this feeding barrier, the air inlet clog could appear which results in the reduction of oxygen over 82% and the risk of incomplete combustion. From these problems, therefore, a new design of combustion furnace which is suitable for RDF-3 as well as RDF-3 mixed with biomass is necessary.

In this research the new design and construction of a separate combustion furnace for RDF mixed with wood was conducted. Combustion tests of the mixed RDF-3 and wood were examined in order to investigate the combustion performance of a proposed furnace.

Materials and Methods

Materials

RDF-3 was prepared through the treatment process of MSW using a Mechanical Biological Treatment waste treatment system of Suranaree University of Technology (SUT-MBT) Woodchips (WC) was obtained from Korat Biomass Company Limited, Nakhon Ratchasima, Thailand. The properties of RDF-3 and woodchip used in this work and their images are shown in Table 1 and Figure 1 respectively.

Table 1. Chemical and physical properties of materials

Parameter	Fuels	
	WC	RDF-3
Size (mm)	10-40	50-300
Moisture (% w.b.)	12.8	13.8
Proximate Analysis [wt.% d.b.]		
Volatile mater (VM)	82.0	87.3
Fixed carbon (FC)	15.8	2.3
Ash (A)	2.2	8.9
Ultimate Analysis [wt.%, d.b.]		
Carbon (C)	46.8	68.5
Hydrogen (H)	6.5	10.9
Nitrogen (N)	0.4	0.4
Sulphur (S)	N.D.	0.1
Oxygen (O) + Other	46.3	20.1
HHV (MJ kg ⁻¹)	17.4	25.8

HHV is a high heating value



Figure 1. Images of (a) Woodchips (b) RDF-3

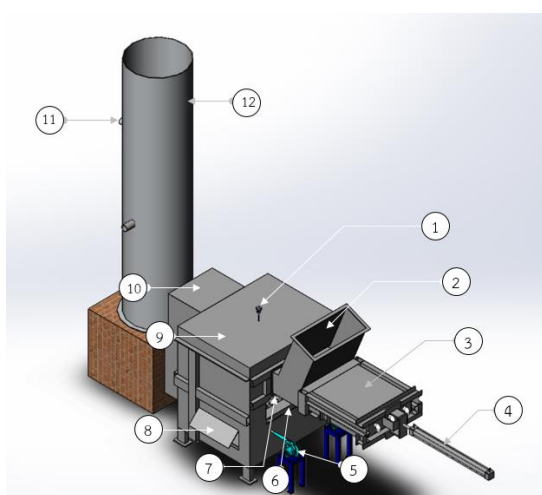


Figure 2. The new designed furnace for co-combustion with pottery kiln: 1) Thermocouples (T_i and T_o) 2) Hopper feeder 3) Stoker (feed RDF and WC) 4) Air cylinder 5) Blower 6) Wood feeder 7) Grille 8) Ash removal chamber 9) Combustion chamber 10) Flue gas outlet 11) Gas sampling position 12) Stack

Equipment and tools

In this work, a direct combustion furnace with a downdraft hot air furnace was designed and constructed. Figure 2 shows the main components of a newly designed co-combustion furnace which consist of a combustion chamber, a hopper, a stoker for RDF, a woodchip feeder, an air blower, an ash removal chamber, and an exhaust gas outlet. To achieve a complete combustion for a fuel feed rate of about $6.48 \text{ m}^3 \text{ h}^{-1}$, the volume of the combustion chamber was designed to be about 0.434 m^3 . The refractory bricks were used to construct a combustion chamber while the SS400 sheet steel was used to cover the outside of furnace. The ash chamber size is about 0.142 m^3 . The exhaust measurement points which are referred to the standard of U.S. EPA Method 2 was also prepared.

Testing Procedure

The testing of RDF-3 and woodchip combustion was divided into 3 steps, first, preheating the furnace to a temperature of $650\text{--}700^\circ\text{C}$ by using 100 kg of firewood. Second, the RDF-3 mixed with woodchip were fed for continue heating up the furnace to 970°C (T_o) and then maintained at this temperature for 3 h . In this work the mixing ratios on weight basis of RDF-3 and woodchip (WC-3: RDF) of $100 : 0$, $90:10$, $80:20$, and $70:30$ (wt.%, w.b.) were selected. During the combustion, an amount of fuel and energy consumption were collected continuously including the flue gas composition emitted. After reaching a complete combustion for each condition the furnace was then cooled down. The amount of ash was then carefully measured.

Temperature Measurement

The combustion temperature was measured at 2 locations, inside the furnace (T_i) and the flue gas outlet (T_o) by using a K-type thermocouple. In this work, the temperatures were recorded with a data logger at 15 min intervals.

Chemical Properties of Sample

The proximate analysis of sample and ash was conducted to evaluate the fuel conversion efficiency. The amount of ash (A), volatile matter (VM), and fixed carbon (FC) on dry basis was determined by following the standard testing methods, ASTM D1102-84, ASTM E872-82, and ASTM D1762-84, respectively. From the standard method the FC can be calculated by following Equation (1) as follows.

$$\%FC = 100 - (\%VM + \%A) \quad (1)$$

Where %FC, %VM, %A are the percentage of fixed carbon, volatile matter, and ash,

The higher heating value (HHV) was measured using a bomb calorimeter (IKA C2000, I.K.A., Germany). Approximately 1 g of dried biomass was pelletized, and benzoic acid was used as a reference standard.

Flue Gas Composition Measurement

The flue gas composition was carried out by using a portable flue gas analyzer (Testo 350 XL). The measured gas compositions consist of oxygen (O₂), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxide (NO_x as NO₂), and sulfur dioxide (SO₂). This measurement has been calibrated from the 7% of excesses oxygen (O₂) on a dry basis and the flue gas composition was recorded at 20 min intervals.

Fuel and Energy Consumption Measurement

The amount of fuel and energy consumption were recorded at a controlled constant temperature regime (970°C) for 3 h. In this work energy consumption refers to the calorific value of fuel used. The data was recorded at 15 min intervals.

Statistical Analysis

All data were analyzed in terms of statistical differences by using Analysis of Variance (ANOVA) method through Microsoft Excel. In the analyses, the statistical differences were carried out from 4 proportions. The statistically different was agreed with the p-value < 0.05 and there are no significant difference if the P-value > 0.05. The determination of data discrepancy was carried out using mean and standard deviation (S.D.)

Results and Discussion

Chemical properties of Mixed Fuels

Table 1 shows properties of raw materials (RDF and WC). It was found that RDF contained a higher value of carbon and volatile matters resulting in a higher value of HHV. Proximate analyses and HHVs of woodchip mixed with RDF

are presented in Table 2. It was found that volatile matter and ash of the fuels increased with increasing RDF ratios. In contrast, fixed carbon was found to decrease with RDF mixing ratio. The HHV was also found to increase progressively with RDF ratio. This could be explained by the relatively high HHV of RDF when compared to woodchip at similar weight. As a result, the fuel consumption of less RDF ratios is expected to be higher than those of more RDF ratios.

Temperature Profile during Combustion

Table 3 and Figure 3 show the temperature changes during combustion of the mixed fuels at a target-controlled temperature of 970°C. It was found that the inside furnace temperature (T_i) and the flue gas outlet temperature (T_o) showed the difference among the several mixing ratios. The outlet temperatures were also found to be higher than the inside temperatures for all fuel mixing ratios. This is due to the direct measurement of flame temperatures located at around T_o position in which the fuel was almost combusted. Meanwhile the temperature of T_i is located inside the furnace where the fresh fuel was continuously fed.

Table 3. Temperature inside the furnace (T_i) and flue gas outlet temperature (T_o) obtained from the combustion at several feed ratios

WC: RDF-3 [wt.% w.b.]	Temperature [°C]	
	T _i	T _o
100: 00	682 ± 36	885 ± 43
90: 10	740 ± 50	924 ± 48
80: 20	823 ± 52	963 ± 55
70: 30	745 ± 64	920 ± 73

Mean ± S.D, T_i inside the furnace, T_o the flue gas outlet.

For pure woodchip combustion (WC: RDF-3 = 100: 00), controlling temperature during the initial heat up was quite difficult. This result is in agreement with Li *et al.* (2015) who found that wood size larger than 10 mm took more than 60 seconds to heat up (~370°C). However, a more stable temperature was achieved later with additional air feeding. At increasing of RDF-3 mixture to 10%, the heating step was faster than that using a pure woodchip. This could be

Table 2. Proximate analysis of mixed fuels

WC:RDF3	Parameters of Proximate [at dry basis]				
	VM [wt.%]	FC [wt.%]	A [wt.%]	FC VM ⁻¹	HHV [MJ kg ⁻¹]
100:00	79.15	18.07	2.52	0.26	17.40
90:10	79.92	16.35	3.49	0.24	18.20
80:20	80.66	14.80	4.34	0.20	19.10
70:30	81.40	13.16	5.27	0.18	19.90

explained by the increasing of volatile matter of the mixed fuels through the RDF portion. Moreover, variation of targeted combustion temperature was observed. From the continuous measurement, variation of temperature changes inside the furnace (T_i) and outlet (T_o) represented by the S.D. values, showed the larger values compared to those of pure woodchip combustion; S.D. = 50°C and 48°C for T_i and T_o , respectively. This could be due to the different combustion characteristics obtained from the mixed RDF which shows over 1.5 times larger calorific value compared with pure woodchip. The dropping of temperature was occasionally observed which could be explained by the rising of total moisture in the mixed fuel.

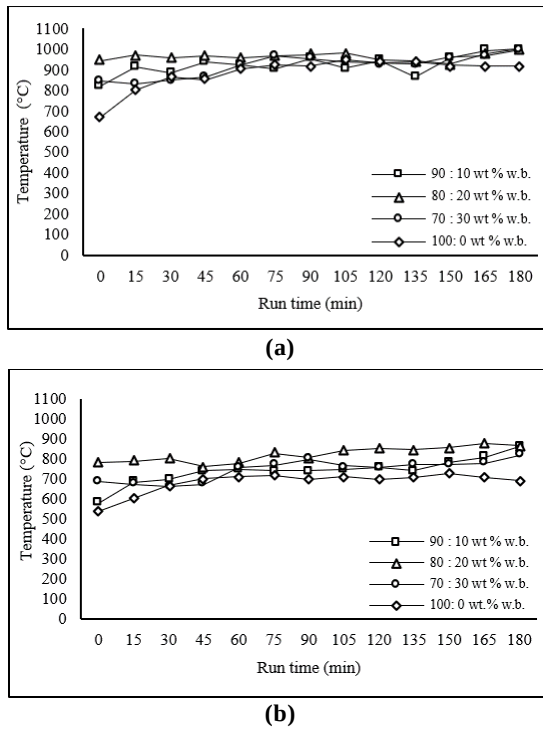


Figure 3. Temperature changes observed at (a) flue gas outlet (b) inside furnace during co-combustions.

At increasing of RDF-3 mixture to 20% and 30% a more temperature changes during combustion were obviously observed. From the test, it was found that around 52°C and 55°C was changed throughout the combustion test, for T_i and T_o , at 20% mixing respectively. At 30% RDF mixing ratio, it was found that more than 60°C of

fluctuate temperature was obtained. This could also be explained by the rising of volatile matter which was in the RDF as well as the decreasing of mixed fuel density causing the negative impact on the combustion characteristic. From the test, it was found that the rapid dropping of temperature and large amount of smoke was observed. The rapid increasing of temperature also then appeared. These results could be suggested by the inefficient air supply occurring during combustion. From Table 2, the ratios of fixed carbon to volatile matter were also found to decrease progressively with increasing RDF mixing ratio. This could support a non-smoothly burning behaviors obtained at increasing of RDF ratio. However, a more rapid ignition behavior of the mixed fuel was achieved (Liu *et al.*, 2015; Aich *et al.*, 2020).

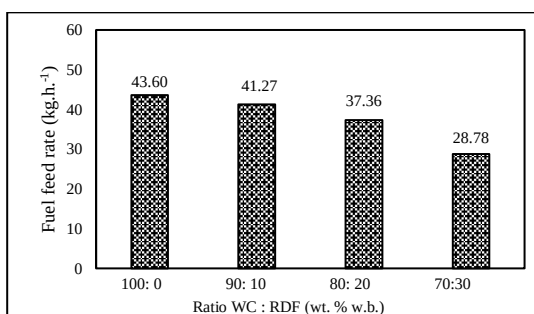
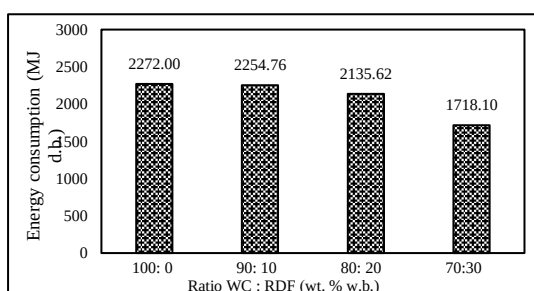
Fuel and Energy Consumption

Figure 4 shows the fuel and energy consumption rates throughout the combustion test, respectively. It was found that the rate of fuel consumption depends on the mixing ratio. To reach the target combustion temperature faster, a higher portion of RDF was required. From Figure 4, the fuel feed rate reduced with the increasing of RDF ratio. The less fuel consumption was found from the mixing ratio of 70:30 which is less than the pure woodchip consumption of around 34.0 wt.%. In other words, to achieve a similar target combustion test comparing to the using of pure woodchips (100 wt.%), the total fuel (RDF + WC) could be reduced by 5.34%, 14.31% and 34.00% when mixing with RDF for 10%, 20% and 30%, respectively. This is expected because RDF contains higher energy, thus requiring less fuel consumption. This result was also observed by Liplap *et al.* (2022) who used RDF with wood chip for energy production using gasification system.

In terms of energy required, as shown in Figure 5 or the total calorific value of the mixed fuel, as shown in Tables 2, as low as 24.38% of energy could be reduced when compared to those of pure woodchip. This could be explained by a larger heat produced from RDF-3 portion which is over 1.4 times higher than those of woodchip. The different feed rate of mixed fuels was also observed. It was found that the fuel feed rate and energy consumption vary directly to the total calorific value of the mixed fuel (García *et al.*, 2021). This could be due to the relatively high heat generation obtained from the combustion of RDF fraction (Chiemchaisri *et al.*, 2010).

Table 4. Shows the results of flue gas composition

Flue Gas Composition	Ratios of WC: RDF-3 (wt.%, w.b.)				STD.
	100:00	90:10	80:20	70:30	
O ₂ (% vol.)	21.12 ± 0.07	21.05 ± 0.16	20.98 ± 0.12	21.15 ± 0.11	N/A
CO (ppm)	1.06 ± 1.33	1.11 ± 1.73	0.84 ± 1.06	3.80 ± 2.42	690 ^a
NO _x as NO ₂ (ppm)	0.00 ± 0.00	0.01 ± 0.01	0.24 ± 0.10	0.17 ± 0.49	200 ^a
CO ₂ IR (% vol.)	0.09 ± 0.06	0.14 ± 0.14	0.17 ± 0.10	0.18 ± 0.24	N/A
SO ₂ (ppm)	0.00 ± 0.00	0.00 ± 0.00	0.05 ± 0.09	0.00 ± 0.00	60 ^a

**Figure 4.** Fuel feed rate at several fuel mixing ratios**Figure 5.** Energy consumption at several mixing ratios

Flue Gas Composition

Table 4 shows flue gas compositions of mixed fuel combustions. It was found that the flue gas compositions of each mixing ratio did not show a significant difference. Oxygen residues was found in the range of 20.98-21.15 % in flue gas. Small quantities of CO₂, SO₂ and NO_x as NO₂ were detected, which were not over the standard (MNRE, 2006). The result obtained in this study is in accordance with Chen *et al.* (2019) who found that an increase in combustion temperature resulted in the decrease of emissions.

Comparing the CO emission observed among the several mixing ratios, it was found that the CO content in flue gas increased with increasing RDF ratio (Akdağ *et al.*, 2016). From the testing, CO increased from 1 ppm to 3.8 ppm after mixing RDF 30 wt.% but it is considered very small. This could

be explained by an insufficient air for volatile combustion which took place at the beginning of material feeding (Kara., 2012; Abu-Elyazeed *et al.*, 2021). This volatile content increased with the RDF ratios. However, all of those emission values remained within the standard specified.

Properties of Solid Residues and Combustion Efficiency of the Mixed Fuels

Table 6 shows the proximate analysis results of the solid residue obtained from the combustion test. It was found that 87-94 wt.% of ash content was observed. The fixed carbon content which referred to the unburned char was found to remain only around 4.7-8.7 wt.%. These could be suggested that the fuels were mostly converted into heat during combustion. The combustion efficiencies of the mixed fuels were also examined by following Equation (2) (Ikeda *et al.*, 2003).

$$\text{Eff.}(\%) = 100 - \left[\left(\frac{U_n}{100 - U_n} \right) \left(\frac{A_0}{100 - A_0} \right) \times 100 \right] \quad (2)$$

Where U_n represents the amount of unburned carbon and A_0 represent the amount of ash in the raw material

In this work, from the very small amount of char remaining from the combustion, the amount of unburned carbon was assumed as the amount of fixed carbon of these chars. Table 5 shows the results of combustion efficiencies for all mixing ratios. It was found that all fuels showed a high combustion efficiency of over 99%. These results could be implied that the mixing of RDF within 30 wt.% did not affect the combustion system which was developed.

Table 5. Combustion efficiency of mixed fuels

Wood : RDF [wt. % : wt. %]	Yield [wt. %]	Combustion efficiency [%]
100:0	4.25	99.75
90:10	4.31	99.80
80:0	4.99	99.78
70:30	5.43	99.71

Yield: represents the amount of unburned carbon

Table 6. Proximate analysis of ash obtained from several fuel mixing ratios

Proximate Analysis [wt.% d.b.]	Ratios of WC: RDF-3 [wt.% w.b.]			
	100:00	90:10	80:20	70:30
Moisture (M)	0.9 ± 0.3	0.8 ± 0.2	0.6 ± 0.2	0.3 ± 0.3
Fixed Carbon (FC)	8.7 ± 2.0	5.0 ± 2.5	4.5 ± 0.9	4.7 ± 1.1
Volatile Matter (VM)	3.0 ± 0.1	2.0 ± 0.4	1.5 ± 0.3	1.4 ± 0.4
Ash (A)	87.4 ± 2.2	92.2 ± 2.6	93.4 ± 1.0	93.6 ± 1.5

Mean ± S.D.

Conclusions

In this work, the new co-combustion furnace for woodchip and RDF for pottery kiln was successfully developed. It was found that RDF can be fed smoothly together with woodchip which was an original fuel. The combustion efficiency of over 99% from the RDF-woodchip fuel was achieved for all mixing ratios. From the isothermal combustion test, it was found that an increase in RDF mixing ratio could reduce the using of total fuel (RDF + Woodchip) by 5.34 wt.%, 14.31 wt.% and 34.00 wt.% after mixing RDF at 10 wt.%, 20 wt.% and 30 wt.%, respectively. At increasing of RDF mixing ratio, non-smoothy burning was found to increase, however, a more rapid ignition behavior of was achieved.

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