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Optimization for Reduction of NO_x and Heat Loss of Parawood Chips Boiler Process Combined with Air Preheater and Controller Using Aspen Dynamics

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ABSTRACT

In a small scale of boiler process, a typical problem is an improper control of air to fuel ratio during the combustion process. Such poor control causes heat loss and undesired emission production. In this study, the main aim was to make the process green in the sense of energy recovery and emissions regulation (CO, NO_x, and SO_x) in an optimum manners, and to design the control system to maintain the optimal conditions using Aspen Plus and Aspen Dynamics. The external flue gas recirculation technique was applied to the process to reduce thermal NO_x. Air preheater was also designed and applied to preheat the feed air combustion temperature for energy recovery purpose. Dynamic simulation scheme was proposed to overcome a limitation of Aspen Dynamics for solid process, and the air to fuel ratio control was then designed to regulate CO, NO_x, and SO_x emission. Boiler level and boiler pressure controllers were also designed for safety purpose. In addition, the steam production controller was also designed for achieving the required steam. Rejection of uncertain moisture content of wood chips was considered. The results have shown that the simulated trajectories were consistent with the measured data collected by wood manufacturing company in the south of Thailand. The optimal operating condition of the process was 5% excess air and 25% flue gas recirculation with 40.5 wt% moisture content of wood chips. The optimal condition with the designed air preheater provided 29% heat recovery in this case, and 35.4% of steam production higher than original process. The proposed control scheme can regulate successfully the CO, NO_x, and SO_x emission under their limitations, and can handle disturbance changes very well.

Keyword: Combustion simulation, Air/fuel ratio, NOX reduction, Flue gas recirculation, Air preheater

1. INTRODUCTION

Combustion is a chemical reaction between the fuels (such as coal, biomass etc.) and oxygen [1]. Chemical energy, which is stored in the fuel, is transformed into the useful heat energy using in the other processes such a boiler process [2]. The boiler is an equipment for producing steam, which provides a means for heat of combustion to be transferred to boiler feed water until it becomes saturated steam or superheated steam [3]. Many factory processes require steam for utilizing in various fields such as food production, power generation etc. For a small scale of the boiler process, a typical problem is improper control of air to fuel ratio during the combustion process [4]. Such the poor control system leads to inefficient combustion process and further causes significant heat losses as well as undesired pollution emission. The green process with a good control structure is then required which aimed at environmental burden regulation (especially for CO, NO_x, and SO_x emission) and energy recovery for raw material consumption reduction.

The conventional combustion method provides high flame temperature in the furnace resulting in considerable high NO_x formation, although it operates in an optimal air to fuel ratio. Flue gas recirculation (FGR) is an effective technique for NO_x emission reduction. There are two ways to reduce NO_x emission. First, the recirculated flue gases absorb heat from the burner resulting in lower peak flame temperature and the formation reduction of thermal NO_x. Second, the recirculated flue gases will lower the O_2 concentration in initial combustion zone, this inhibits fuel NO_x conversion [5].

Robinson and Luyben (2008) [6] performed a simulation of a steady-state coal gasification in

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Aspen Plus, and developed a dynamic modeling of the coal gasification using Aspen Dynamics. High molecular weight hydrocarbon, which has the same hydrogen to carbon ratio founding in coal, was used for representing the coal in the Aspen Dynamics. A proportional-integral (PI) control system was designed to control the performance of the process. Jin et al. (2014) [7] also performed the dynamic modeling of oxy combustion of the coal by using Aspen Dynamics, pseudo-coal was proposed. Lan et al. (2018) [8], Gaglianoa et al. (2017) [9], Pei et al. (2013) [10] and Doherty et al. (2013) [11] performed the steady-state simulation of biomass gasification. RYIELDS was used for decomposition of the biomass to the conventional elements, and RGIBBS was used as the fluidized gasifier. The simulation results showed that higher temperature of fluidized bed and higher feed air temperature gave higher amount of CO and NO_x but lower amount of CO_2. Nevertheless, higher excess air ratio in the combustion process and higher biomass moisture provided lower CO amount. Gamrat et al. (2016) [12] and Shi et al. (2018) [5] investigated the effect of flue gas recirculation on NO_x emissions. For a coke oven heating system, they found that the 20% recirculated flue gas resulted in 50% reduction of the NO_x emission. For the oxy-fuel natural gas combustion, the 40% recirculated flue gas resulted in 85% reduction of the NO_x emission.

In this study, main aim was to make the process green by designing and simulating a control system for heat energy recovery and regulation of CO, NO_x, and SO_x emissions according to the emission standards regulated by Industrial Estate Authority of Thailand or IEAT. Steady-state process simulation results were initially verified by comparing to the sets of the measured data collected from wood manufacturing company in the south of Thailand. For pollutant emissions point of view, the optimum value of air to fuel ratio was defined by sensitivity analysis. Moreover, the external flue gas recirculation (EFGR) technique was applied to the process for the thermal NO_x reduction. For heat recovery point of view, air preheater unit was designed and applied here to preheat the feed air temperature. Dynamic simulation scheme was proposed to overcome a limitation of the Aspen Dynamics for a solid process. Air to fuel (A/F) ratio control was further designed at the optimal condition. Boiler level and boiler pressure controllers were designed for safety purpose as well as the steam production control. Rejection of uncertain moisture content in wood chips was considered. Control robustness test was also investigated to specify the control limits.

2. BOILER PROCESS

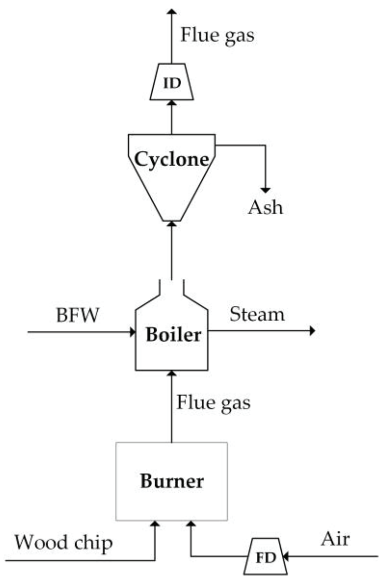


Figure 1. Block flow diagram of the original boiler process.

The boiler is an equipment used to generate steam by applying heat from combustion to boiler feed water (BFW). Figure 1 shows a block flow diagram of the original biomass boiler process of wood manufacturing company in the south of Thailand. Here, parawood chips are used as a combustion raw material, and there composition analysis is shown in Table 1. Combustion air is fed to the burner via forced draft (FD) fan. Process steam capacity in this case is 4-7 ton/hr at steam pressure of 5.5 bar. Flue gas from boiler is passed through a cyclone in order to separate ash before discharging through stack.

Main drawback of the original process is that the combustion process operates without A/F ratio control providing inefficient combustion, significant heat loss, and undesired emission production especially CO, NO_x, and SO_x [4]. The emission control was then focused by controlling A/F ratio at its designed value. In addition, a flue gas recirculation technique was applied to reduce NO_x emissions. Another disadvantage is the flue gas at stack still have high energy content which can be recovered to the process. Air preheater is an interesting option to improve a thermal efficiency of the boiler process by transferring the heat energy from flue gas to the combustion air.

Table 1. Composition analysis of parawood chips (as received basis).

Parameter	Unit	Result
Proximate analysis		
Moisture	wt %	40.48
Volatile matter	wt %	48.55
Fixed carbon	wt %	10.17
Ash content	wt %	0.80
H.H.V.	kcal/kg	2,895
L.H.V.	kcal/kg	2,251
Ultimate analysis		
Carbon	wt %	29.67
Hydrogen	wt %	8.15
Nitrogen	wt %	0.097
Sulphur	wt %	0.067
Oxygen	wt %	62.02

Table 2. Normal operating data of parawood manufacturing company.

Stream / Block name	Description	Value
AIR	Flow rate	17,700 kg/hr (9,060 ft^3/min)
	Temperature	30 °C
	Pressure	1.01 bar
WOOD CHIP	Flow rate	1,500 kg/hr
	Temperature	30 °C
	Pressure	1.01 bar
	Moisture content	40.48 wt %
BFW	Flow rate	7,650 kg/hr
	Temperature	100 °C
	Pressure	5.5 bar
FD fan	Forced	16 in-water
	Maximum flow rate	9,060 ft^3/min
ID fan	Induced	8 in-water
	Maximum flow rate	30,000 ft^3/min
BOILER	UA	11,390 W-K

*U= heat transfer coefficient, A= exchanger area

3. Simulation of parawood chips combustion boiler process

In this study, the simulation of parawood chips combustion boiler process was achieved under a normal condition as operating at the wood manufacturing company by Aspen Plus v.9 (as shown in Figure 2). The reference condition was given as shown in Table 2. In the Aspen Plus software, parawood chips were defined as non-conventional solid then their proximate analysis, ultimate analysis and heat of combustion (Table 1) were required as input. The value of combustion heat used is high heating value (HHV) in dry basis, HCOALGEN and DCOALIGT models were used for calculation of enthalpy and density [13]. R-YIELD and R-GIBBS blocks were considered here to represent a combustion reaction. The R-YIELD block simulated the decomposition of parawood chips by converting the non-conventional solid to (1) conventional gas consisting of H_2O, H_2, N_2, O_2, and S, (2) conventional solid which was C (3) and non-conventional elements which was ash. Moreover, the R-YIELD block calculated the enthalpy change of the decomposition process (Q-DECOMP) which was transferred to the R-GIBBS block. Since the decomposed product components must be specified in the R-YIELD block, atomic balance of the defined products was then achieved via a solver tool in EXCEL in sense of minimizing sum of absolute difference of defined products and ultimate analysis results. The optimum results are shown in Table 3. The R-GIBBS block simulated the equilibrium reactor, it calculated phase and chemical equilibriums by minimizing Gibbs free energy. All possible products of the combustion in the R-GIBBS, consisting of H_2O, H_2, O_2, CO, CO_2, N_2, NO_2, NO, S, SO_2, SO_3, and ash, were in the gas phases except for ash which was in solid phase.

To validate the process simulation, Mean Absolute Error (MAE) of stack temperature (FLUSTACK stream in Figure 2) deviation between measured and simulated data was considered. The results are shown in Figure 3. It is found that the simulation error was around 3% (considering with 27 scenarios of the collected data). The error was caused from inconstant and uncontrolled of the moisture content in the wood chips since of the rainy season in Thailand.

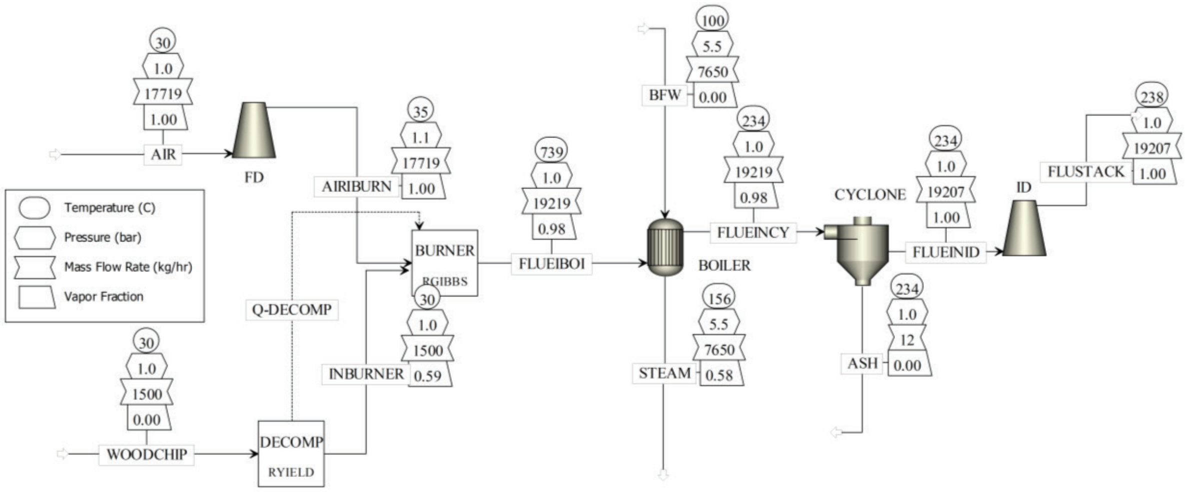


Figure 2. Process flow diagram under original operating conditions (Structure 1).

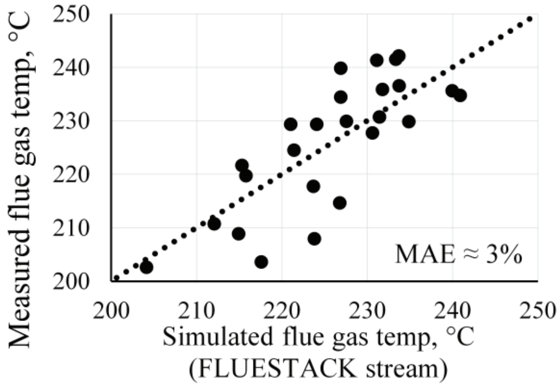


Figure 3. The comparison between simulated and measured flue gas temperature.

Table 3. Optimum distribution of decomposed product yield (R-YIELD).

Basis: 100 g total weight of wet basis

Decomposed elements from atom balance		**Calculating in mole atom**	**Mole atom from ultimate analysis**
2.47 mol C		2.47 mol C	2.47 mol C
1.90 mol H_2	3.80 mol H	8.34 mol H	8.15 mol H
	4.54 mol H		
2.27 mol H_2O	2.27 mol O	3.69 mol O	3.88 mol O
0.710 mol O_2	1.42 mol O		
0.002 mol S		0.002 mol S	0.002 mol S
0.0035 mol N_2		0.007 mol N	0.007 mol N
		SAE = 0.38	

4. Effect of flue gas recirculation and excess air on the pollution emissions, stack heat loss, and steam production

The efficient combustion conditions require the appropriate amount of oxygen to completely burn the given amount of fuel. In practice, more air than theoretical air referred to an excess air must be supplied to completely burn the fuel. The equation for calculating excess air is shown in equation (1) referred to [14].

$$\%\text{ Excess air} = \frac{\%O_2 - \dfrac{\%CO}{2}}{20.9 - \left(\%O_2 - \dfrac{\%CO}{2}\right)} \times 100 \quad (1)$$

Where; $\%O_2$ is the percent by volume of oxygen containing in flue gas and %CO is the percent by volume of carbon monoxide containing in flue gas

The conventional combustion method provides high flame temperature in the furnace which affects directly to the conversion of N_2 and O_2 from air to NO_x. Hence, flue gas recirculation (FGR) technique was applied. Flue gas recirculation is an effective technique for reducing NO_x emission. There are two ways to reduce NO_x. First, the recirculated flue gases absorb heat from the burner resulting in lower peak flame temperature and the formation reduction of thermal NO_x. Second, the recirculated flue gases will lower the O_2 concentration in initial combustion zone, this inhibits fuel NO_x conversion [5]. In this work the external flue gas recirculation (EFGR) technique was used as shown in Figure 4. The concept was that flue gas was separated from a location downstream of the main boiler bank, and then mixed with the combustion air before fed to the burner.

The objective of this section is to find the optimal %excess air and optimal %flue gas recirculation in the sense of CO, NOx, and SOx emissions lower than their limitations, which equal to 690, 200, and 60 ppm respectively [15] Sensitivity analysis was investigated by varying air flow rate (AIR) and the percentage of flue gas recirculation (FLURECIR) while mass flow rate of wood chips (WOODCHIP) was fixed at a normal operating value which is 1,500 kg/hr at 40.48 moisture wt%.

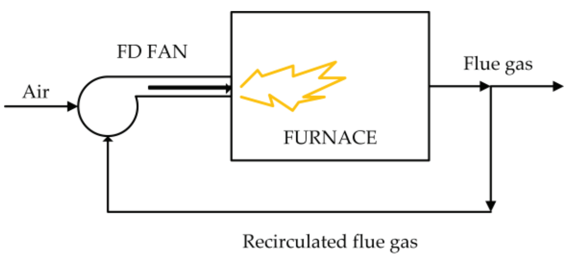


Figure 4. External flue gas recirculation (EFGR)

4.1. CO, NO_x, and SO_x emissions

% Excess air and %flue gas recirculation were varied in the range from 0 - 50% excess air and 0 - 30% flue gas recirculation. From Figure 5(a) shows that increasing of %flue gas recirculation provided a decrease in flame temperature. This is because the recirculated flue gases increase the total gas volume and absorb heat from the burner. The cooling effect obtains from the moisture and CO_2 contained in the flue gas [18]. As a result, the NO_x formation was significantly decreased as shown in Figure 5(b). At 25% flue gas recirculation provided the NO_x emissions under its limitation in every excess air operating and provided the reduction of NO_x around 70% compared with the condition without flue gas recirculation.

As seen in Figure 5(c), CO emissions was significantly decrease while increasing %flue gas recirculation. Same results were found in [16] which reported that the increasing of flue gas recirculation provided a decrease in CO emissions for the flue gas recirculation < 30%. In addition, [17] concluded that the CO emissions are stable while increasing flue gas recirculation ratio in the range of 0-30%, and significantly increase if flue gas recirculation ratio more than 30% due to dilution effect and low flame temperature.

For SO_x emissions as shown in Figure 5(d), Calpenn Associates, Inc. [18] claimed that the flue gas recirculation for stoker boilers can reduce SO_x emissions. It is because of the lower flame temperature provides the lower reaction rate. However, the sulfur content in wood chips is not too high to make the SO_x higher than its limitation.

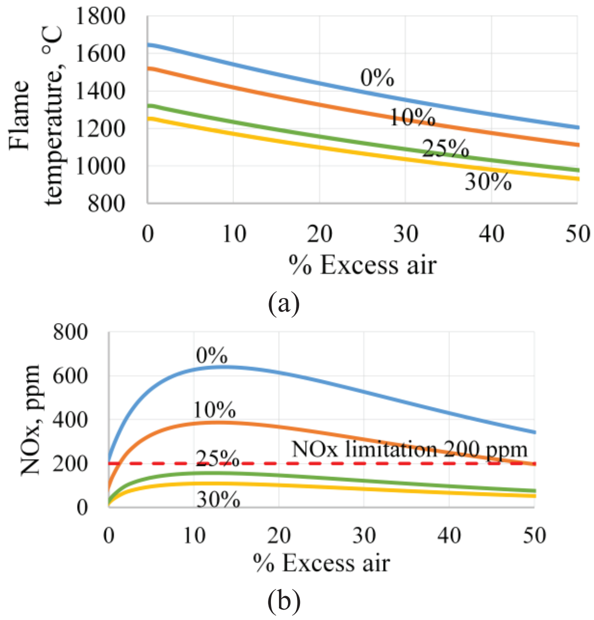


Figure 5. Effect of excess air at different amount of flue gas recirculation on (a) Flame temperature, (b) NO_x, (c) CO, (d) SO_x.

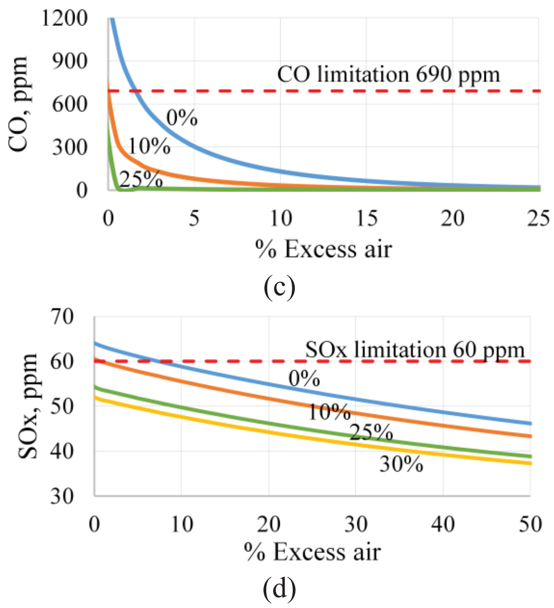


Figure 5. (cont.) Effect of excess air at different amount of flue gas recirculation on (a) Flame temperature, (b) NO_x, (c) CO, (d) SO_x.

In this section, the criteria for choosing the optimal %flue gas recirculation and %excess air was that it could provide the pollution emissions under their limitations. It is noted that at 25% flue gas recirculation provided the NO_x emissions under its limitation in every excess air operating and provided the reduction of NO_x around 70%. The optimal flue gas recirculation was then chosen at 25%. %Excess air should be selected at a low value because it provided a low heat loss. However, at 0% excess air should not be selected although the emissions are lower than limitations. This is because more air must be supplied to burn all fuel completely. Hence, 5% excess air (5,730 kg/hr) was chosen as an optimal excess air in this case. This provided 6, 136, and 52 ppm of CO, NO_x, and SO_x emissions respectively.

4.2. Stack heat loss and Steam production

Heat loss at stack (FLUSTACK) can be calculated by equation (2).

$$Q_{loss}=\frac{m_{flue}C_{p_{flue}}}{10^6}(T_{flue}-T_{ref}) \qquad (2)$$

Where; Q_{loss} is heat loss of flue gas at stack (MJ/hr), m_{flue} is flue gas mass flow rate (kg/hr), Cp_{flue} is heat capacity at constant pressure of flue gas (J/kg-K), T_{flue} is temperature of flue gas at stack (°C), and T_{ref} is reference temperature at 25 °C.

From equation (2), the amount of heat loss depends on the temperature and flow rate of flue gas at stack. Figure 6(a) shows that increasing excess air increases the stack temperature because excess air is also heated up by a portion of heat from combustion leading to lower flame temperature [19]. Moreover, the increased excess air also increases overall flue gas flow rate. These lead to lower enthalpy and lower heat transfer efficiency of boiler resulting in increasing the temperature of flue gas at stack. Hence, the terms of m_{flue} and T_{flue} increase which mean increased in stack heat loss. It is noted that the amount of excess air is a key factor which has an influence on heat loss.

Figure 6(b) and 6(c) show that stack heat loss increases with the increase in %flue gas recirculation, and steam production decreases with the increase in %flue gas recirculation because of less heat applied into the boiler. It is noted that both of the optimal %flue gas recirculation and %excess air should be selected at the low value in order not to lose the heat through flue gas. From the discussion on section 4.1, the optimal %flue gas recirculation was 25% and the optimal %excess air was 5%. This provided 5,900 kg/hr of steam production.

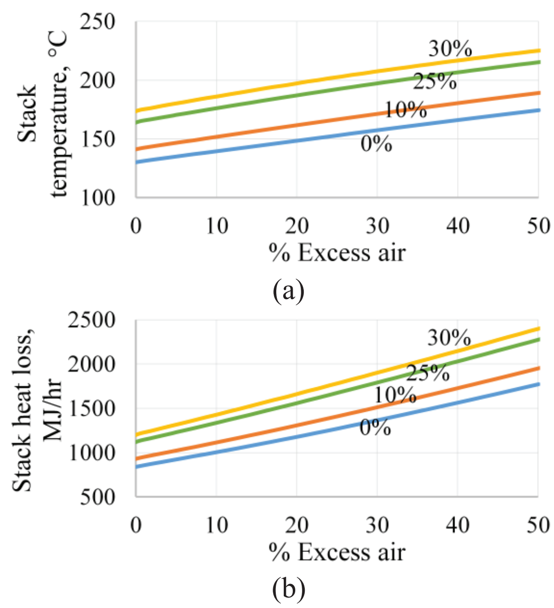
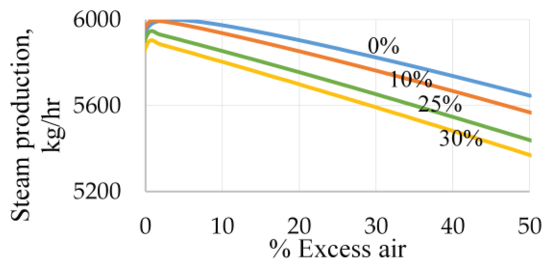


Figure 6. Effects of excess air at different amount of flue gas recirculation on (a) stack temperature, (b) stack heat loss, and (c) steam production.



(c)

Figure 6. (cont.) Effects of excess air at different amount of flue gas recirculation on (a) stack temperature, (b) stack heat loss, and (c) steam production.

4.3. The Optimal operating conditions

As the above discussion on section 4.1 and 4.2, the optimal excess air and optimal flue gas recirculation was 5% and 25% respectively (or air flow rate of 5,730 kg/hr) at parawood chips flow rate of 1,500 kg/hr as shown in Figure 7. They provided 6 CO ppm, 136 NO_x ppm, 52 SO_x ppm, and 5,900 kg/hr of steam production which the pollution emissions were under their limitations.

Results comparison between optimal conditions and original conditions are shown in Table 4. It can be seen that the optimal conditions provided the amount of emissions higher because the less amount of oxygen was supplied. Meanwhile, the amount of steam production was higher than original conditions about 32.4%.

Although the optimal excess air and flue gas recirculation can provide higher efficiency of the process. However, another method to improve more efficiency of the process was the heat recovery from remaining heat of flue gas which discussed in the next section.

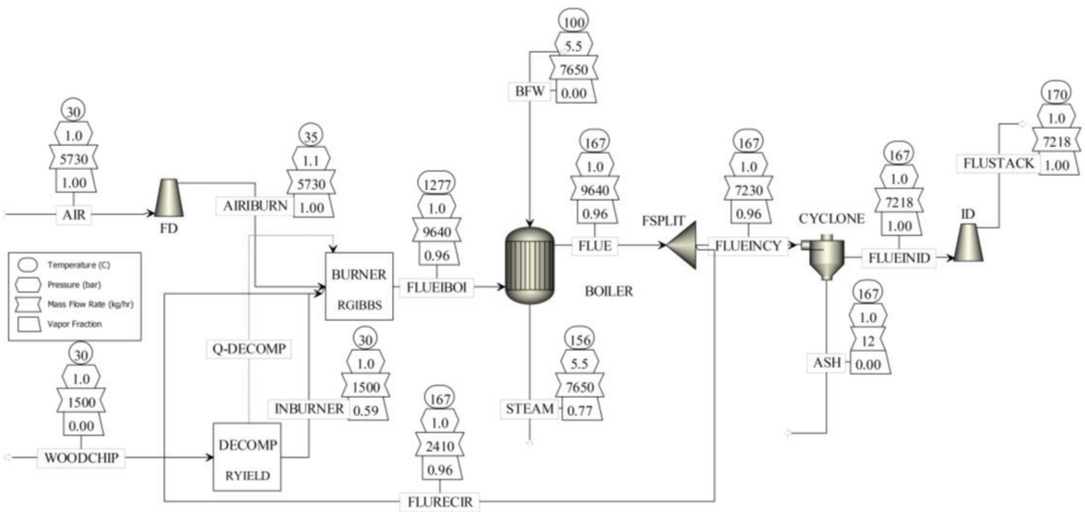


Figure 7. Process flow diagram under optimal conditions (Structure 2).

Table 4. Result comparison of the original process and optimal process.

Process	Emissions (CO, NO_x, SO_x), ppm	Steam production, kg/hr
Original conditions at 168% excess air (17,719 kg/hr)	0.01, 22, 32	4,457
Optimal conditions at 5% excess air (5,730 kg/hr) and 25% FGR	7, 136, 52	5,900

5. Applying air preheater for heat recovery purpose

The objective of this section is to improve the efficiency of the process by using the heat recovery method. The remaining heat of flue gas was transferred through fresh air by shell and tube heat exchanger called air preheater.

5.1. Theoretical design of air preheater

In this work, the requirement of air temperature is higher than 70 °C. The design method based on the theoretical design refers to Sukmanee (2015) [20]. Air preheater was a shell and tube heat exchanger, which flue gas flowed inside the tubes and air flowed outsides. One tube pass was used to prevent fouling of flue gas. The design assumptions were no heat loss, as well as properties of flue gas and air were constant. Operating and properties data for design is shown in Table 5. Designed air preheater specification is shown in Table 6.

5.2. Process simulation combined with air preheater by Aspen Plus

Figure 8 shows the proposed process flow diagram combined with air preheater. The air preheater was used to heat the AIR stream by using the energy from the FLUEINEX stream. At the optimal operating conditions (1,500 kg/hr of parawood chips, 5,730 kg/hr or 5% excess air, and 25% flue gas recirculation), air temperature was heated up to 82 °C. The simulation results of were shown in Table 7.

It is noted that the effect of preheated air provided more supplied heat which can produce a higher amount of steam. However, the emissions also increased but not more than the limitations. For results of steam production, the optimal process condition with air preheater provided steam production more than the original process about 35.4 % and provided steam production more than the optimal process condition without air preheater about 2.2%.

Table 5. Operating and properties data for air preheater design.

Properties	Shell side (Air)	Tube side (Flue gas)
Molecular weight (kg/kmol)	29	28
Mass flow rate* (kg/h)	6,876	8,662
Density (kg/m^3)	1.16	1.00
Heat capacity (kJ/kg-K)	1.02	1.05
Absolute viscosity (mPa-s)	0.020	0.022
Conduction coefficient (W/m.°C)	0.026	0.050
Inlet temperature (°C)	30	170 °C
Outlet temperature (°C)	70 (defined)	139 (calculated)
Pressure inlet (kPa)	105	103

*; Mass flow rate was got from simulation but added 20% for over design.

Table 6. Designed air preheater specification.

Detail	Shell side (Air)	Tube side (Flue gas)
Mass flow (kg/h)	6,876	8,662
Inlet Temperature (°C)	30	170
Outlet Temperature (°C)	70	139
Heat duty (kW)	78.08	
No. pass	1	1
Tube Arrangement		Triangular stainless 304
Tube outside diameter (mm)		88.9
Tube pitch (mm)		118.2
Number of Tube		41
Inside diameter (mm)	1,200	82.09
Thickness (mm)	6	3.404
Baffle		
Type	Segmental	
% cut	25 [21]	
Spacing (mm)	1,500.00	
Heat transfer coefficient (W/m^2.^{o}C)	17.55	
Required heating area (m^2)	43.42	
Existing heating area (m^2)	51.53	

For result of boiler heat duty, the optimal process condition with air preheater provided heat recovery compared with the original process about 29% and provided heat recovery compared with the optimal process condition without air preheater about 1.9%.

It can be seen that the effect of preheated air from 30 °C to 82 °C slightly increased the thermal efficiency and steam productivity. It is suggested that the temperature of preheated air should be more but must consider the increase in heat exchanger price and also pollution emissions.

Table 7. Result comparison of the original process and optimal process with and without air preheater.

Process	Emissions (CO, NO_x, SO_x), ppm	Steam production, kg/hr	Boiler heat duty, MJ/hr
1	0.01, 22, 32	4,457	11,398
2	7, 136, 52	5,900 (32.4% increase compared to 1)	14,422 (26.5% recovery compared to 1)
3	10, 172, 59	6,033 (35.4% increase compared to 1)	14,699 (29% recovery compared to 1)

1 is Original process, 2 is Optimal process condition, and 3 is Optimal process condition combined with air preheater

6. Conventional controller design by Aspen Dynamics

The aim of this section is to design PID controller for regulating the optimal condition by adjusting air to fuel ratio. The pollution emissions which consisted of CO, NO_x, and SO_x including steam production were monitored. Moreover, the pressure and level of boiler were controlled for safety purpose.

6.1. Switch the steady state model in Aspen Plus to dynamic model in Aspen Dynamics

The steady state model in Aspen Plus was switched to the dynamic model in Aspen Dynamics using flow driven mode. Since solid component (C in INBURNER) and non-conventional components (WOODCHIP and ASH) were not allowed in the Aspen Dynamics, then RYIELD module had to be removed.

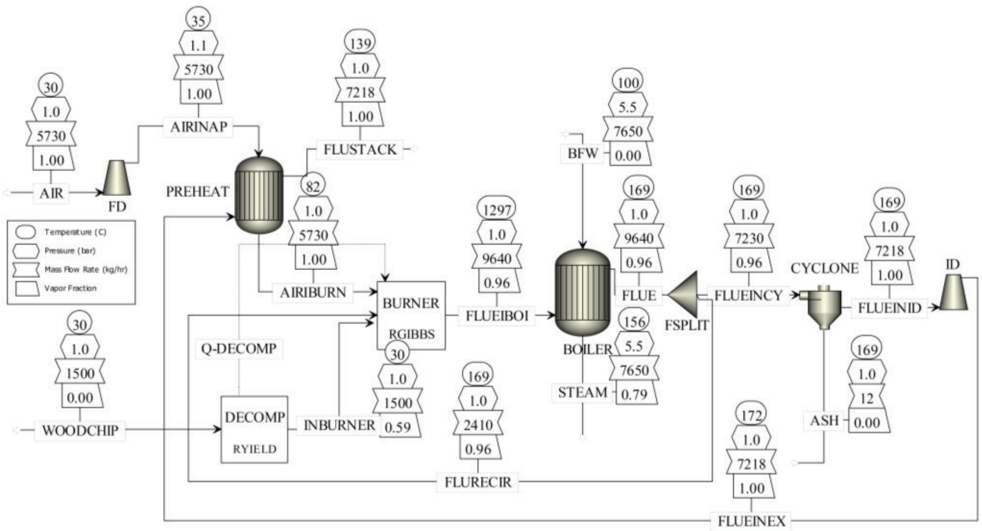


Figure 8. Process flow diagram under optimal conditions combined with air preheater (Structure 3).

The approximate model to handle these problems were proposed and described as follows:

1. Ash was assumed to be separated completely from flue gas, then it was not considered in this case. As a result, the cyclone unit was removed.

2. All of the components of parawood chips (C, H, O, S, and N) were totally decomposed into gas phase products (INBURNER). Then, C and H elements were replaced by organic compound or hydrocarbon (C_nH_n) [6]. Two criteria considered here were as following: (1) major content of wood chips is cellulose, which has the molecular formula as $(C_6H_{10}O_5)_n$ and decomposition temperature about 200 °C [22], and (2) From ultimate analysis, atomic ratio of C:H in ash free basis is 8.37:1 by mass. From both criteria above, $C_{12}H_{18}$ was then chosen, since it has 203 °C decomposed temperature and the mass ratio of C:H is 8:1. Figure 9 shows the approximate model of parawood chips decomposition.

3. The heating energy value of "Q-DECOMP" stream represented the enthalpy change in the decomposition process of parawood chips into its constituent elements [13].

This energy had to be transferred from BURNER (R-GIBBS) to DECOMP (R-YIELDS). Since DECOMP was removed due to a limitation of Aspen Dynamics. Then a prediction equation of the Q-DECOMP was developed in this work as a function of wood chips flow rate (1300 - 2200 kg/hr) and wood chips moisture content (30 - 50%). In this case, the relationship between the enthalpy of wood chips decomposition (Q-DECOMP) and wood chips flow rate at different moisture content was a linear function as shown in Figure 10. Hence, the approximate model equation for QDECOMP was developed as shown in equation (3).

$$\text{QDECOMP} = \text{Wood chip flow rate} \times [(569.13 \times \text{Moisture content mass frac}) - 1246.2] \quad (3)$$

4. In order to control the level and pressure of boiler, boiler needed to be changed from “HEATX” to “FLASH2” as shown in Figure 11. The vessel type was also changed from “Instantaneous” to “Vertical” with 4 meters of length and 1 meter of diameter. The unit name “HEATX” was added for carrying the heat from flue gas to boiler which the value of heat duty (stream “QTOBOIL”) needed to manually specified in dynamic model by using the value from steady state model.

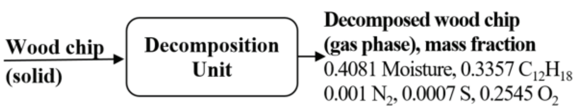


Figure 9. Approximate model of wood chips decomposition.

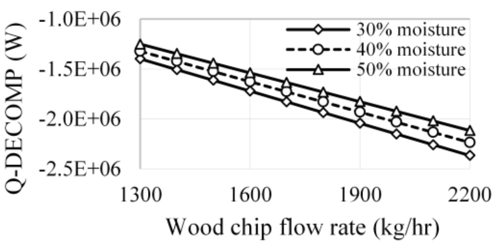


Figure 10. Relationship between heating value Q-DECOMP and wood chips flow rate at different moisture content.

6.2. Control loop description

Figure 12 shows the process simulation developed by Aspen Dynamics. There were a total of 11 loops which consisted of 5 loops of controllers (loops number 1-5), 2 loops of heat calculators (loops number 6-7), and 4 loops of indicators (loop number 8-11).

1. First, the loop number 1 was a ratio controller between air flow rate and wood chips flow rate. It calculated the optimal set point of air to fuel ratio (A/F). The air to fuel ratio depended on the moisture content of wood chips as shown in Figure 11. It can be seen that it was the 4th order polynomial relationship between A/F and moisture content at 30-50 wt% (equation 4). The result of optimal A/F at 30-50 wt% moisture content was shown in Table 8. From result, the wood chips with lower moisture content meant a higher amount of combustible elements which needed a higher air flow rate in the combustion. And, they provided a higher amount of CO and NO_x ppm and steam production. In the block “AF_calc” as shown in Figure 11 was used for calculating the A/F ratio by using equation 4 and then converting to air flow rate.

$$A/F = -2838.5 \text{ x moist}^4 + 4534.9 \text{ x moist}^3 - 2664.1 \text{ x moist}^2 + 678.71 \text{ x moist} - 58.963 \quad (4)$$

Where; **moist** is mass fraction of moisture content of wood chips.

2 and 3. “Steam_Flowrate” and “BOILER_LC” were override control. The controlled variables of both controllers were different. For “Steam_Flowrate” controller, the controlled variable was flow rate of steam production and another “BOILER_LC” controller was a level control of boiler which set point was defined in the range of 2.5 to 3.5 meters. While the manipulated variable of both controllers was the same which was boiler feed water flow rate. Only one signal of controller output was selected by the selector which was the high selector in this case. Consider the situation, if the steam flow rate went below its set point, the output signal was then higher and now it was higher than output signal of level controller. The selector was then choosing the output signal from steam flow rate controller and was then sent the signal to adjust boiler feed water flow rate.

4. “BOILER_Drain” was used for an emergency case when the water level of boiler was too high (higher than 3.5 meters).

5. “BOILER_PC” was the boiler pressure controller with the manipulated variable was the steam flow rate.

6. “QDECOMP” loop was used for calculation of decomposition heating value of wood chips by using equation (3).

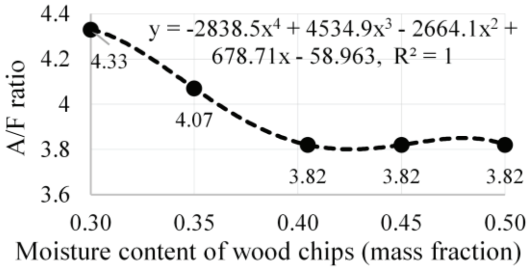


Figure 11. Relationship between optimal A/F ratio and moisture content of wood chips.

Table 8. The result of optimal A/F ratio at different moisture content of wood chips.

Wood chips moisture content, mass fraction	Air flow rate, kg/hr	%Excess air	A/F ratio	Emissions (CO, NO_x, SO_x), ppm	Steam production, kg/hr
0.30	6,500	2.3	4.33	(71,177,54)	7,502
0.35	6,100	3.1	4.07	(32,174,57)	6,808
0.4048	5,730	5.0	3.82	(10,170,59)	6,028
0.45	5,730	11.3	3.82	(1.5,163,59)	5,350
0.50	5,730	19.0	3.82	(0.16,117,59)	4,600

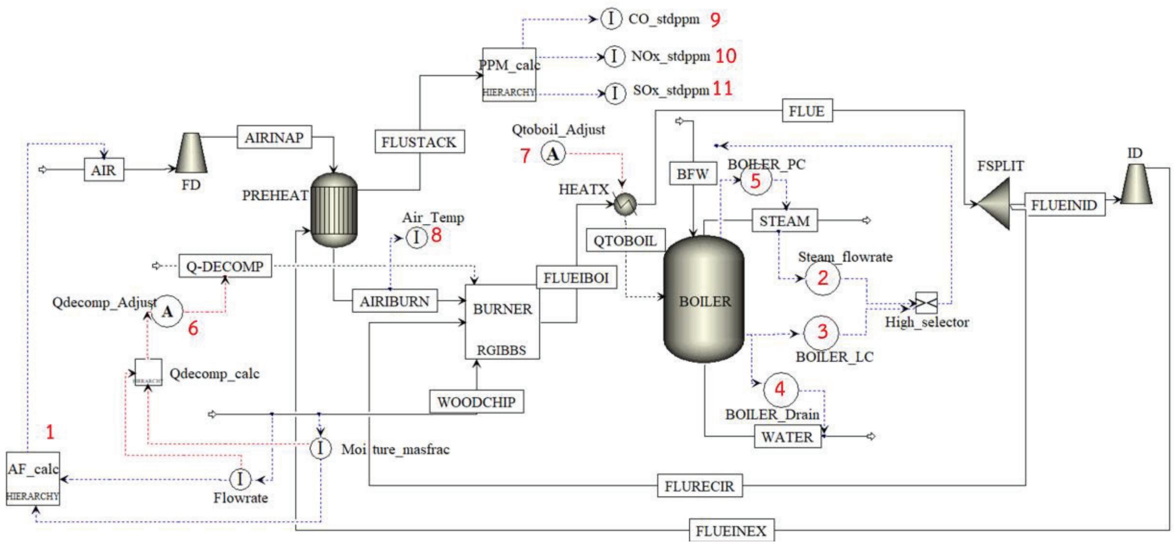


Figure 12. Process simulation with controllers by Aspen Dynamics

7. “QTOBOIL” was used for manual specifying of the heat duty of boiler which got from steady state model in Aspen plus.

8. “Air_Temp” was a preheated air temperature indicator.

9, 10, and 11.“CO_stdppm”, “NOx_stdppm”, and “SOx_stdppm” were the CO, NO_x, and SO_x, ppm indicators respectively.

6.3. Robustness test

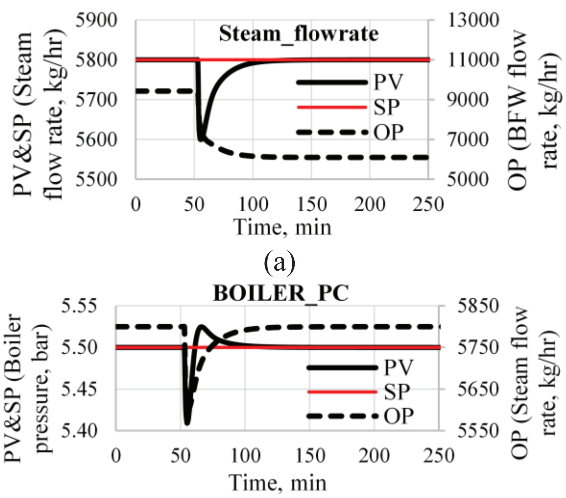
Robustness of controller was investigated in this section by slightly changing disturbance variables from their design conditions [23]. In this case, the disturbances consisted of wood chips flow rate, wood chips moisture content and inlet temperature of boiler feed water (BFW).

Figure 13 shows controller responses in case of the wood chips flow rate step-change. The wood chips flow rate was stepped down from 1,500 to 1,400 kg/hr at time 53 min. The air flow rate was adjusted along the air to fuel ratio which was 3.82 from 5,730 kg/hr to 5,348 kg/hr. It can be seen that the dynamics were quite fast. The steam production instant decreased when the wood chips flow rate was decreased because the heat of combustion from fuel was decreased. After that, the BFW flow rate was continuous decreased in order to increase the steam production to its set point. As a result, the boiler level was decreased from 3.50 meter to 3.31 meter. For the emissions, all of CO, NO_x, and SO_x ppm increased due to the denominator of ppm, which was total volume flow, was decreased.

Figure 14 shows controller responses in case of the wood chips moisture content step-change. The moisture content was stepped up from 40.5% to 45% at time around 25 min. The steam flow rate instant decreased when the moisture content was increased. It can be seen that the steam flow rate cannot reach the set point of 5,800 kg/hr of steam because when the BFW flow rate continuously decreased, the boiler level also continuously decreased until the minimum allowance at 2.5 meters the controller was switched from “Steam_flowrate” to “BOILER_LC” to maintain the boiler level higher than 2.5 meters. Then, the BFW flow rate was forced to increase by “BOILER_LC” controller. It is noted that the heat of combustion from wood chips at 1500 kg/hr and 45% moisture content was not enough for producing steam at 5,800 kg/hr. It should be supplied more fuel or should be supplied fuel with lower moisture content. Table 9 shows the possible maximum steam production at different wood chips flow rate and moisture content.

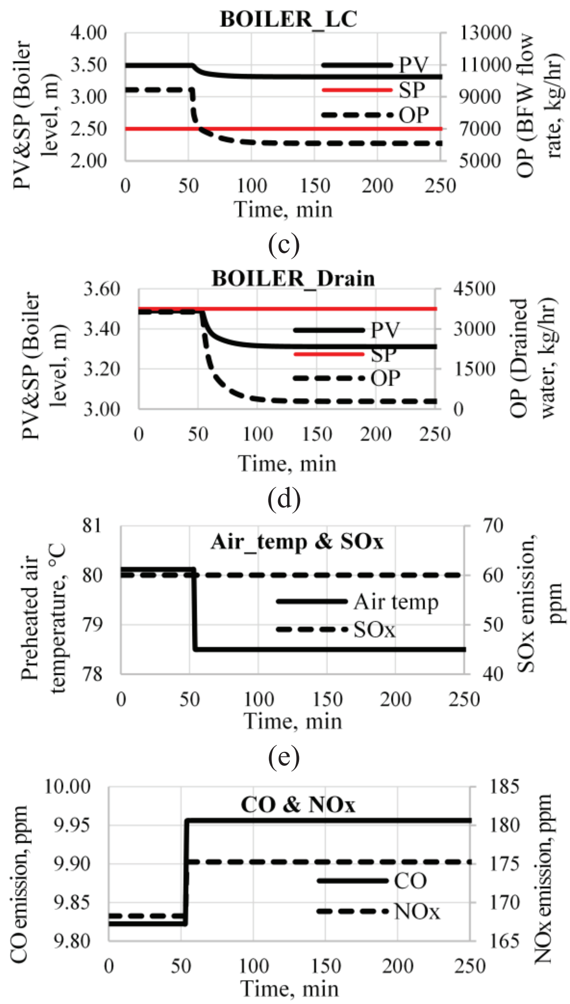
Figure 15 shows controller responses in case of the BFW inlet temperature step-change. The BFW inlet temperature was stepped down from 100°C to 80°C at time around 28 min. The controllers can perfectly maintain their set points.

These results show that the dynamic model can be self-balanced although disturbance occurred. However, the caution was that the defined set point of steam production must be related together with wood chips flow rate and wood chips moisture content as shown in Table 9.



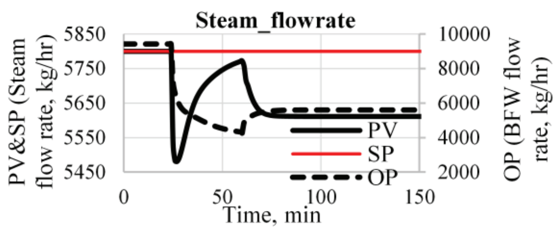
(b)

Figure 13. Robustness test in case of wood chips flow rate change (from 1,500 kg/hr to 1,400 kg/hr).



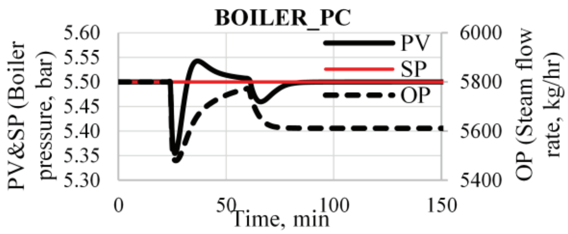
(f)

Figure 13. (cont.) Robustness test in case of wood chips flow rate change (from 1,500 kg/hr to 1,400 kg/hr).



(a)

Figure 14. Robustness test in case of wood chips moisture content change (from 40.5 wt% to 45 wt%).



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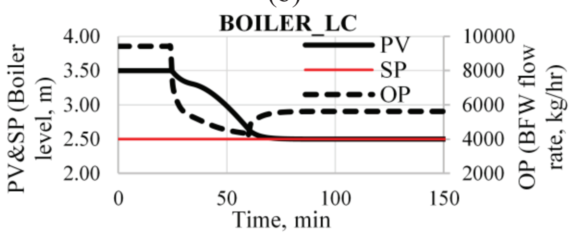
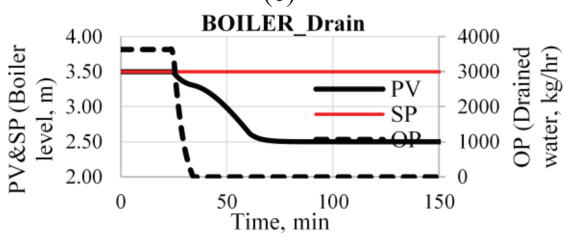
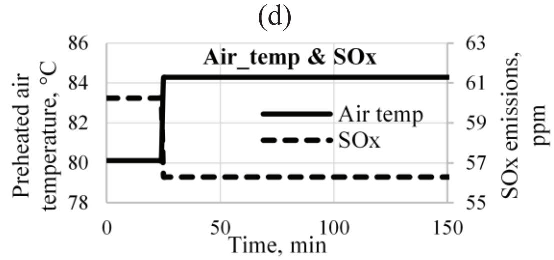


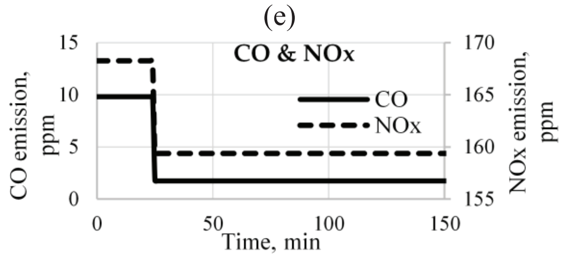
(c)



(d)

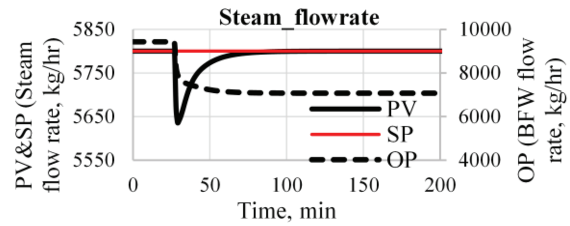


(e)

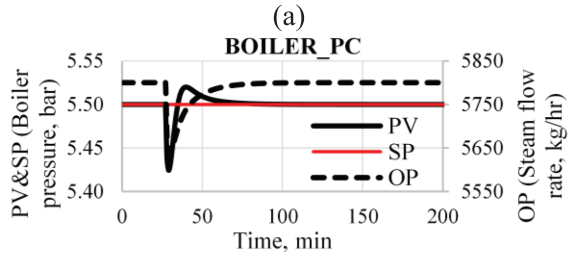


(f)

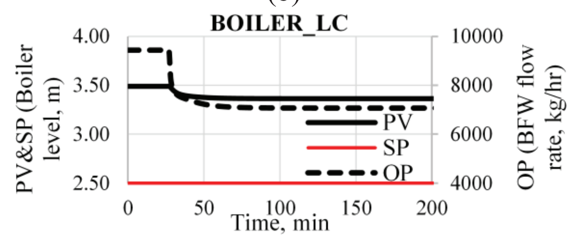
Figure 14. (cont.) Robustness test in case of wood chips moisture content change (from 40.5 wt% to 45 wt%).



(a)



(b)



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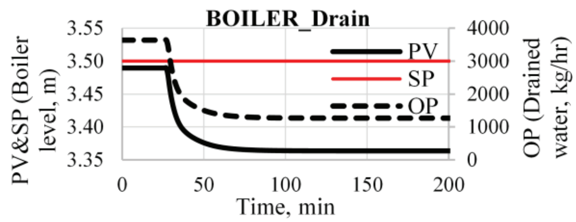

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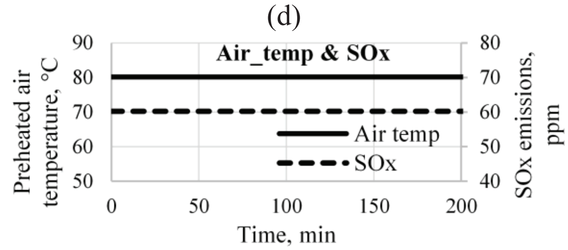

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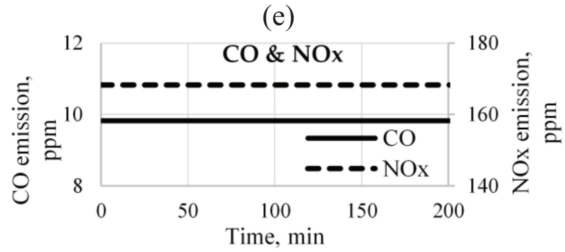

(f)

Figure 15. (cont.) Robustness test in case of BFW inlet temperature change (from 100 to 80 °C).

Table 9. Possible maximum steam production at different wood chips flow rate and moisture content.

Wood chips flow rate, kg/hr	Possible maximum steam production, kg/hr
At moisture content 30 wt%.	
1,300	6,365
1,400	6,809
1,445	7,000
At moisture content 35 wt%.	
1,300	5,836
1,400	6,248
1,500	6,650
1,590	7,000
At moisture content 40.48 wt%.	
1,300	5,247
1,400	5,620
1,500	5,985
1,600	6,342
1,700	6,693
1,790	7,000
At moisture content 45 wt%.	
1,300	4,740
1,400	5,076
1,500	5,406
1,600	5,729
1,700	6,045
2,000	6,953
At moisture content 50 wt%.	
1,300	4,179
1,400	4,475
1,500	4,766
1,600	5,050
1,700	5,328
2,000	6,126

7. Conclusion

This work was divided into 2 main sections. First, a steady-state simulation of wood chips combustion boiler process was achieved by using Aspen Plus v.9. The optimal condition of air to fuel ratio combined with the flue gas recirculation technique was determined in the sense of using energy to be cost effective and in the meanwhile, the emissions consisted of CO, NO_x, and SO_x were in their limitations. Furthermore, air preheater was designed and combined for energy recovery purpose.

In this case, manufacturing and pollution requirements are steam productivity of 4,000 to 7,000 kg/hr, the CO, NO_x, and SO_x emissions are less than 690, 200, and 60 ppm respectively and preheated air temperature more than 70 °C. The simulation model was further used for description of excess air and flue gas recirculation effect on the various factors consisted of CO, NO_x, SO_x emissions, flame temperature, stack temperature, stack heat loss, and steam production.

Second, a dynamic simulation scheme of wood chips combustion boiler process was proposed using Aspen Dynamics v.9. There had 5 controllers consisted of air to fuel ratio controller which was ratio controller type, override control between boiler level and steam flow rate control which were both PI controller, boiler pressure control which was PID controller, and boiler drained water control which was P controller. Robustness tests were performed to prove the performance of the controller by stepping change the disturbance variables consisted of wood chips flow rate, wood chips moisture content, and BFW temperature. The simulation results can be summarized as follows.

1. Model validation was achieved by comparing with the sets of measured data collected by wood manufacturing company in the south of Thailand. Prediction error of flue gas temperature at stack is less than 5% (considering with 26 scenarios of the collected data).

2. CO emissions release hugely at a lower excess air than 0% because incomplete combustion has occurred. After that, CO emissions decrease considerably with increasing %excess air.

3. NO_x reaches a maximum value at around 10-15% excess air and then continuously decrease when increasing %excess air.

4. SO_x comes from the sulfur (S) contained in fuel reacts with the O_2 contained in combustion air. SO_x formation directly depends on the combustion temperature.

5. Increase of excess air leads to increase of the stack temperature and stack heat loss.

6. For the case of steam production, less heat from flue gas applies to generate steam when increasing excess air since the heat loss at stack increases. As a result, steam production also decreases when increasing excess air

7. Flue gas recirculation technique was applied for reducing NO_x emissions. 25% flue gas recirculation provides the reduction of NOx around 70% compared with the process without flue gas recirculation.

8. Optimal operating condition of the process is 5% excess air (5,730 kg/hr air flow

rate) and 25% flue gas recirculation with 40.5 wt% of moisture content of wood chips and 1,500 kg/hr of wood chips flow rate. It can produce steam higher than original process condition (168% excess air and no flue gas recirculation) about 32.4%.

9. Designed air preheater type is shell and tube heat exchanger. Flue gas is inside tubes and air is outside. The exchanger consists of 41 tubes with 88.90 mm OD, 3.405 mm thickness and 1,212 mm OD of shell with 6 mm thickness (1 tube pass and 1 shell pass). The preheated air was heated up from 30 °C to 82 °C. The effect of preheated air provides more supplied heat which can produce a higher amount of steam. It provides steam production more than the optimal process condition without air preheater about 2.2%.

10. For the dynamic model, Robustness tests were performed to prove the performance of the controller by stepping change the disturbance variables consisted of wood chips flow rate, wood chips moisture content, and BFW temperature. The results show that the dynamic model can be self-balanced although disturbance occurred. However, the caution is that the defined set point of steam production must be related together with wood chips flow rate and wood chips moisture content as shown in Table 9.

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