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Experimental Study on Combustion Characteristics in a CFB during Co-firing of Coal with Biomass Pellets in Thailand

Thanet Unchaisri*, Suneerat Fukuda*,[1], Awassada Phongphiphat*, Suvit Saetia[+], and Boonrod Sajjakulnukit*

Abstract – *This paper studies the effect of operating conditions, including excess air ratio and biomass shares in fuel mixtures on emissions (CO, NO_x, SO_2) and ash characteristics from coal combustion during co-firing of coal with biomass pellets. The experiments were performed in a circulating fluidized bed (CFB) reactor of 80 kW_{th} capacity. The domestic biomass, including rice straw, eucalyptus and empty fruit bunch were used in pellet form as the supplementary fuels for co-firing with coal. In the experiments, the excess air ratios were varied over a range of 1.28–2.10, and the fuel feed rate was kept at 14 kg/h. The mass fractions of biomass pellets were at 25 wt% and 50 wt%. The combustion time was around eight hours after reaching a stable temperature. Flue gas emissions (CO, NO_x, SO_2) were measured with a TESTO 350 XL flue gas analyzer. In order to investigate the effect of blending biomass pellets with ash characteristics, fly ash and bottom ash were collected and analyzed by X-Ray Fluorescence (XRF) and a Scanning Electron Microscope with Energy Dispersive X-ray Spectrometer (SEM-EDS), respectively. The results showed that the excess air could promote complete combustion with decreasing CO emission. With the further increase in excess air, CO emission increased because of the insufficient residence time for complete combustion and the cooling effect. During co-firing experiments, the bed temperature in riser decreased by about 150–200℃ as compared to coal combustion. NO_x emissions for co-firing with rice straw pellets and empty fruit bunch pellets were lower than the emissions from coal. At high excess air, NO_x concentration for co-firing of coal with 50 wt% eucalyptus pellets was higher than the concentration for coal alone. SO_2 emissions for co-firing with biomass pellets in all cases were lower than those from coal. The bed agglomeration was not observed in the spent bed during co-firing of coal with biomass pellets up to 50 wt%. However, the bed particles were coated with layers of elemental compositions corresponding with fuel ashes. FactSage software in the "Phase Diagram" module was used to predict the melting temperature of ash when coating the bed particles. The highest and the lowest melting temperatures of ash were 1734°C and 1410°C for coal combustion and co-firing of coal with empty fruit bunch at 50 wt%, respectively.*

Keywords – biomass, circulating fluidized bed, coal, combustion, emissions.

1. INTRODUCTION

In Thailand, coal is widely used in electricity generation and in industry sectors. The imported coal is mainly used in the industrial sector, *e.g.*, for producing cement. To decrease the dependence on coal imports, the abundantly available agricultural residues or biomass, the by-products from agricultural production and agro-processing, have been used as a supplementary fuel for co-firing with coal in industrial boilers. The addition of biomass not only reduces the fuel cost but also lowers NO_x and SO_x. The circulating fluidized bed (CFB) boiler has several advantages, such as the effective reduction of nitrogen oxides, fuel flexibility, temperature homogeneity, high combustion efficiency and low pollutant (*e.g.*, SO_x) emissions. CFB has also been adopted for the co-firing of coal with biomass. However, some compositions (*e.g.*, alkali salts and chlorine) in biomass fuels are higher than in coal. Consequently, their combustion introduces ash-related problems, including fouling and agglomeration.

Many researchers studied the effects of operating conditions, including excess air ratio, secondary air feeding position and mass fraction of biomass on emissions (CO, NO_x, SO_2) and combustion efficiency during coal/biomass combustion and co-firing of coal with biomass in the CFB. Atimtay *et al.* (2017) [1] and Youssef *et al.* (2009) [2] studied the influence of excess air ratios on CO emission and combustion efficiency in the pilot-scale CFB. They reported that the combustion efficiency could be improved by the increase of excess air to increase the char reaction rate and promote the oxidation of CO to CO_2.

The increased secondary air feeding position along the riser decreased NO_x emission, as reported by the study of Saikaew *et al.* (2012) [3]. The NO_x emission could be promoted by the fuel-nitrogen oxidation at the lower secondary air feeding position, which is the high bed temperature zone with rich oxygen concentration. The staged combustion could reduce NO_x emission, as reported by the study of Diego *et al.* (1996) [4]. The oxygen concentration at the lower zone of the riser was reduced by increasing the secondary air ratio, resulting in a decrease in the char combustion rate. The remaining char and CO could promote NO_x reduction reactions [5].

*The Joint Graduate School of Energy and Environment and Center of Excellence on Energy Technology and Environment, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand.

[+]Department of Chemical Engineering, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand.

[1] Corresponding author;
Tel: + 662 872 9014-5 Ext. 4148. Fax: +662 872 6978.
E-mail: suneerat@jgsee.kmutt.ac.th.

Generally, the contents of nitrogen (N) and sulfur (S) are higher in coal than biomass. According to the studies of Xie *et al.* (2007) [6] and Saikaew *et al.* (2012) [3], biomass addition during co-firing with coal has a beneficial effect on gaseous emissions except for CO emission. The CO emission must be considered in biomass combustion due to its high volatile matter content.

Some studies used the CFB modeling to analyze and simulate a combustion system including hydrodynamics, heat transfer, combustion characteristics and emissions. Gungor (2008) [7] developed a model to simulate results compared with four experimental results derived from wood [8], olive cake [9], rice husk [10], and wood chip [11] combustion in CFB combustors. In this study, operational parameters such as excess air and superficial velocity were investigated on bed temperature and CO and NO_x emissions. The model was validated with experimental results. In addition, Gungor (2013) [12] applied a model with mono-combustion to simulate CO, NO_x, and SO_2 emissions from co-firing of coal with rice husk and compared results to the experimental results reported by Xie *et al.* (2007) [6]. A computational fluid dynamics (CFD) model for the simulation of combustion behaviors including temperature, CO_2, and O_2 in a 550-MW_{th} furnace burning coal with biomass mixtures was presented by Bhuiyan and Naser (2015) [13].

Apart from the issue of gaseous emission, some studies have investigated the ash behavior and bed agglomeration during CFB combustion of biomass or coal/biomass mixtures [14]-[17] with different aims, such as to identify the causes and mechanism of bed agglomeration and to propose possible solutions to reduce bed agglomeration. Since the occurrence of bed agglomeration is fuel- and operation-specific, dedicated study of various fuel combinations is necessary for a good system understanding and successful operation, especially when co-firing at the higher limit of the biomass share.

Among the various biomasses available in Thailand, rice straw and empty palm bunches have very high potential, equivalent to around 11,931 and 1,183 ktoe [18], respectively. Since rice straw and empty fruit bunches are naturally fibrous and have high alkali content, they are considered difficult fuels. The high amount of alkalis causes ash-related problems, including bed agglomeration [14], [15], [17] and fouling [15], [16]. Eucalyptus is another economic crop in Thailand and is used in the paper industry. The waste from paper production, *e.g.*, bark, could also be used as fuel.

This study focuses on investigating the performance of co-firing coal with rice straw, eucalyptus, and empty fruit bunch. The biomass is used in pellet form to ease the feeding control. In addition, the effects of excess air ratio and blending ratio on combustion efficiency, gaseous emissions (NO_x, SO_2, CO), and ash characteristics after combustion are investigated. To examine the ash transformation, the thermochemical equilibrium simulation is conducted using FactSage (version 6.4) to estimate the melting temperature of ash and explain the ash behavior towards agglomeration. FactSage software is employed to predict the distribution of chemical composition in coal and biomass ashes at various temperatures [19], [20]. Moreover, Fusco *et al.* (2017) [21] used a ternary phase diagram, K_2O-CaO-SiO_2, derived from FactSage to predict the solid, solid + liquid, and liquid phases of biomass ashes at different temperatures. The factors affecting co-firing are examined using a lab-scale circulating fluidized bed combustor at 80-kW_{th} capacity to simulate the conditions close to those occurring in commercial ones.

2. EXPERIMENTAL

2.1 Fuels and Bed Material

The domestic biomass pellets, including rice straw pellets, eucalyptus pellets, and empty fruit bunch, were used for co-firing with coal in a CFB. The bulk density (following ASTM E873-82) was in the range of 650–680 kg/m^3 for rice straw, eucalyptus, and empty fruit bunch pellets. The biomass pellets used in the experiment were 8–10 mm in diameter and 20–50 mm long. Silica sand was used as the bed material. The main compound of sand is SiO_2 (97%) with a particle density of 2,670 kg/m^3 and bulk density of 1424 kg/m^3. The average particle density levels (following ASTM E828-81) for sand and coal were determined to be 476 μm and 1.66 mm, respectively. The analytical data for the fuels used in this work are given in Table 1.

2.2 Apparatus

The experiments were carried out in an 80-kW_{th} capacity circulating fluidized bed reactor as schematically shown in Figure 1. The CFB is made from steel and insulated with 50 mm thick refractory and ceramic wool. The CFB comprises a riser 0.15 m i.d. and 5.4 m high and an internal cyclone connected with a downcomer measuring 0.10 m i.d. and 3.6 m high. An L-valve measuring 0.10 m i.d. and 0.17 m long was installed between the riser and downcomer. In addition, a dust cyclone was installed at the exit of the CFB reactor in order to capture fly ash from gas stream. Ten K-type thermocouples were installed at different locations of the reactor so as to continuously obtain temperature data. To monitor and measure the pressure inside the reactor, thirteen pressure transducers were added. The primary air was preheated to 200°C before being introduced at the bottom of the riser during the tests.

2.3 Experimental Procedure

The operating parameters, excess air (EA) ratio and fuel blends, were investigated for combustion performance and bed agglomeration during the co-firing of coal with biomass pellets. In the experiments, the fuel feed rate was kept constant at 14 kg/h. The airflow rate was adjusted to corresponding excess air ratios, which fell in the range of 1.28–2.10. The experimental time was approximately eight hours after the stable temperature was reached. For each of the three fuels (rice straw pellet (SP), eucalyptus pellet (Euca), and empty fruit bunch pellet (EFB)) used for co-firing with coal, the mass fraction of supplement fuels varied from 25% to

50%. The proportion of biomass was increased in fuel mixtures as far as possible to simulate the effects of an industrial-scale boiler. However, the mass fraction of biomass added to fuel mixtures was limited by fuel feed systems. In order to investigate the combustion performance in the CFB, temperature and pressure were measured continuously. Flue gases (CO, NO_X, SO_2) were sampled at the cyclone exit and analyzed by a multigas analyzer (Testo 350XL).

Table 1. The proximate, ultimate, and fuel ashes analyses.

	Coal	Rice straw pellet	Eucalyptus pellet	Empty fruit bunch pellet
Proximate analysis (wt%)*				
Moisture	12.7	8.4	8.5	9.5
Volatile matter	47.8	65.5	69.3	76.2
Fixed carbon	27.4	13.7	10.9	6.2
Ash	12.1	12.4	11.3	8.1
HHV (MJ/kg)	20.9	13.2	15.8	16.6
Ultimate analysis (wt%)**				
Carbon	66.2	36.9	42.3	46.7
Hydrogen	6.1	5.2	4.7	6.5
Oxygen***	12.3	43.7	37.5	37.9
Nitrogen	1.0	0.5	3.1	0.6
Sulfur	0.6	0.1	0.0	0.0
Inorganic elements (wt%)				
SiO_2	33.1	61.0	6.2	18.6
Al_2O_3	23.9	1.9	0.6	0.4
CaO	6.0	3.3	62.4	14.5
MgO	3.2	1.9	4.3	5.4
Na_2O	0.9	0.8	1.9	1.6
K_2O	0.8	17.5	15.0	46.1
Fe_2O_3	9.9	1.1	0.8	2.1
P_2O_5	0.2	1.7	2.4	4.0
TiO_2	2.1	-	0.0	0.0
SO_3	8.7	1.3	2.0	3.6
Cl	-	4.5	2.0	3.7
Other	11.2	5.0	2.4	0.1

* Wet basis
** Dry basis
*** O = 100 - (%C + %H + %N + %S+ %dry basis ash)

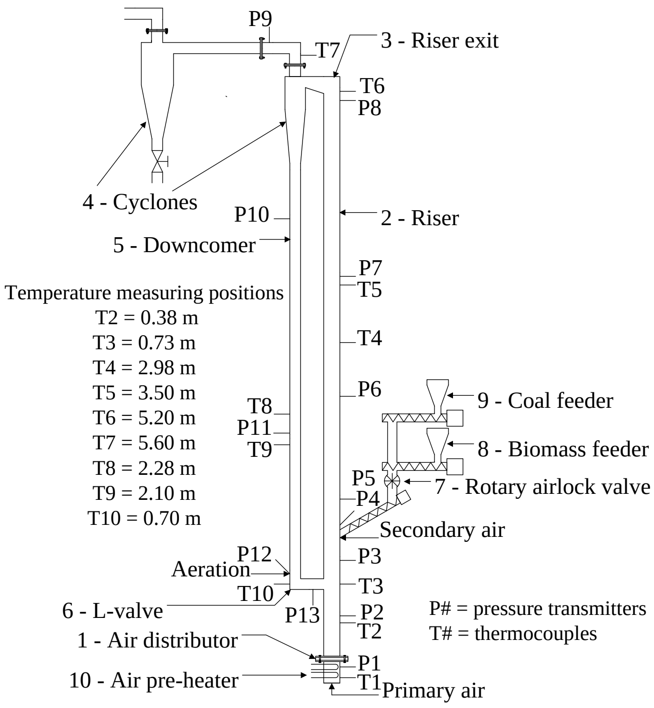

Fig. 1. Schematic diagram of the CFB reactor.

The start-up procedures can be divided into 4 main steps:

Step 1: Preheating the reactor. The empty reactor began at an ambient temperature and was heated by continuously adding ignited charcoal and leaving it to burn until the temperature T3 reached 530°C.

Step 2: Preheating the bubbling sand bed. Sand was added into the riser about 2 kg at a time together with charcoal in order to keep the temperature T3 at 500°C. This step was repeated until the sand mass in the riser reached 10 kg. The bed was controlled in bubbling fluidization mode.

Step 3: Increasing bed temperature and sand mass. Coal began to be fed into the riser when the average riser temperature (T2–T6) reached 430°C. This was to ensure that the coal was ignited. More sand was added into the riser about 2 kg at a time. The feed rates of air and coal were increased after adding sand in order to increase the riser temperature to 500°C, 550°C, and 600°C and to increase the superficial gas velocity. This step was repeated until the total sand mass in the riser was 26 kg and the averaged riser temperature (T2–T6) reached 580–600°C, as indicated in Figure 2.

Step 4: Beginning solids circulation. The L-valve was opened for aeration to start circulation in the system.

Then, the superficial gas velocity (U_g) was accelerated to circulation mode (5 m/s), and the fuel feed rate was increased to 14 kg/h. As shown in Figure 2, the temperatures in the standpipe (T8) and the L-valve (T10) increase after circulation. The temperatures in the riser, standpipe and L-valve slightly increase and approach a stable state.

Combustion efficiency (η_c) was calculated by the heat-loss method [22], [23] as shown in Equations 1 to 3.

$$\eta_c = 100 - (q_{uc} + q_{ic}) \tag{1}$$

The heat loss due to unburned carbon (q_{uc}) was estimated using the unburned carbon in fly ash (C_{fa}, wt.%), the fuel ash content (A , wt.%, on as-received basis) and the fuel lower heating value (LHV , kJ/kg, on as-received basis).

$$q_{uc} = \left(\frac{32,866}{LHV}\right)\left(\frac{C_{fa}}{100 - C_{fa}}\right)A \tag{2}$$

The heat loss owing to incomplete combustion (q_{ic}) was predicted using the actual CO and CH_4 emissions in the flue gas (both in ppm, on a dry gas basis).

$$q_{ic} = 10^{-4}(126.4CO + 358.2CH_4)V_{dg}\frac{(100 - q_{uc})}{LHV} \tag{3}$$

Where V_{dg} is the volume of “dry flue gas” (Nm^3/kg) during combustion of 1 kg fuel at the actual air.

The bed particles were collected after the experiment and analyzed using a scanning electron microscope integrated with an energy dispersive X-ray spectrometer (SEM-EDS) to observe their morphology and elemental compositions. Fly ash was collected and analyzed by X-Ray Fluorescence (XRF) to identify the elemental compositions. Thermodynamic equilibrium calculation based on FactSage software (version 6.4) using the “Phase Diagram” module was applied for estimating the melting temperature of fuel ash and EDS data derived from the ash coating the bed particles.

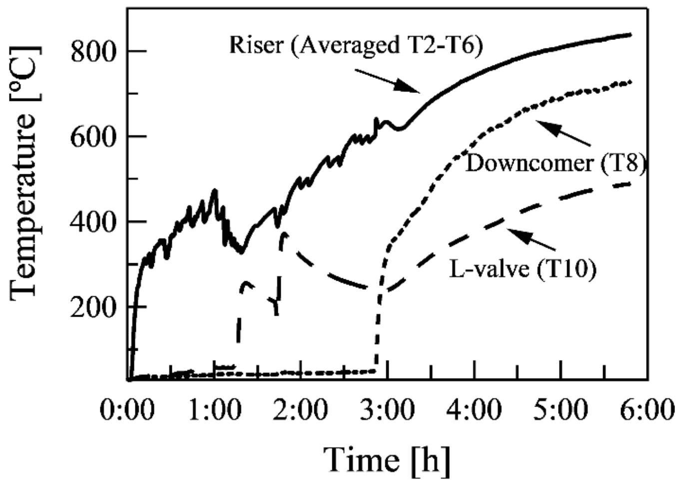

Fig. 2. Temperature in CFB reactor during start-up.

3. RESULTS AND DISCUSSIONS

3.1 *Typical Temperature and Pressure Profiles*

Figure 3 shows the typical temperature and pressure profiles of coal combustion at excess air ratio 1.41 in the CFB reactor. It can be observed that the temperatures along the riser (T2–T6) were quite uniform.

The temperatures (T3) of bed particles, fuel, and gases were reduced by the cooling effect, which involves the introduction of air in the L-valve and secondary air. The lowest temperature in the circulation loop was found at T7 which was observed near the reactor exit and atmosphere temperature. The solids and gases flew through the cyclone and into the standpipe, resulting in the accumulation of bed material in the standpipe. As a result, the temperatures (T8–T9) increased slightly. The temperature T10 was decreased by introducing air into the L-valve. The high-pressure points were found at P2 and P12, which were near air distribution and L-valve, respectively. The pressure at the cyclone exit (P9) was the lowest in the circulation loop because the pressure tap was installed near the atmosphere. The low-pressure points were in the standpipe, exit of the internal cyclone (P10) and solids circulation loop (P11). The pressure profile showed a stable operation and agreed with the experimental result of Arena *et al.* (1998) [24] who studied the hydrodynamics of an L-valve in a CFB, the literature reported that the highest and the lowest pressure positions were found at L-valve and exit of cyclone, respectively.

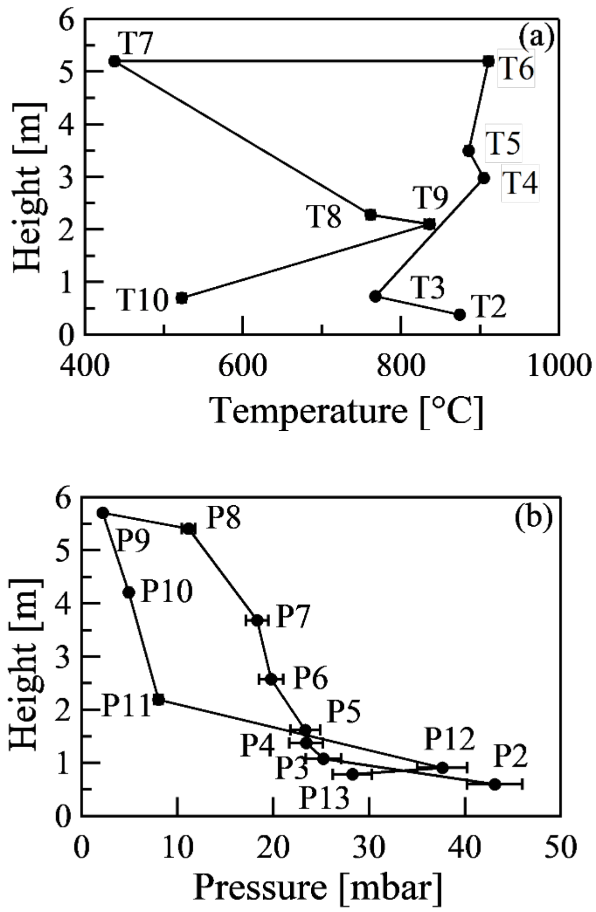

Fig. 3. Typical temperature (a) and pressure (b) profiles of a CFB reactor during coal combustion.

3.2 Temperature Distribution and Average Bed Temperature

Figures 4(a) and (b) show the temperature distribution along the riser and the averaged bed temperature, respectively, for three kinds of biomass fuel blended with coal compared to coal alone at different blending ratios and excess air ratios. The higher-volatile-matter content in the fuel requires more air to combust. In each test, the excess air ratios were adjusted, corresponding to volatile matter content in the fuels, as follows: C 100: 1.28–1.55, C 75 + SP 25: 1.44–1.77, C 50 + SP 50: 1.46–1.94, C 75 + Euca 25: 1.39–1.85, C 50 + Euca 50: 1.36–1.99, and C 50 + EFB 50: 1.49–2.01. The bed temperature represents the average of the five thermocouples that were installed along the riser (T2–T6). The temperature distributions for all mixtures and coal show similar patterns. In Figure 4(a), the bed temperatures were in the ranges of 842–893°C for coal combustion, 717–739°C for co-firing of coal with 25 wt% rice straw pellets, 650–690°C for co-firing of coal with 50% rice straw pellets, 717–742°C with 25 wt% eucalyptus pellets, 662–725°C with 50 wt% eucalyptus pellets, and 661–711°C with empty fruit bunch pellets. Regardless of biomass type, the temperature distributions decreased about 150–200°C by increasing the proportion of the biomass share 25 wt% and 50 wt%.

An increase in excess air reduces the bed temperature (as shown in Figure 4(b)) due to the increased convective heat loss and reduced residence time from the increased gas velocity in the riser. The temperature distribution and average bed temperature were affected by the heating value of the fuels (as shown in Table 1). Since the fuel feed rate was fixed at 14 kg/h for all tests, the heat input and the bed temperature decreased with the increase of the blending biomass pellets. The heating value of eucalyptus pellets was higher than that of the rice straw pellets and yielded the higher bed temperature, as clearly observed in case of co-firing with 50 wt% biomass. The heating value of empty fruit bunch pellets was slightly higher than that of the eucalyptus pellets. However, when co-firing coal with empty fruit bunch and eucalyptus pellets at 50 wt%, the bed temperature for empty fruit bunch pellets was lower than that of eucalyptus pellets at lower regions of the riser. After that, the bed temperature for empty fruit bunches slightly increased. This result could be explained by the considerable amount of volatile matter in empty fruit bunch pellets that was released and combusted in the upper zone.

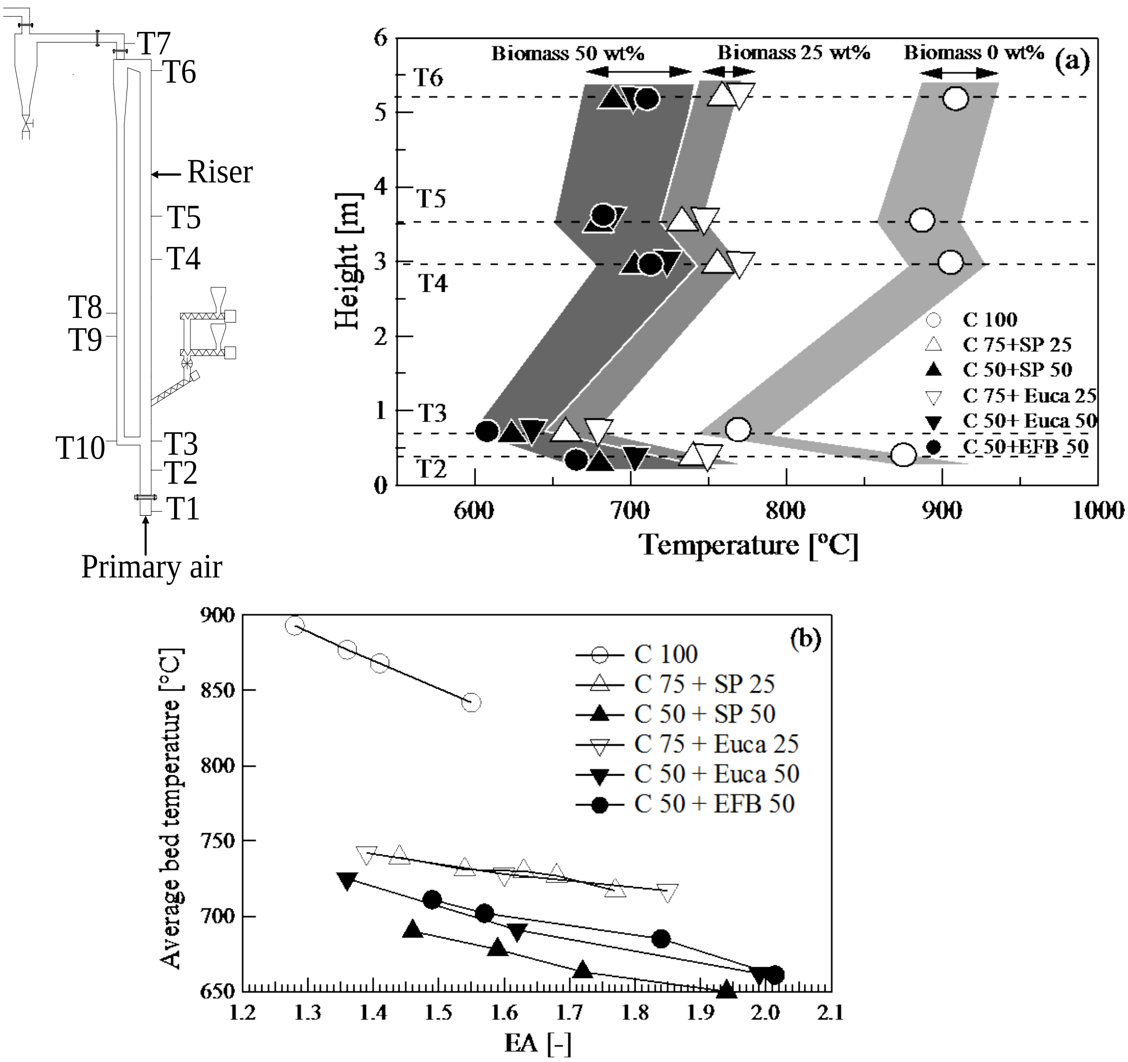

Fig. 4. Effect of fuel mixture and excess air ratio on temperature distribution (a) and average bed temperature (b).

3.3 CO Emission

The emission of CO is shown in Figure 5 at different biomass shares and excess air ratios. CO emissions decreased as the excess air (EA) increased to reach the minimum value. After that, an increase in CO emissions was observed due to excessive air cooling in the riser (referred to as the average bed temperature in Figure 4(b)). The minimum CO emissions were found at EA = 1.41 for coal combustion, EA = 1.84 for co-firing of coal with empty fruit bunch pellets at 50 wt%, EA = 1.54 and 1.60 for co-firing with rice straw pellets, and EA = 1.39 and 1.62 for co-firing with eucalyptus pellets at 25 wt% and 50 wt%, respectively. In the case of increasing biomass pellets in the blended fuels, a higher amount of air was applied for volatile combustion, resulting in a higher amount of excess air being found. The excess air increased with the increase of the superficial gas velocity, as shown in Table 2. Consequently, the heat loss from unburned carbon (q_{uc}) and CO emission slightly increased. These results implied that the higher proportion of biomass in fuel mixtures required more air and residence time for complete combustion. With the increase of the biomass proportion, a significant increase of unburned carbon in fly ash and a decrease in bed temperature were observed. These experimental results corresponded with the simulation co-combustion of coal with biomass in 550-MW_{th} furnace using computational fluid dynamics (CFD) model presented by Bhuiyan and Naser (2015) [13], the CFD model estimated a major increase in unburned carbon (q_{uc}) in fly ash with increasing the biomass proportion. The CO emission level and the bed temperature were inversed. This result could be explained by the increase in the char reaction rate as well as the promoted oxidation of C, CO to CO_2 at higher bed temperatures.

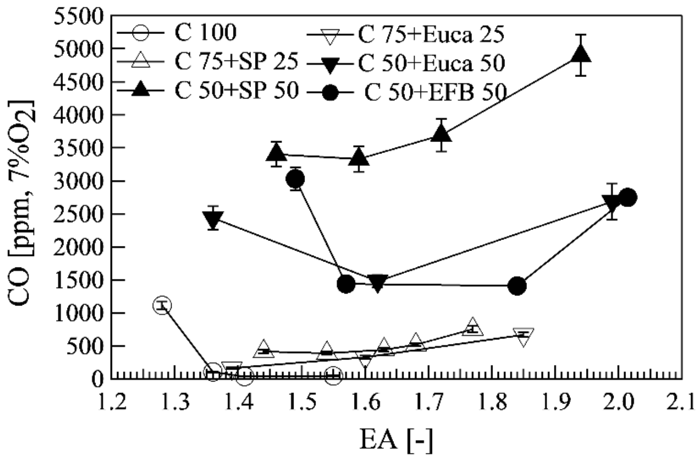

Fig. 5. Effect of fuel mixture and excess air ratio on CO emission.

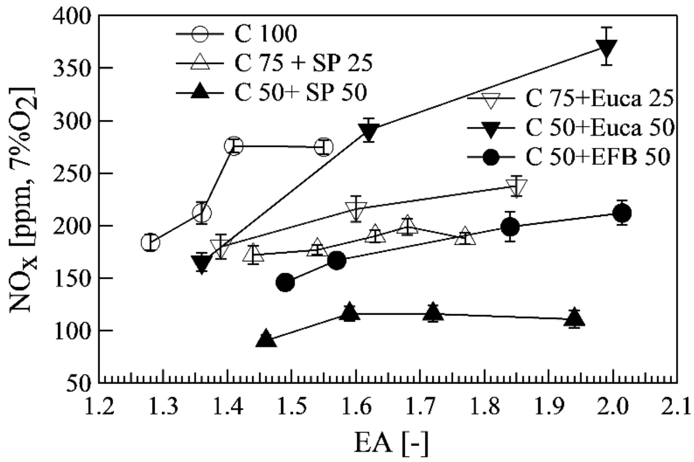

Fig. 6. Effect of fuel mixture and excess air ratio on NO_x emission.

3.4 NO_x Emission

The NO_x emission levels at various excess air ratios and for the three biomasses blended with coal are shown in Figure 6. The results revealed that the NO_x concentration was reduced in the flue gas by co-firing coal with biomass pellets. This is attributable to the low nitrogen contents in rice straw pellets and empty fruit bunch pellets, as compared to coal (as seen in Table 1). Increasing their share would dilute the N content of the mixed fuel and thus reduce NO_x emissions. However, co-firing of coal with eucalyptus pellets at 50 wt% was an exception. NO_x emission was significantly high when EA was high. This result could be explained by the high nitrogen content in both coal and eucalyptus pellets. The high volatile nitrogen content in eucalyptus causes homogeneous reactions, which play an important role in NO_x formation through the following reactions (4)–(5) [25]:

$$HCN + \frac{1}{2}O_2 \rightarrow CNO \quad (4)$$

$$CNO + \frac{1}{2}O_2 \rightarrow NO + CO \quad (5)$$

The formation of NO_x could be promoted by the high CaO content in eucalyptus. In the study of Hao and Bernard (1998) [26], limestone ($CaCO_3$) was used to capture SO_2 emission from coal combustion in a CFB. The results revealed that SO_2 decreased, while NO_x increased. The CaO could catalyze the formation of NO_x from ammonia and hydrogen cyanide (reactions (6)-(7)) [26], which could release volatile nitrogen from eucalyptus.

$$NH_3 + O_2 \xrightarrow{CaO} NO + N_2 \quad (6)$$

$$HCN + O_2 \xrightarrow{CaO} NO + N_2 \quad (7)$$

At a low EA range, the presence of char and CO emission (as seen in Figure 5) could promote the NO_x reduction reactions [5].

3.5 SO_2 Emission

Figure 7 shows the effect of fuel mixtures and excess air ratios on SO_2 emission. SO_2 emission for coal combustion was very high due to its sulfur content (as shown in Table 1). SO_2 concentration in the case of co-firing coal with biomass pellets was reduced due to the dilution effect of sulfur in fuel mixtures.

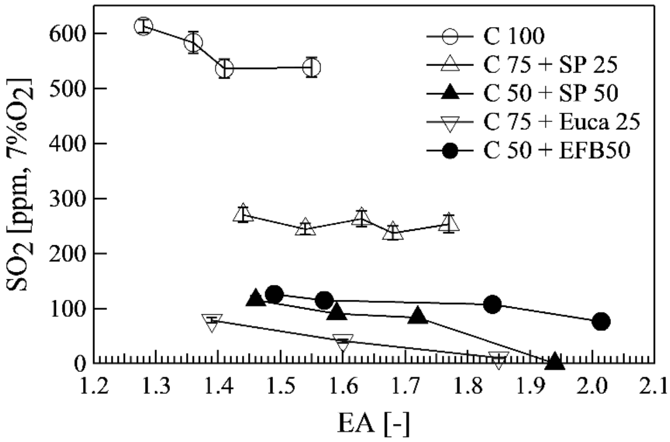

Fig. 7. Effect of fuel mixture and excess air ratio on SO_2 emission.

Table 2. Heat loss and combustion efficiency of the CFB reactor during coal combustion and co-firing with biomass pellets.

Excess air (%)	O_2 at stack (vol.%)	Bed temperature (°C)	Unburned carbon in fly ash (wt.%)	CO (ppm, 7% O_2)	Heat loss (%) due to Unburned carbon q_{uc}	Heat loss (%) due to Incomplete combustion q_{ic}	Combustion efficiency (%)	Total air (Nm^3/s)	Ug (m/s)
C100									
1.28	4.54	893	2.66	1115	0.39	0.47	99.1	0.039	7.56
1.36	5.58	877	0.90	108	0.13	0.05	99.8	0.042	7.93
1.41	6.11	868	0.72	35	0.11	0.01	99.9	0.043	8.14
1.55	7.49	842	0.72	45	0.11	0.02	99.9	0.047	8.76
C75+SP25									
1.44	6.46	739	2.08	417	0.37	0.18	99.5	0.039	6.53
1.54	7.38	731	1.61	388	0.28	0.17	99.6	0.042	6.93
1.63	8.18	730	2.07	441	0.37	0.19	99.4	0.044	7.34
1.68	8.53	727	2.17	518	0.39	0.22	99.4	0.045	7.52
1.77	9.15	717	2.76	755	0.49	0.33	99.2	0.047	7.02
C50+SP50									
1.46	6.57	690	2.58	3403	0.56	1.53	97.9	0.033	5.05
1.59	7.86	678	1.88	3332	0.41	1.50	98.1	0.036	5.48
1.72	8.82	663	2.87	3692	0.63	1.66	97.7	0.039	5.88
1.94	10.18	650	3.28	4899	0.72	2.20	97.1	0.044	6.65
C75+Euca25									
1.39	5.96	742	2.32	162	0.39	0.07	99.5	0.038	6.52
1.6	7.91	728	2.63	328	0.45	0.14	99.4	0.044	7.36
1.85	9.63	717	3.43	669	0.59	0.29	99.1	0.051	7.67
C50+Euca50									
1.36	5.54	725	3.73	2438	0.74	1.09	98.2	0.033	4.93
1.62	8.07	691	3.47	1479	0.69	0.66	98.7	0.039	5.86
1.99	10.45	662	3.95	2688	0.79	1.20	98.0	0.048	7.20
C50+EFB50									
1.49	6.97	711	3.73	3033	0.57	1.32	98.1	0.039	5.80
1.57	7.59	702	3.03	1435	0.46	0.63	98.9	0.041	6.16
1.84	9.59	685	2.76	1408	0.42	0.62	99.0	0.047	7.02
2.01	10.57	661	3.04	2749	0.46	1.20	98.3	0.052	7.82

As seen in Table 1, rice straw pellets have slightly higher sulfur content than eucalyptus pellets. Therefore, SO_2 emissions from co-firing with rice straw were higher than those from co-firing with eucalyptus compared at 25 wt% mass fraction. Empty fruit bunch pellets have no sulfur content; however, SO_2 emissions from co-firing with empty fruit bunch pellets were higher than those from co-firing with rice straw pellets compared at 50 wt%. The increased SO_2 emissions also coincided with the higher average bed temperature (referred to in Figure 4(b)). Hence, the SO_2 concentration depends on both the amount of sulfur content and the temperature. According to the study of Zhao *et al.* (2016) [27], the three air-dried algae biomasses were used for combustion in the furnace at different temperatures. The result revealed that SO_2 emission increased as the temperature increased.

As observed in Figure 7, SO_2 emission from co-firing with eucalyptus at 25 wt% was the lowest, and there was no SO_2 emission in the case of co-firing with eucalyptus at 50 wt%. SO_2 emission could be reduced by the high CaO content in eucalyptus through the following reaction (Equation 8) [26].

$$CaO + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4 \quad (8)$$

3.6 Combustion Efficiency

Table 2 shows the heat loss and the combustion efficiency of the CFB reactor for coal combustion and co-firing of coal with biomass pellets at different mass fractions and excess air ratios. The results, as shown in Figure 8, indicate that the tendency of combustion efficiency and CO emission (indicated in Figure 5) were similar for coal combustion and co-firing with biomass pellets. The combustion efficiency for all cases were in the range of 97%–99%. At low excess air ratios, the CO emission was high and combustion efficiency was low due to heat loss from incomplete combustion (q_{ic}).

As expected, the increase in excess air ratios initially improved combustion. However, excess air ratios that were too high decreased the combustion efficiency due to the cooling effect and the insufficient time for complete combustion as indicated in the superficial gas velocity (U_g)and unburned carbon in fly ash (as shown in Table 2).

3.7 Ash Characteristics

Fly ash was collected after the experiment and analyzed by XRF analysis to find the elemental composition. The analysis results are shown in Figure 9. The composition of fly ashes relates well with the composition of fuel ashes (as shown in Table 1) and their proportion in the fuel mixtures. The high alkali metals, *i.e.*, K, Na, and Cl, in fly ash of biomass pellets give a high tendency of ash-related problems. During combustion, alkali metals are partly released into flue gas and form compounds like hydroxides and chlorides and, at higher temperatures, react with SO_2 to form sulphates following the reaction presented in Equation 9.

$$2MCl + SO_2 + \frac{1}{2}O_2 + H_2O \rightarrow M_2SO_4 + 2HCl \quad (9)$$

Where M is K or Na.

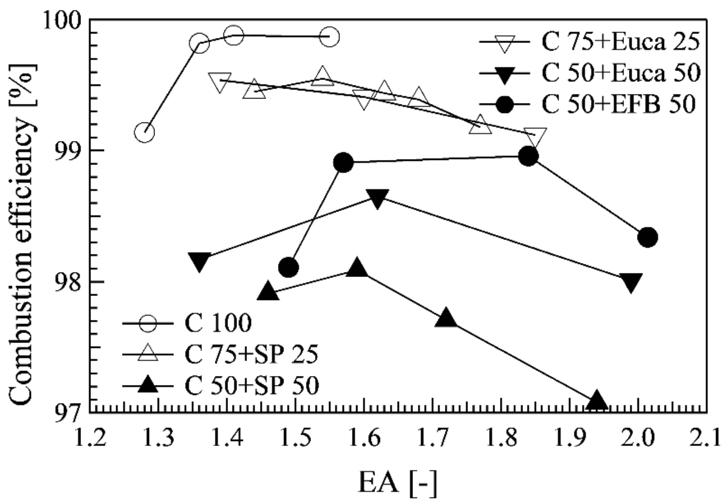

Fig. 8. Effect of fuel mixture and excess air ratio on combustion efficiency.

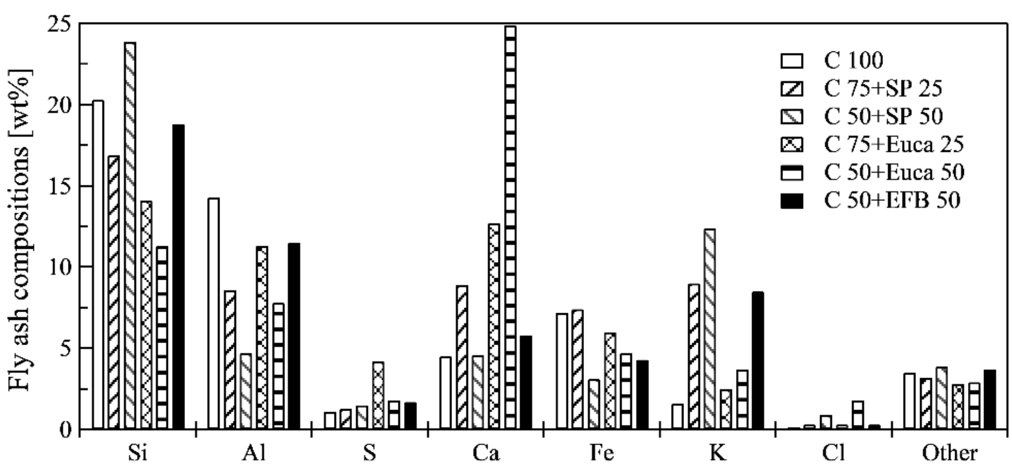

Fig. 9. Composition of fly ashes.

Alkali metal sulphates have low melting temperatures and become sticky [14], which then may deposit on the heat exchanger surface in the boiler or, if in excessive amount, may block the flue gas pass. With the higher amount of potassium and chlorine in co-firing of coal with rice straw pellets at 25 wt% and 50 wt%, eucalyptus pellets at 25 wt% and 50 wt%, and empty fruit bunch pellets at 50 wt%, fouling would be expected.

The spent bed was prepared by cutting in cross-sections and polishing surfaces before the SEM/EDS analysis. The SEM/EDS analysis of spent bed is presented in Figure 10. In case of coal combustion as shown in Figure 10(a), Spot 1 is the center of the cross-section surface, which contains high Si due to the main portion of bed particles consisting of 97% SiO_2. The spent bed was coated with a thin layer of coal ash (Spot 2–5 are identified as indicated in Ca, Fe, Mg). The elements such as Al and Ca, which are rich in coal ash (as indicated in Figure 10(a)), could increase the melting temperature of ash [28] and reduce the melting temperature of molten ash, which could create adhesive bed particles. Therefore, the bed agglomeration tendency decreases. High Si and K contents and low Ca contents were observed around the spent bed, as shown in Figures 10(b) and (c) when co-firing of coal with rice straw pellets at 25 wt% and 50 wt%, respectively.

The spent bed was coated with a potassium-rich layer for co-firing coal with 50 wt% rice straw pellets (Figure 10(c)) and 50 wt% empty fruit bunch pellets (Figure 10(f)).

The Ca concentration in the case of co-firing coal with eucalyptus pellets at 25 wt% and 50 wt% was higher than co-firing with rice straw pellets at the same blending ratios. This suggests that Ca reacts with the presence of Si and K, which may result in the production of potassium-calcium-silicates and calcium silicates.

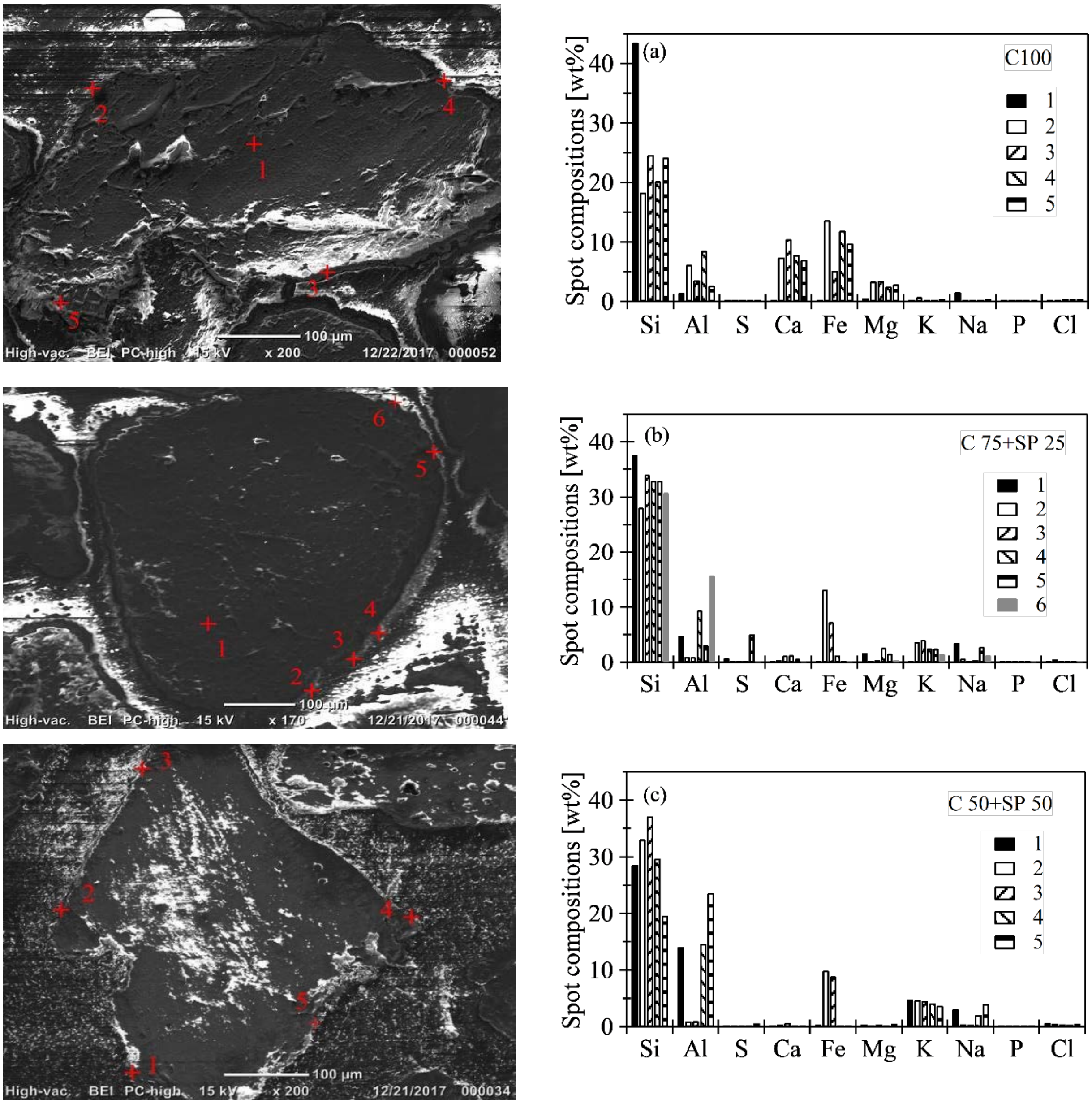

Fig. 10. SEM/EDS analyses of bed material after combustion.

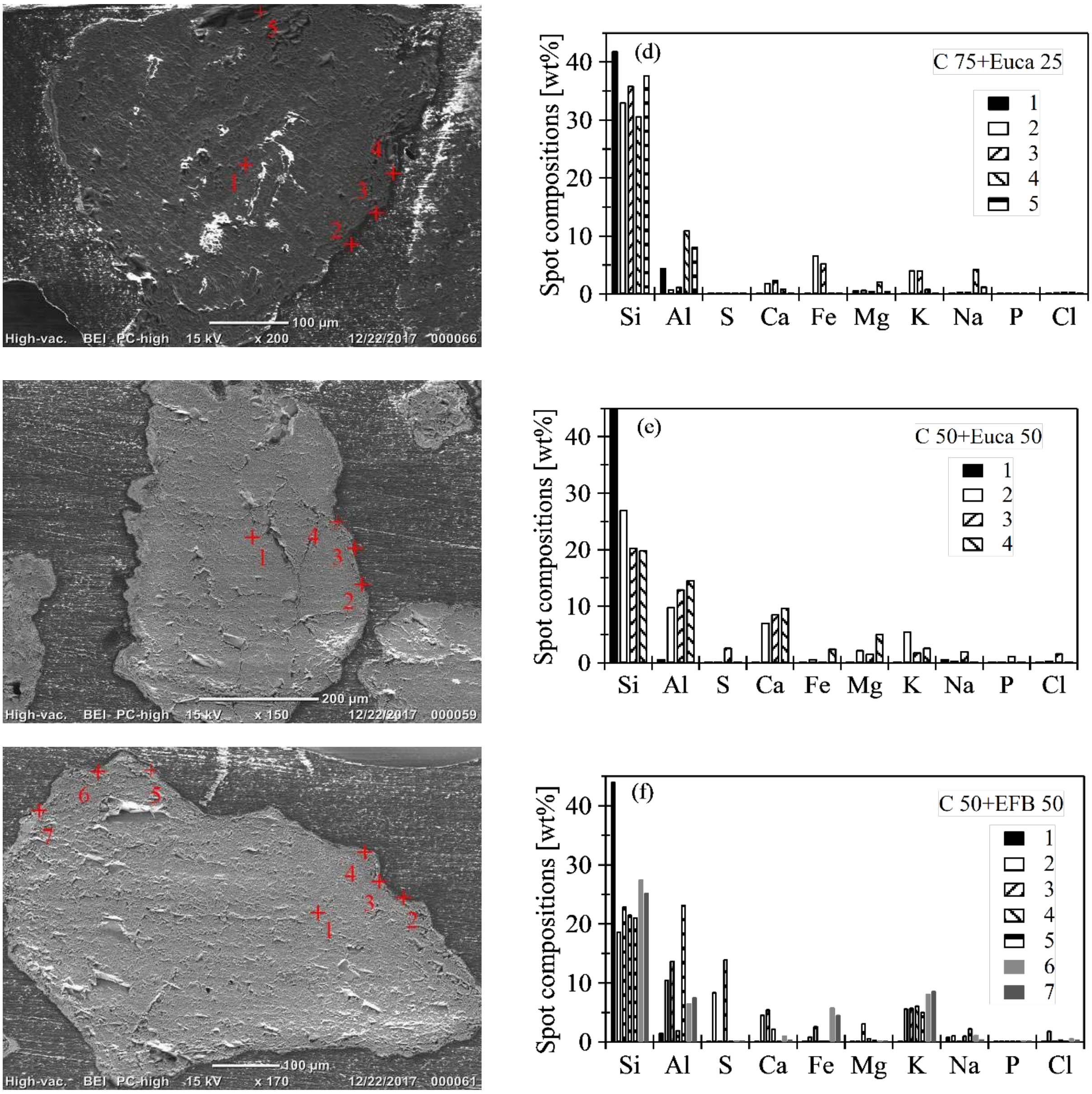

Fig. 10. SEM/EDS analyses of bed material after combustion *(continued)*.

The presence of Si, Ca, and high K was observed in the case of co-firing coal with empty fruit bunch pellets. The compositions of these elements would form potassium-calcium-silicates.

The melting point of potassium silicates, potassium-calcium-silicates, and calcium silicates are about 700°C, 900°C, and 1300°C, respectively [29]. Therefore, the co-firing of coal with eucalyptus pellets at 25 wt% and 50 wt% is likely to create compounds with higher melting temperatures than in the case of the co-firing of coal with rice straw pellets and empty fruit bunch pellets. Moreover, the tendency of agglomeration was lower.

From literature, agglomeration was proposed by two mechanisms [14]: (1) the direct contact with ash melts and (2) the condensation/deposition of the inorganic gases, which react into the bed grains. In the case of co-firing of coal with rice straw pellets at 25 wt% and 50 wt% and empty fruit bunch pellets at 50 wt%, the ash contained high Si and K but low Ca, which suggests that K and Si would form potassium silicates. Potassium silicate can later form a eutectic compound and starts to melt at a temperature of 750°C [14], leading to bed agglomeration via mechanism (1) and the reaction with the quartz mineral in the bed material via mechanism (2). However, for all experiments in this study, a connection between bed particles to form agglomerates was not observed. The presence of Fe_2O_3 in coal ash (as shown in Table 1) could reduce the risk of agglomeration. Since Fe_2O_3 reacts with any alkali present in the bed (as indicated in Equations 10 to 11), it forms eutectic mixtures with melting temperatures exceeding 1,135°C [14]. In addition, the CFB reactor was operated at a high gas velocity of 5.8–8.8 m/s (as indicated in Table 2), which is a typical range of velocity used in CFB mode. High attrition is expected and helps prevent agglomeration, as stated by Yu *et al.* (2011) [30].

$$Fe_2O_3 + M_2O \rightarrow M_2Fe2O_4 \qquad (10)$$

$$Fe_2O_3 + M_2CO_3 \rightarrow M_2Fe_2O_4 + CO_2 \quad (11)$$

Where M is K or Na.

To estimate the melting temperature of fuel ash, the main compositions of fuel ash (K_2O, CaO and SiO_2) and EDS data were normalized and then plotted in the K_2O-CaO-SiO_2 ternary phase diagram, as shown in Figure 11. The EDS compositions from coal combustion (C 100) and coal ash analyzed by XRF (as shown in Table 1) had melting temperatures around 1734°C and 1711°C, respectively. The EDS compositions derived from co-firing of coal with rice straw pellets, eucalyptus pellets and empty fruit bunch pellets at blending levels of 25 wt% and 50 wt% appeared in the SiO_2 rich area, as indicated in Figure 11. K_2O contents in EDS data from co-firing with biomass pellets were in a narrow range (C 75 + SP 25: 4–6 %, C 50 + SP 50: 6–10 %, C 75 + Euca 25: 7 %, C 50 + Euca 50: 12–16 %, and C 50 + EFB 50: 12–18 %). The melting temperatures for all EDS data could be arranged in the following order: C 100 (1734°C), C 75 + Euca 25 (1628°C), C 50 + Euca 50 (1520°C), C 75 + SP 25 (1575°C), C 50 + SP 50 (1490°C), and C50 + EFB 50 (1410°C). A similar trend was observed in fuel ash. This result revealed that the melting temperature decreased while the biomass blending ratio increased and the K_2O concentration increased as well.

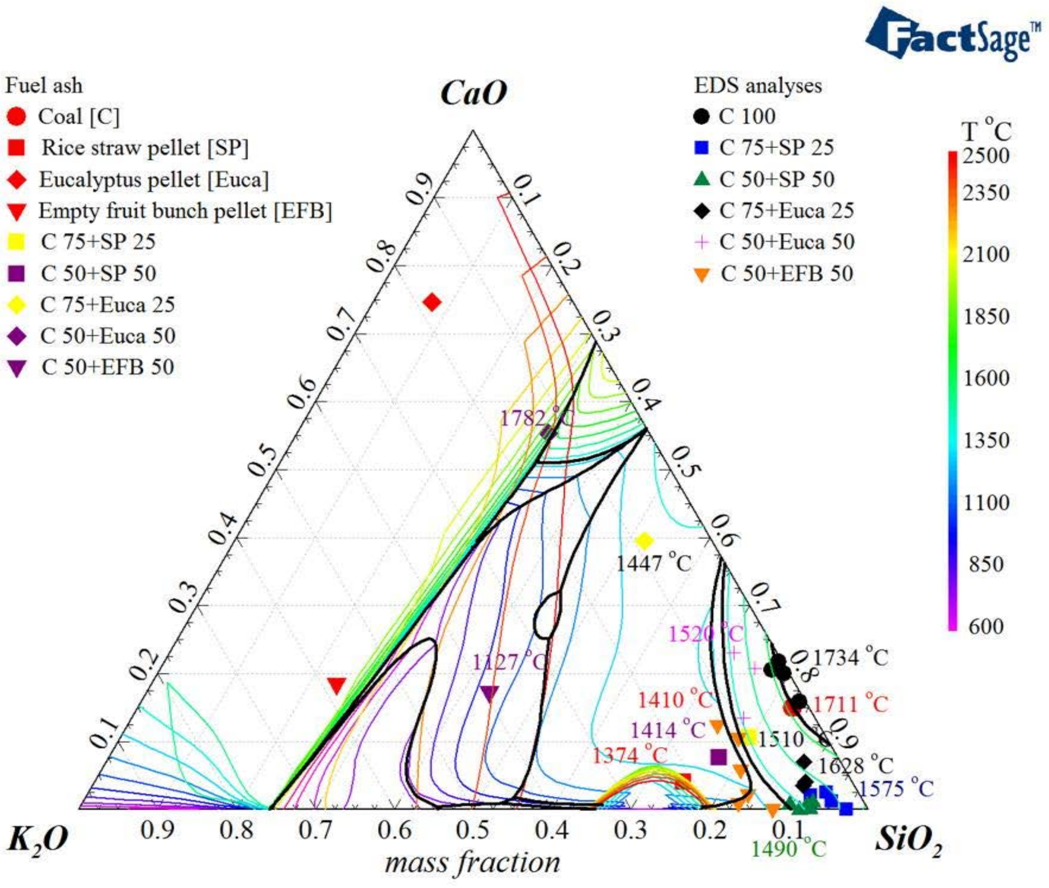

Fig. 11. The compositions of fuel ashes and EDS data in K_2O-CaO-SiO_2 ternary phase diagram.

The oxides in the fuel ash can be divided into acid oxides (*e.g.*, SiO_2, Al_2O_3, TiO_2) and basic oxides (*e.g.*, K_2O, CaO, MgO, Fe_2O_3). The presence of alkaline oxides, such as K_2O, CaO, contributes to the decrease in melting points. This effect was evident in the case co-firing coal with empty fruit bunch pellets containing large quantities of K_2O and CaO (as indicated in Table 1). As a result, the melting temperatures of ashes derived from EDS data (1410°C) and fuel ash analyzed by XRF analysis (1127°C) in case of co-firing with empty fruit bunch pellets were the lowest compared with the other cases. The melting temperatures for EDS data predicted by FactSage then explains the behavior of the observed ash. In addition, the high superficial velocity used for the CFB operation is likely to prevent formation of agglomerates due to attrition.

4. CONCLUSIONS

The effect of operating conditions such as excess air ratio and biomass share were investigated for gaseous emissions, combustion efficiency, and ash characteristics. It was determined that an increase in excess air could promote complete combustion. As a result, CO emission decreased, and combustion efficiency increased. At high excess air levels, CO emission increased due to the cooling effect. The high excess air would be needed to combust volatiles released as observed in the case of high biomass shares. In addition, CO emissions from co-firing of coal with biomass pellets depended mainly on three factors: temperature, residence time, and volatile matter content. The combustion efficiency levels were between 97% and 99% for coal combustion and co-firing of coal with biomass pellets. The heat losses from unburned carbon were insignificant. Low NO_x emissions were observed at low excess air levels, as NO_x can be reduced by CO and carbon, which are commonly used in NO_x reduction reactions. NO_x emissions in the cases of co-firing coal with rice straw and empty fruit bunch pellets were lower than those of coal due to the low nitrogen content in rice straw pellets and empty fruit bunch pellets. The highest NO_x emissions were found in the case of co-firing coal with eucalyptus pellets at 50 wt% because of the high nitrogen content in eucalyptus pellets. SO_2 emission for coal combustion was higher than that of co-firing coal with biomass pellets due to the high sulfur content in coal. Increasing biomass shares would dilute the sulfur content of the mixed fuel and thus reduce SO_2 emissions. The bed particles collected after the combustion tests showed no occurrence of agglomeration over the course of an eight-hour observation. However, with the SEM analysis of spent bed, it was found that the bed particles were coated with layers of elemental compositions corresponding to those of the fuel ashes. The melting temperatures in ash derived from EDS data predicted by FactSage simulation were in the range of 1410°C–1734°C. Therefore, the presence of compositions including K_2O and CaO in fuel ash could reduce the melting temperature in fuel ash.

ACKNOWLEDGEMENT

The authors would like to thank Prof. Sankar Bhattacharya, Department of Chemical Engineering, Monash University, Australia, for the valuable suggestions in this research.

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