Kinetic analyses and synergistic effects of CO_2 co-gasification of low sulphur petroleum coke and biomass wastes

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ABSTRACT

This study presents thermogravimetric analyses (TGA) of CO_2 co-gasification of petroleum coke with low sulphur (PC) and various types of biomass wastes including agricultural (rice husk (RH), rice stalk (RS) and cotton straw (CS)) and by-product wastes (saw dust (SD) and sugar cane bagasse (SCB)). Their reactivities, synergistic effect and kinetics were studied and compared in detail. The homogeneous model (HM) and shrinking core models (SCM) were applied to estimate the kinetic parameters. The results indicated that obvious synergistic effect was observed during the co-gasification of the blends. The PC gasification reactivity was significantly improved by the addition of biomass wastes. The model of R2 was found to be most suitable for the co-gasification. The activation energy of PC was decrease from 293.72 kJ/mol to117.04 kJ/mol by the addition of SD. The co-gasification of PC and biomass waste is a promising way for the efficient utilization of PC and biomass wastes.

1. Introduction

Over the last few periods, biomass energy has attracted an increasing interest as it is an environmental friendly and renewable energy resource to alleviate the shortage of fossil energy and reduce the potential environmental impact of fossil fuels (Chen et al., 2017; Edreis et al., 2014; Emami-Taba et al., 2013; Fu et al., 2011; Zhu et al., 2016, 2017a,b). Sudan, as the largest agricultural country in Africa, has a great amount of biomass wastes. However, due to the lack of technological these wastes are used in a traditional way by burning directly to produce thermal energy for cooking purposes and other uses.

Petroleum coke (PC) has advantages of high calorific value and low ash content for the utilization as fuel and chemicals. However, it has a very low reactivity due to its aromatic nature (Edreis et al., 2014; Nemanova et al., 2014). It is well known that the aromatic carbon atoms are less reactive than aliphatic carbons. This cause a severe gasification condition such as high temperature and long reaction time (Edreis et al., 2013, 2014). Besides, it is well known that the high sulphur content is another disadvantage for the PC utilization as fuel. But the Sudanese PC has rather low sulphur content.

It is believed that the gasification is promising technology for converting the heavy oil residue PC and biomass into valuable synthetic gas (Edreis et al., 2017; Edreis and Yao, 2016; Huo et al., 2014; Nemanova et al., 2014). The co-gasification of PC and biomass is found to be a good choice to effectively convert them to syngas (Edreis et al., 2013, 2014; Nemanova et al., 2014). Because the biomass gasification produces much H_2O, CO_2 and other volatiles, which are the agents for the PC gasification and can promote the PC gasification effectively (Edreis et al., 2013; Edreis et al., 2014). Besides, the minerals in biomass, such as potassium and sodium, can be a catalyst for promoting the PC gasification (Edreis et al., 2013, 2014; Yan et al., 2018). This is the so-called synergistic interactions.

The synergistic interactions during conversion of the combining fuels such as coal or PC with biomass have been investigated by several authors (Edreis et al., 2013, 2014). The synergistic effect between coal or PC and biomass during the thermal co-process was observed by some researchers (Aboyade et al., 2012; Edreis et al., 2013, 2017, 2014; Fermoso et al., 2010a,b; Haykiri-Acma and Yaman, 2007; JuntaoWei et al., 2017; Sadhukhan et al., 2008; Wei et al., 2017b; Wu et al., 2017). On the other hand, negative synergistic effect was reported by others

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(Gil et al., 2010; Idris et al., 2010; Xiang-guo, 2006). Among them, Zhang et al. studied the synergistic effect of the co-gasification of petroleum coke and corn cob using thermogravimetric analyzer (TGA). They found that the AAEM in biomass ash led to the synergistic effect in co-gasification process. Edreis et al. carried out petroleum coke and sugar cane bagasse in non-isothermal CO_2 co-gasification using thermogravimetric analyzer. Their results indicated significant synergistic effect in the whole process (Edreis et al., 2013). They also investigated the effects of H_2O concentration and blended ratio on H_2O co-gasification of low sulphur petroleum coke and sugar cane bagasse, and found that there was a significant effect when H_2O concentration and the blending ratio were greater than 50% (Edreis et al., 2014). Wei et al. studied the synergistic effect on co-gasification reactivity of biomass-petroleum coke blended char. Their results indicated the presence of synergistic effect on co-gasification reactivity after complete generation of biomass ash, and gradually weakened with increasing temperature from 1000 °C to 1100 °C after reaching the most significant value at 1000 °C (Wei et al., 2017b). Fermoso et al. conducted H_2O co-gasification of a bituminous coal (PT) and two types of biomass, which were chestnut residues (CH) and olive stones (OS), using non-isothermal thermogravimetric method. It was noted that significant effects were detected from PT/OS blend. However, no significant effects was observed in case of PT/CH blend (Fermoso et al., 2010b). Thus, the synergistic effect between petroleum and biomass during their co-gasification was not clear. One of the main reasons is that the reaction mechanisms of their co-gasification was not yet studied in detail and not clear. Thus, in this paper the gasification behaviours, kinetics and reactivity of the petroleum coke with low sulphur (PC) and five different biomass wastes: rice husk (RH), rice stalk (RS), saw dust (SD), cotton straw (CS) and sugar cane bagasse (SCB) with CO_2 were conducted via thermogravimetric Analyzer (TGA). The synergistic effect between PC and biomasses during co-gasification was investigated through the comparison between experimental and calculated TG/DTG results of the blends. The reaction kinetics of this process was then studied by applying the homogeneous model (HM) or the first order chemical reaction (O1) and shrinking core models (SCM) or Phase boundary controlled reactions (R(2) and R(3) through the Coats–Redfern method. The reaction mechanism was then discussed.

2. Experimental

2.1. Materials

The Sudanese PC with low sulphur and five typical biomass wastes were used as raw materials. The samples were crushed and sieved to obtain particle sizes < 0.295 mm, in order to ensure that the temperature gradients in the samples were minimized. The mixture of PC and each biomass waste with a ratio of 1:1 (mass/mass) was tested. Proximate and ultimate analyses were carried out in a TGA-2000 (Navas Instruments, Spain) and an Euro-CA 3000 (HEKAtech, Italy) elemental analyzer, respectively. The calorific values were determined using a Parr 6300 automatic isoperibol calorimeter. The results of ultimate and proximate analyses were listed in Table 1. The ash compositions of PC and biomass wastes were presented in Table 2.

2.2. Method

2.2.1. CO_2 gasification experiments

The single gasification and co-gasification of the PC and biomass wastes were carried out by a thermogravimetric analyzer (TGA NETZ-SCHSTA 449/F3). Pure CO_2 was used as an agent gas with at a flowing rate of 100 mL/min. The sample weight was ranged from 7 to 8 mg. then it was heated from room temperature up to 1300 °C at a constant heating rate 10 °C/min. In order to examine the reliability of the test data all experiments were implemented two or three times.

2.2.2. Reactivity measurements

The TG data were expressed as a function of conversion X, which is defined as:

$$X = \frac{w_i - w_t}{w_i - w_f} \tag{1}$$

where w_i is the initial sample mass (mg), w_t refers to the sample mass at given time t (min), and w_f is the final sample mass at the end of gasification (mg).

Generally, the gasification reactivity was calculated by the method proposed by Okoroigwet and so on (Okoroigwet, 2015; Yassine El may, 2012).

$$R_m = 100 \sum \frac{R_{DTG_{max}}}{T_{DTG_{max}}} \tag{2}$$

where, R_m the reactivity (%/min °C), R_{DTGmax} is the maximum weight loss rate (%/min) and T_{DTGmax} the corresponding peak temperature (°C).

2.2.3. Synergistic effect study

In order to investigate the synergistic effect between the PC and biomass wastes during their co-gasification, the comparison between experimental and calculated TG/DTG data of the blends was used. For this method the theoretical TG/DTG curves of the blends were calculated as the sum of the weight loss/weight loss rates of each individual sample, by using Eq. (3) (Edreis et al., 2014). They were then compared with their experimental TG/DTG curves.

$$w = x_{PC}(w)_{PC} + x_B(w)_B$$
$$or$$
$$\frac{dw}{dt} = x_{PC}\left(\frac{dw}{dt}\right)_{PC} + x_B\left(\frac{dw}{dt}\right)_B \tag{3}$$

where w and $\left(\frac{dw}{dt}\right)$ are the corresponding weight loss (%) and weight loss rates (%/min) of the individual materials. The x_{PC}, x_B are the mass fractions of PC and biomass in the blends, respectively.

2.2.4. Kinetic study

Kinetic studies of the single gasification and blends co-gasification were conducted by using Coats–Redfern equation (Coats and Redfern, 1964), which was as follow:

$$\ln\left[\frac{g(X)}{T^2}\right] = \ln\left[\frac{AR}{\beta E}\left(1 - \frac{2RT}{E}\right)\right] - \frac{E}{RT} \tag{4}$$

where, R is the universal gas constant (8.314 J K/mol). T is the absolute temperature (K). t is the reaction time (min). β is constant heating rate during gasification, $\beta = \frac{dT}{dt}$. $g(X)$ is the reaction mechanism model in integral form as shown in Table 3.

It is obvious that, the expression of $\ln\left[\frac{AR}{\beta E}\left(1 - \frac{2RT}{E}\right)\right]$ in Eq. (4) is basically constant for the activation energy values of E in the temperature range of gasification (Çepelioğullar and Pütün, 2013; Gong et al., 2012). So, a straight line can be achieved when the left side of Eq. (4) was plotted versus $1/T$. The value of E then can be obtained through the slope of the straight line (Yan et al., 2014). The pre-exponential factor (A) can also be obtained through the intercept of Eq. (4). The reaction rate constant (k) was then obtained by Arrhenius's equation (5).

$$k = A \exp\left(\frac{-E}{RT}\right) \tag{5}$$

The reaction mechanism model ($g(X)$) used for the calculation were homogeneous model (HM) or first order chemical reaction (O1), and shrinking core models (SCM) or Phase boundary controlled reactions R (2) and R(3) as shown in Table 3. The HM assumes a homogeneous reaction throughout the particle (Edreis et al., 2014). The reaction mechanism of the model O 1 represents the process controlled by the chemical reactions, rather than the effect of intra-particle diffusion, and

Table 1
Proximate & elemental analyses and lower heating values of PC and wastes biomasses.

Samples	Proximate analysis (wt%)[a]				Elemental analysis (wt%)[b]					LHV (MJ/kg)[b]
	Ash	VM	FC	M	C	H	N	S	O[c]	
PC	2.66	14.91	81.20	1.23	92.09	3.76	1.66	1.08	3.03	35.52
RH	14.11	64.14	16.38	5.37	40.72	5.19	0.69	0.08	33.86	15.03
RS	16.50	69.77	10.28	3.45	40.25	4.58	0.99	0.07	34.15	14.62
SD	3.90	79.45	13.47	3.18	49.78	5.85	0.28	0.02	36.99	17.79
CS	6.60	80.92	10.00	2.48	46.09	5.60	0.96	0.06	38.22	15.93
SCB	4.41	76.94	11.33	7.23	46.95	6.06	0.13	0.08	42.44	16.30

[a] As received basis.
[b] Dry ash basis.
[c] Calculated by difference.

Table 2
Ashes analyses of PC and wastes biomasses.

Oxide	Na_2O	MgO	AL_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3	TiO_2	P_2O_5
PC	2.19	1.25	2.24	1.19	40.7	3.12	44.23	2.33	0.62	0.94
RH	1.78	0.47	0.91	87.83	2.01	4.68	1.15	0.12	0.04	0.93
RS	0.96	2.33	0.91	51.99	6.50	17.81	7.68	0.84	0.04	2.49
SD	12.84	5.56	6.50	16.47	7.64	7.76	24.89	4.57	0.58	2.42
CS	0.68	3.55	1.75	40.97	3.74	25.14	6.48	0.59	0.03	5.81
SCB	0.70	4.41	17.04	54.62	1.52	4.41	7.54	7.32	0.89	1.41

Table 3
Expressions of $f(x)$ and $g(x)$ for the kinetic model functions usually employed for solid-state reactions (Pl Edreis et al., 2014; Gil et al., 2010).

Model	Symbol	$f(x)$	$g(x)$
Chemical reaction or homogenous model (HM)			
First-order	O1	$(1-x)$	$-\ln(1-x)$
Phase boundary controlled reactions or shrinking core model (SCM)			
Two dimensions (Contracting Cylinder)	R_2	$2(1-x)^{\frac{1}{2}}$	$1-(1-x)^{\frac{1}{2}}$
Three dimensions (Contracting Sphere)	R_3	$3(1-x)^{\frac{2}{3}}$	$1-(1-x)^{\frac{1}{3}}$

the reaction happened simultaneously in the whole particle. However, the model R2 and R3 assume that the process is controlled by the diffusion, rather than the chemical reaction. Because the chemical reaction is much faster than diffusion. Besides, the SCM assumes that the reaction initially occurs at the external surface of the particle and gradually moves inside. So, here is a shrinking core in the non-reacted solid.

3. Results and discussion

3.1. Gasification behaviour and reactivity analyses

The experimental TG/DTG curves of single biomass wastes and blends gasification were presented in Figs. 1 and 2, respectively. It was observed that the gasification of single sample and blends occurred in two stages; pyrolysis stage (stage1) at a lower temperature (< 450 °C) and char gasification stage (stage 2) at a higher temperature (> 650 °C). However, PC presented only one char gasification stage at a higher temperature (> 700 °C). This was related to lower volatile matter content of the PC.

The gasification characteristic parameters (such as maximum rates of the weight loss (DTG_{max}), corresponding maximum temperature (T_{max}), initial weight loss temperature (T_i) and final weight loss temperature (T_f)) of PC, biomass wastes and blends obtained from the TG data, were listed in Table 4. It was found that the highest and lowest DTG_{max} for single samples at stage 1 were 7.76%/min for SD and 5.76%/min for RS. Correspondingly, the highest DTG_{max} of the blends was provided by PC: SD with value of 5.37%/min. In stage 2 of the
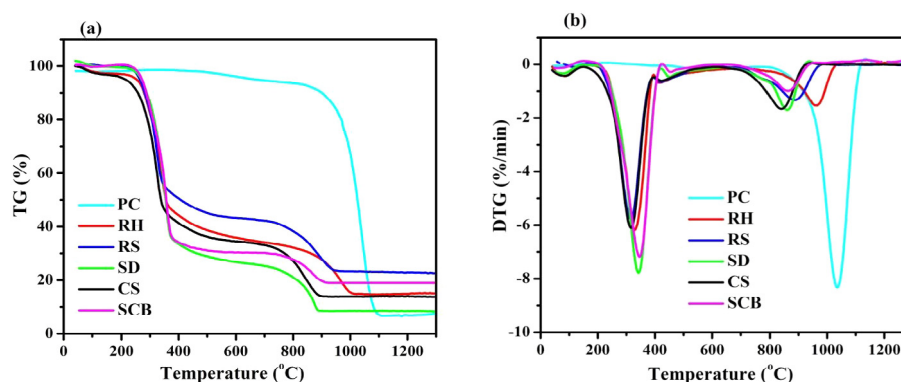

Fig. 1. Experimental TG/DTG curves of single PC and the biomasses wastes for CO_2 gasification.
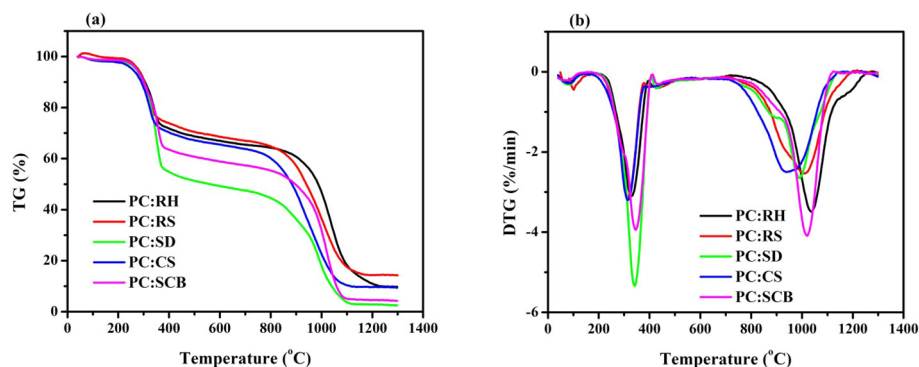
Fig. 2. Experimental TG/DTG curves of the blends for their CO_2 co-gasification.

Table 4
Characteristics of the PC, wastes biomasses and the blends gasification.

Stage	Characteristics	PC	RH	RS	SD	CS	SCB
S1	T_i		160	152	150	146	146
	T_f		422	419	440	426	447
	T_{max}		332	324	342	322	343
	DTG $_{max}$		6.17	5.76	7.76	6.10	7.14
S2	T_i	877	672	634	622	624	628
	T_f	1144	1064	1010	968	964	990
	T_{max}	1035	965	885	858	837	862
	DTG $_{max}$	8.30	1.54	1.33	1.67	1.65	1.04

Stage	Characteristics		PC:RH	PC:RS	PC:SD	PC:CS	PC:SCB
S1	T_i		160	160	157	152	150
	T_f		426	426	458	428	438
	T_{max}		325	320	346	318	345
	DTG $_{max}$		3.05	3.10	5.37	3.24	3.87
S2	T_i		730	675	656	658	654
	T_f		1270	1240	1180	1186	1168
	T_{max}		1042	1020	992	955	1018
	DTG $_{max}$		3.53	2.54	2.67	2.60	4.12

S1: pyrolysis stage and S2: gasification stage, T_i: initial reaction temperature (°C), T_f: final reaction temperature (°C), T_{max}: the temperature (°C) when gasification rate reaches the maximum; DTG_{max}: the maximum rate of mass loss (%/min).

single SD showed the highest DTG_{max} value of 1.67%/min, while the SCB reflected to lowest value of 1.04%/min. On the other hand, the blend of PC: SCB provided the highest DTG_{max} value of 4.12%/min. Whereas the blend of PC: RS presented the lowest value of 2.54%/min.

The PC reactivity (R_m) was only 0.8%/min °C which was much lower than those of the biomass wastes. The reactivities of RH, RS, SD, CS and SCB were 2.01, 1.97, 2.47, 2.02 and 2.21%/min °C, respectively. The reactivities of the blends of PC: RH, PC: RS, PC: SD, PC: CS and PC: SCB were 1.28, 1.22, 1.82, 1.29 and 1.53%/min °C, respectively. The blends of PC: SD and PC: SCB had the highest reactivities, compared to that of other blends. It can be concluded that the PC reactivity was significantly improved by the addition of biomass wastes during their co-gasification. Compared to other biomass wastes, the SD was found to be the most reactive and best choice for gasification reactivity promotion of PC.

3.2. Synergistic effects analysis

The significant difference between the calculated and experimental results implies significant synergistic effect (Edreis et al., 2014). The comparisons between experimental and calculated TG/DTG curves of the co-gasification were presented in Fig. 3. It was observed that the calculated curves were rather close to the experimental curves at stage 1 of all blends, except PC: SD. For stage 2 the significant synergistic effect was occurred for all the blends in the order of PC: CS, PC: RS, PC: SD, PC: RH and PC: SCB. One of the main reasons of the synergistic effect was due to the high reactivity of the biomass. During the blends gasification, the biomass decomposed rapidly, and forms much free radical and hydrogen-rich and oxygen-rich volatile matters, such as CO_2, H_2O, and CH_4. It is well known that such compounds can act as a good agent for PC gasification (Ellis et al., 2015; JuntaoWei et al., 2017; Wei et al., 2017a). Another reason was due to the catalytic effect of the minerals in biomass. The biomass waste ashes content much minerals, such as Fe, Al, Na, Mg, Ca and K, as shown in Table 2. These metals are considered as a good catalyst for PC gasification (Edreis et al., 2014; Ellis et al., 2015; Wei et al., 2017b).

3.3. Kinetic analysis

The highest correlation coefficients were given by plotting *forthe* for the single and the blend samples, as presented in Figs. 4 and 5, respectively. The value of E and A was obtained from the slope of each line in Figs. 4 and 5. The high correlation coefficient values indicated that the corresponding reaction model was reasonably fitted the experimental data. All the models showed high correlation coefficients ($R^2 > 0.95$) for the both reaction stages for all of samples. For stage 1 the highest value of correlation coefficient of RH and PC: RH were 0.9961 and 0.9974 which were achieved by model R3 and model R2, respectively. Whereas the highest value for RS and PC: RS were 0.9934 and 0.9769 which were obtained by model O1. For SD, CS, PC: SD and PC: CS the highest values were 0.9980, 0.9914, 0.9961 and 0.9886 which detected by model R3. Finally, for SCB and PC: SCB, the highest values were 0.9922 and 0.9919 were obtained by model R2. On the other hand, for stage 2 the highest value of correlation coefficient of PC was 0.9993 which detected by model R3. The highest correlation coefficient values of RH and PC: RH were 0.9813 and 0.9892 which achieved by model R2 and model O1, respectively. For the RS and PC: RS, the highest values were 0.9990 and 0.9997 provided by model R2 and model O1, respectively. However, the highest values for the CS and PC: CS were 0.9991 and 0.9997 which were achieved by model R2 and model O1, respectively. Finally, the highest values for the SD, SCB, PC:
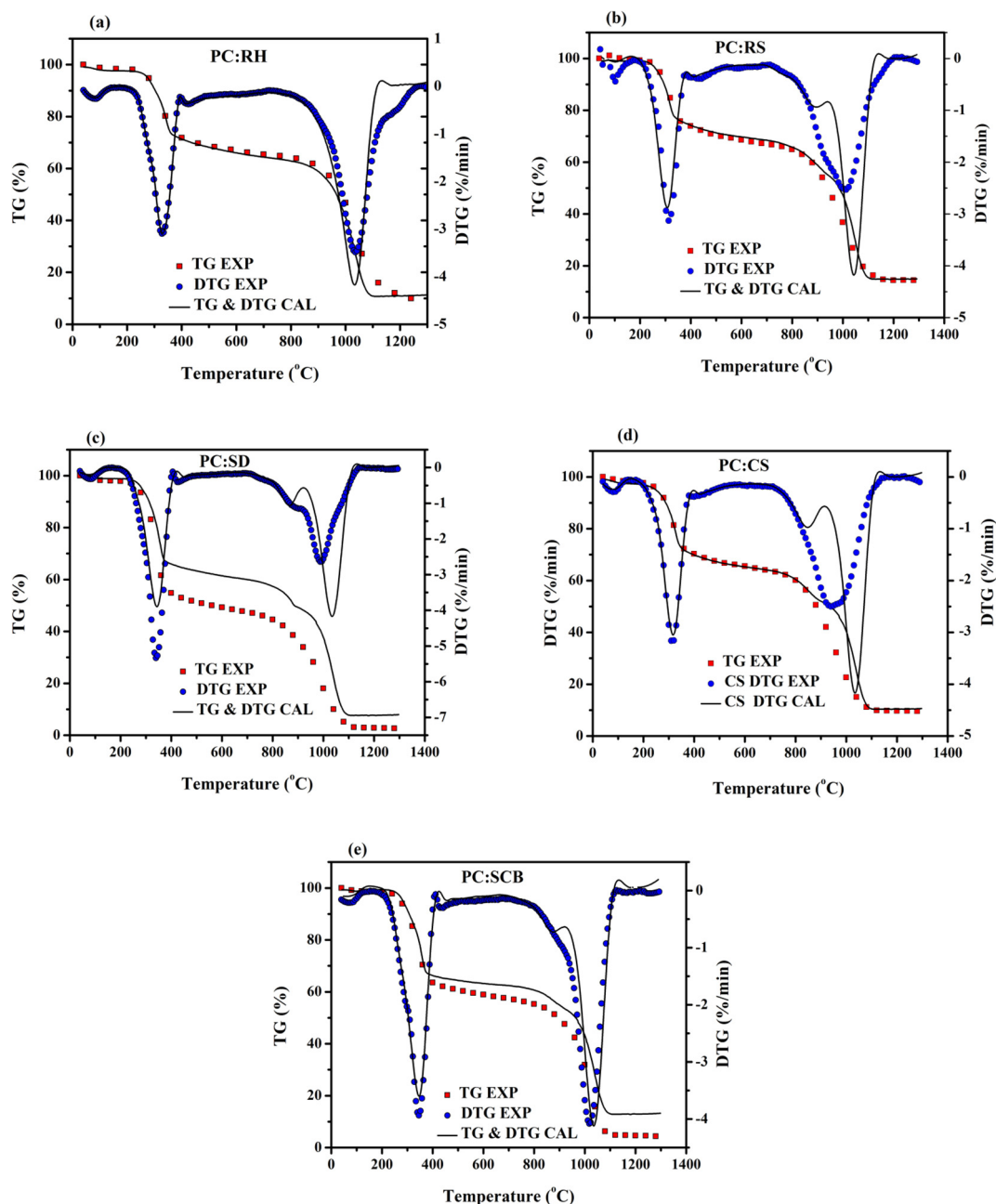
Fig. 3. Comparisons between experimental and calculated TG/DTG curves of the co-gasification.

SD and PC: SCB were 0.9914, 0.9992, 0.9940 and 0.9901 which were achieved by model R2, respectively. Although the values of correlation coefficients obtained by different model for different sample were different, but the values were all rather high as mentioned above. So, it is impossible to judge which model is most suitable according to only this value.

With respect to the kinetic parameters, the pre-exponential factor and activation energy were related to the material structure and re-activity, respectively. Reactions with the high activation energy required high temperature or long reaction time (Edreis et al., 2014). The

kinetic parameters of the single and blend samples were listed in Tables 5 and 6, respectively. It was found that for both reaction stages of samples, the lower values of (E, A and k) were achieved by the boundary controlled reactions models (R2 and R3), however the higher values were obtained by the first order chemical reaction model (O1). For stage 1 the lowest values of E were 56.37 kJ/mol for SD and 61.52 kJ/mol for the PC: SD blend, which achieved by model R2. However the highest values were 83.95 kJ/mol for RS and 90.76 kJ/mol for PC: RS blend, obtained by model O1. For stage 2 the lowest values of E were 113.27 4 kJ/mol for SD and 117.04 kJ/mol for PC: SD
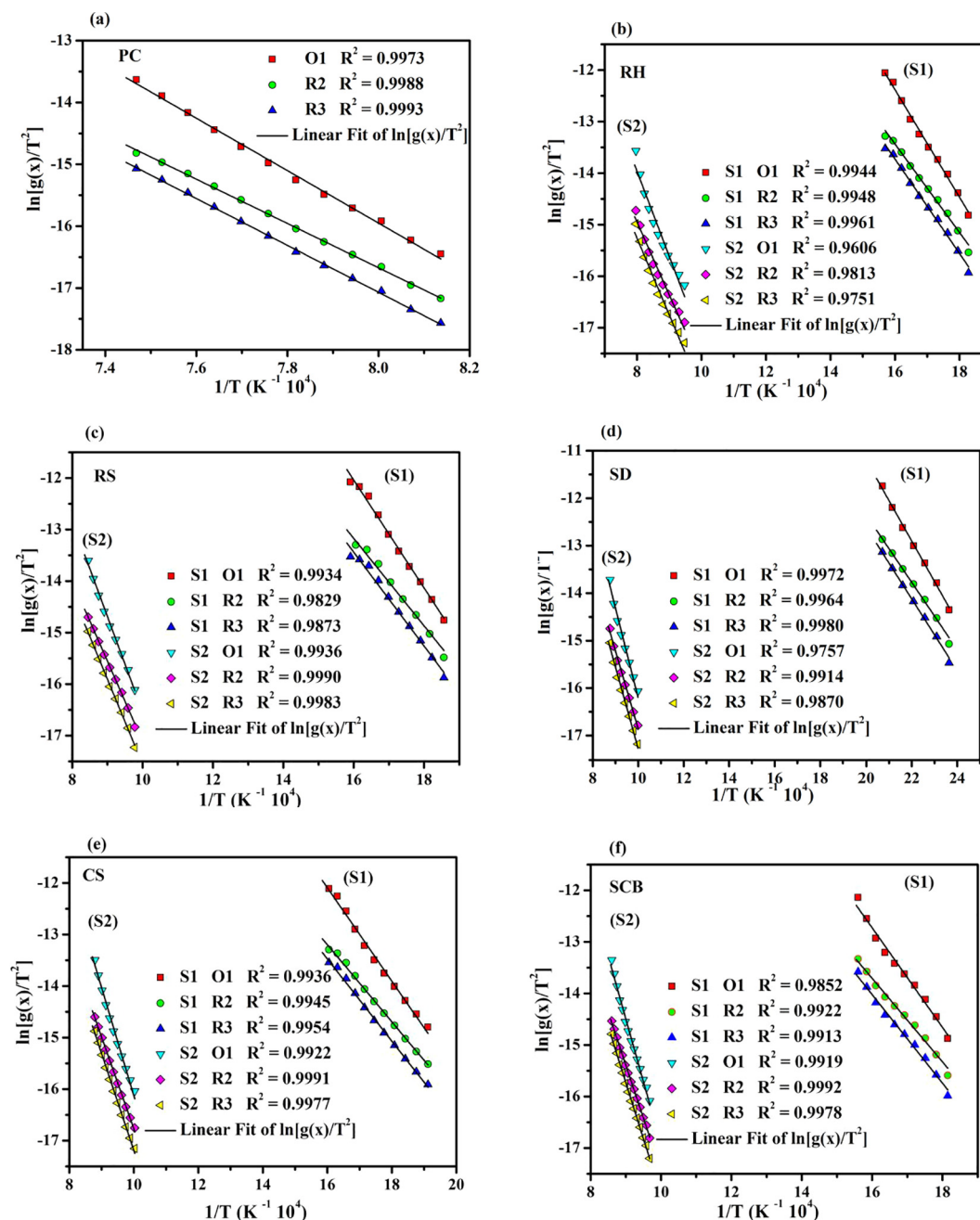
Fig. 4. Plots of In [g(x)/T²] against 1/T that gave the highest correlation coefficient values of single samples

blend, which was provided by model R2. Whereas, the highest values were 198.01 kJ/mol for RS and 216.22 kJ/mol for PC: RH blend, obtained by model O1.

The highest k values for the single samples were 1.35E+08 and 2.87E+10 (1/min), which were achieved by model R2 at stage 1 and stage 2 of SD, respectively. However, the lowest values 2.87E+07 and 2.07E+04 (1/min) were obtained by model O1 at stage 1 of RS and stage 2 of RH, respectively. For the blend samples, the highest k values were 1.03E+08 and 3.94E+06 (1/min), which provided by model R2 at stage 1 and stage 2 of the PC: SD blend, respectively. Whereas, the lowest k values were 1.93E+07 and 6.05E+03 (1/min) detected by model O1 at stage 1 of the PC: RS blend and stage 2 of the PC: RH blend,

respectively. According to the value of correlation coefficient, relatively low and reasonable value of activation energy, and physical significance of each kinetic model, it was judged that the model R2 is most suitable for co-gasification of PC and biomass.

The PC activation energy reduction during co-gasification of the blends was listed in Table 6. It was showed that the addition of biomass wastes to PC significantly reduced the PC activation energy. Compared to other biomass wastes, the SD showed the highest PC activation energy reduction, while the RH provided the lowest reduction values. Compared to other models, R2 showed the highest reduction in PC activation energy. The calculated average values of the activation energy of the blends at stage 2 were higher than the experimental values
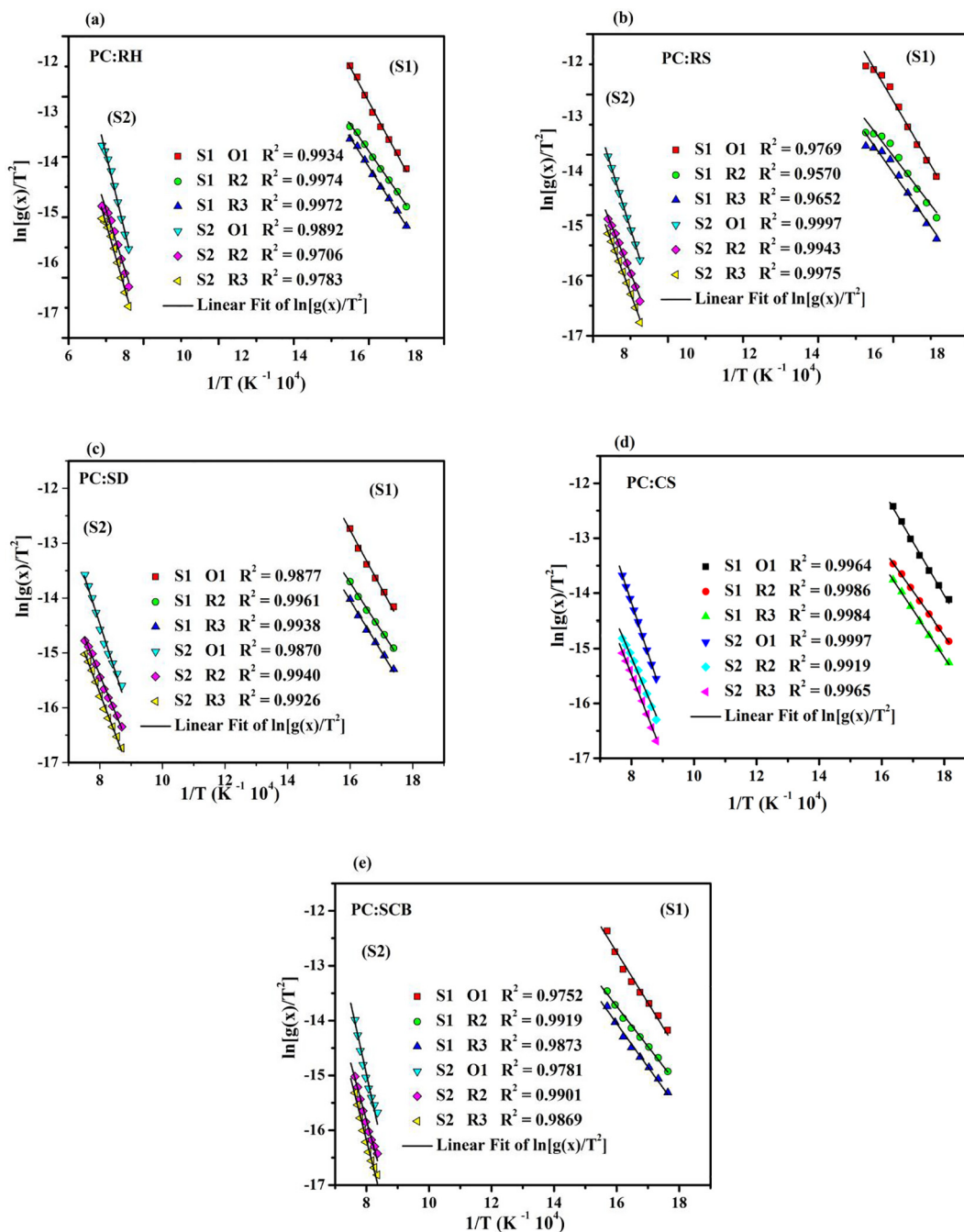
Fig. 5. Plots of In [g(x)/T2] against 1/T that gave the highest correlation coefficient values of blend samples.

for the corresponding blends. This result confirmed again the existing of significant synergistic effect between PC and biomass during their co-gasification. It was also observed from Tables 5 and 6 that the activation energy for blends was rather similar to those of the corresponding biomass and much smaller than that of PC. This implies that the biomass reduced the PC activation energy and promoted its gasification reaction. Among the biomass wastes, the SD was found to be the most reactive one, since it provided the lowest activation energy, highest reactivity and highest PC activation energy reduction. These validated the results in Section 3.1.

4. Conclusion

The gasification of biomass wastes and the blends occurred in two reaction stages. However, the PC gasification was only happened in one reaction stage at higher temperature ($> 700 \,^{\circ}\text{C}$). The synergistic effect was observed during the co-gasification of the blends. The PC gasification reactivity was significantly improved by the addition of biomass wastes. The model R2 was found to be most suitable for the co-gasification. The activation energy of PC was decrease from 293.72 kJ/mol to117.04 kJ/mol by the addition of SD. The co-gasification of PC and

Table 5
The reaction rate (k) and pre-exponential factor (A) values of single fuels.

Samples	Models	S1			S2		
		E	A	k	E	A	k
PC	O1				293.72	1.63E+11	2.88E+01
	R2				251.52	1.22E+11	5.40E+02
	R3				264.87	1.34E+11	2.14E+02
RH	O1	81.61	1.74E+10	3.01E+07	198.01	7.78E+10	2.07E+04
	R2	66.39	1.25E+10	7.82E+07	167.55	5.73E+10	1.56E+05
	R3	68.45	1.42E+10	5.55E+07	177.18	6.35E+10	8.29E+04
RS	O1	83.95	1.76E+10	2.87E+07	146.28	4.49E+10	6.23E+05
	R2	72.60	1.42E+10	5.51E+07	123.33	3.33E+10	2.66E+06
	R3	76.24	1.52E+10	4.48E+07	133.09	3.80E+10	1.45E+06
SD	O1	69.83	1.52E+10	4.56E+07	135.89	3.94E+10	1.21E+06
	R2	56.63	1.03E+10	1.35E+08	113.27	2.87E+10	4.98E+06
	R3	58.37	1.26E+10	7.68E+07	124.48	3.19E+10	3.20E+06
CS	O1	76.66	1.54E+10	4.37E+07	143.79	4.35E+10	7.31E+05
	R2	66.39	1.25E+10	7.82E+07	124.83	3.40E+10	2.43E+06
	R3	69.68	1.34E+10	6.50E+07	130.87	3.69E+10	1.66E+06
SCB	O1	75.35	1.50E+10	4.71E+07	170.33	5.91E+10	1.30E+05
	R2	62.54	1.16E+10	9.71E+07	145.17	4.43E+10	6.69E+05
	R3	66.33	1.25E+10	7.85E+07	153.14	4.87E+10	4.00E+05

E: (kJ/mol), A (1/min), k (1/min), S1: pyrolysis stage and S2: gasification stage.

Table 6
The reaction rate (k) and pre-exponential factor (A) values of the blends.

Samples	Models	S1			S2			E reduction (%)
		E	A	k	E	A	k	
PC:RH	O1	88.53	1.86E+10	2.41E+07	216.22	9.16E+10	6.05E+03	26.38
	R2	73.61	1.45E+10	5.21E+07	178.21	6.41E+10	7.75E+04	29.15
	R3	76.97	1.55E+10	4.30E+07	190.28	7.23E+10	3.47E+04	28.16
PC:RS	O1	90.76	1.99E+10	1.93E+07	154.77	4.97E+10	3.61E+05	47.31
	R2	78.19	1.58E+10	4.01E+07	128.59	3.58E+10	1.92E+06	48.87
	R3	82.21	1.71E+10	3.18E+07	136.83	3.99E+10	1.14E+06	48.34
PC:SD	O1	75.94	1.52E+10	4.56E+07	143.01	4.31E+10	7.69E+05	51.31
	R2	61.52	1.13E+10	1.03E+08	117.04	3.04E+10	3.94E+06	53.47
	R3	66.72	1.26E+10	7.68E+07	124.48	3.38E+10	2.48E+06	53.00
PC:CS	O1	88.35	1.59E+10	1.86E+07	146.75	3.01E+10	6.05E+05	50.04
	R2	73.68	1.45E+10	5.18E+07	118.36	1.78E+10	3.64E+06	52.94
	R3	78.29	1.59E+10	3.98E+07	125.18	2.13E+10	2.38E+06	52.74
PC:SCB	O1	84.16	1.77E+10	2.84E+07	174.16	6.15E+10	1.01E+05	40.71
	R2	67.63	1.29E+10	7.30E+07	148.14	4.59E+10	5.52E+06	41.10
	R3	72.48	1.42E+10	5.55E+07	156.38	5.06E+10	3.24E+05	40.96

E: (kJ/mol), A (1/min), k (1/min), S1: pyrolysis stage and S2: gasification stage.

biomass waste is a promising way for the efficient utilization of PC and biomass wastes.

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