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Thermodynamic evaluation of biomass gasification with air in autothermal gasifiers

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ABSTRACT

Biomass gasification with air in autothermal gasifiers is studied and compared with another fuel from thermodynamic aspect. The results indicate that the chemical energy values of product gases from biomass are 2.16–5.20 times as the corresponding physical energy values, while the chemical exergy values are 4.50–13.45 times as the corresponding physical exergy values. The energy and exergy efficiencies of biomass gasification are respectively in ranges of 52.38–77.41% and 36.5–50.19%, and mainly increase first and then decline when ER or gasification temperature increases. Higher carbon and hydrogen content in the ultimate analysis generates higher gaseous energy and exergy values, while results in lower energy and exergy efficiencies. Higher ash content makes biomass produce lower energy and exergy values/efficiencies.

1. Introduction

Yielding less SO_2 and NO_x emissions respectively due to less content of S and N, and the product CO_2 can be fixed in plant by photosynthesis, biomass is environmentally friendly. Its application is interested by many researchers in the world. Biomass gasification is one of the most promising conversion technologies [1]. In autothermal gasifiers, fuel reacts with gasification agent and produces heat to sustain high temperature atmosphere for the other reactions. Being simple and practicable, biomass gasification with air in autothermal gasifiers is widely studied and used [2–4]. Based on the first law of thermodynamics, mass and energy analyses are widely conducted on energy utilization. Unlike mass and energy analyses, exergy analysis is mainly based on the second law of thermodynamics, and does not obey conservation law for the unavoidable irreversibility of reaction processes. Furthermore, information for exergy calculation and analysis is limited because chemical exergy values of gases are rare. Compared with mass and energy analyses, exergy analysis is more difficult, and exergy studies are less on energy utilization, especially on biomass gasification. Therefore, this paper focuses on energy and exergy analyses of biomass gasification.

Abuadala et al. [5] evaluated biomass gasification for dry hydrogen from energy and exergy aspect, the gasification agent is steam. Rao et al. [6] conducted energy and exergy analyses on refuse gasification in a countercurrent fixed-bed gasifier. Prins et al. [7] compared the exergy efficiency of biomass gasification with that of coal gasification by using Aspen Plus software. Based on equilibrium model, Karamarkovic et al. [8] studied the energy and exergy efficiencies of biomass gasification at different temperatures, while Prins et al. [9] compared energy and exergy analyses of biomass air gasification with steam gasification. Ptasinski et al. [1] used equilibrium and quasi-equilibrium models to compare the thermodynamic efficiency of biomass gasification with that of coal gasification. Pellegrini et al. [10] applied the non-stoichiometric approach to the chemical equilibrium model for sugarcane bagasse gasification from exergy aspect.

In autothermal gasifiers, the temperature is determined by the equivalence ratio (ER, the used air for gasification divided by the required air for stoichiometric combustion). To ensure the high temperature for gasification, air/oxygen is usually used as agent. This paper aims to evaluate biomass gasification with air in autothermal gasifiers from energy and exergy aspect. Specifically, this paper studies the energy and exergy distribution, the energy and exergy efficiencies, and compares these with another fuel which has significant difference in composition. The factors (ER and gasification temperature) are also analyzed.

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Nomenclature

a, d	coefficients of constant pressure specific heat capacity
C, S	weight fractions in ultimate analysis
H_2, CH_4	molecular formulas or volume fractions of gases
ex	standard specific exergy (kJ $kmol^{-1}$)
$\dot{En}$	energy rate (kW)
$\dot{Ex}$	exergy rate (kW)
En	energy based on one kilogram of biomass (kJ)
Ex	exergy based on one kilogram of biomass (kJ)
c_p	constant pressure specific heat capacity (kJ $kmol^{-1}$ K^{-1})
$\dot{m}$	mass flow rate (kmol s^{-1} or kg s^{-1})
g	gravitational acceleration (m s^{-2})
V	velocity (m s^{-1})
Z	height (m)
T	temperature (K)
P	pressure (Pa)
h	specific enthalpy (kJ $kmol^{-1}$)
s	specific entropy (kJ $kmol^{-1}$ K^{-1})

Greek letters

β	correlation factor
η	efficiency or percentage

Superscripts

0	standard
ki	kinetic
po	potential
ph	physical
ch	chemical

Subscripts

0	ambient condition
air	related to air
gas	related to gases
tar	related to tar
uc	related to unreacted carbon
loss	related to the lost
biomass	related to biomass

Abbreviations

ER	equivalence ratio
LHV	low heating value (MJ kg^{-1})
HHV	high heating value (MJ kg^{-1})

2. Thermodynamic analysis

Fig. 1 illustrates the schematic diagram of autothermal gasifiers. Based on this diagram, thermodynamic studies are performed.

2.1. Mass conservation

The mass entering the autothermal gasifier contains biomass and air. The products of gasification are product gas, ash and unavoidable byproducts (tar and unreacted carbon). The mass conservation embodies:

$$\dot{m}_{\mathrm{biomass}} + \dot{m}_{\mathrm{air}} = \dot{m}_{\mathrm{gas}} + \dot{m}_{\mathrm{tar}} + \dot{m}_{\mathrm{uc}} + \dot{m}_{\mathrm{ash}} \tag{1}$$

where $\dot{m}_{\mathrm{biomass}}$, $\dot{m}_{\mathrm{air}}$, $\dot{m}_{\mathrm{gas}}$, $\dot{m}_{\mathrm{tar}}$, $\dot{m}_{\mathrm{uc}}$ and $\dot{m}_{\mathrm{ash}}$ denote the mass rates of biomass, air, product gas, tar, unreacted carbon and ash, respectively.

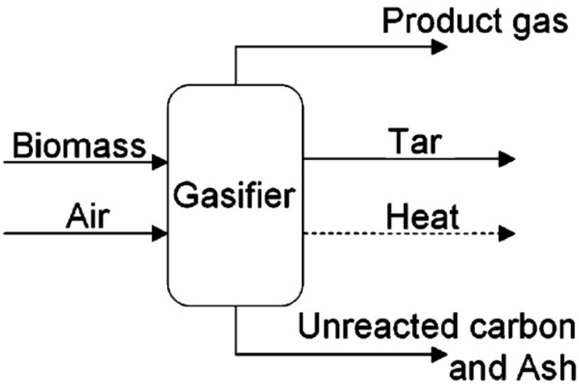

Fig. 1. Schematic diagram of autothermal gasifiers.

2.2. Energy conservation

An autothermal system is heated by itself. The oxidation between biomass and air provides heat and sustains a high temperature atmosphere for the other reactions in gasifier. The energy transferred from the gasifier can be described by Fig. 1. According to energy conservation law, the corresponding energy balance of an autothermal gasifier can be written as:

$$\dot{En}_{\mathrm{biomass}} + \dot{En}_{\mathrm{air}} = \dot{En}_{\mathrm{gas}} + \dot{En}_{\mathrm{tar}} + \dot{En}_{\mathrm{uc}} + \dot{En}_{\mathrm{loss}} \tag{2}$$

where $\dot{En}_{\mathrm{biomass}}$, $\dot{En}_{\mathrm{air}}$, $\dot{En}_{\mathrm{gas}}$, $\dot{En}_{\mathrm{tar}}$, $\dot{En}_{\mathrm{uc}}$ and $\dot{En}_{\mathrm{loss}}$ represent the energy rates of biomass, air, product gas, tar, unreacted carbon and the lost part, respectively. $\dot{En}_{\mathrm{loss}}$ relates to the energy from ash and the lost heat.

The total energy of a stream flow is:

$$\dot{En} = \dot{En}^{\mathrm{ki}} + \dot{En}^{\mathrm{po}} + \dot{En}^{\mathrm{ph}} + \dot{En}^{\mathrm{ch}} \tag{3}$$

Here, $\dot{En}^{\mathrm{ki}}$, $\dot{En}^{\mathrm{po}}$, $\dot{En}^{\mathrm{ph}}$ and $\dot{En}^{\mathrm{ch}}$ represent the kinetic, potential, physical (or sensible [11]) and chemical energy rates of the stream, respectively. Neglecting $\dot{En}^{\mathrm{ki}}$ $(= \dot{m}V^2/2)$ and $\dot{En}^{\mathrm{po}}$ $(= \dot{m}gZ)$, Eq. (3) reduces to:

$$\dot{En} = \dot{En}^{\mathrm{ph}} + \dot{En}^{\mathrm{ch}} \tag{4}$$

For combustible gases, Eq. (4) equals:

$$\dot{En} = \dot{m}(h + \mathrm{HHV}) \tag{5}$$

where $\dot{m}$, h and HHV represent the mass flow rate, specific enthalpy and high heating value of the stream, respectively. The above equation is suitable for air, product gas and tar. While for biomass and unreacted carbon, the total energy can be simplified to:

$$\dot{En} = \dot{m}\mathrm{HHV} \tag{6}$$

The specific enthalpy of a component is:

$$h = h_0 + \int_{T_0}^{T} c_p \, \mathrm{d}T \tag{7}$$

where h and h_0 respectively represent the specific enthalpy at the specified temperature T and the environmental temperature T_0. The specific enthalpy values of some gases at the environmental temperature are shown in Table 1. c_p is the constant pressure specific heat capacity in kJ $kmol^{-1}$ K^{-1}, and the empirical equation is:

$$\bar{c}_p = a + bT + cT^2 + dT^3 \tag{8}$$

The coefficients a–d of constant pressure specific heat capacity of some gases are given in Table 2.

The high heating value of biomass ($\mathrm{HHV}_{\mathrm{biomass}}$) can be experimentally measured or calculated from the proximate [13] or ultimate [14] analysis of biomass. When the LHV of biomass is

Table 1
Specific enthalpy, entropy and standard chemical exergy of some gases at 25 °C, 1 atm.

Gas	[a]h_0 (kJ kmol^{-1})	[a]s_0 (kJ kmol^{-1} K^{-1})	[b]ex^{ch} (kJ kmol^{-1})
N_2	8669	191.502	720
O_2	8682	205.033	3970
H_2	8468	130.574	236,100
CO	8669	197.543	275,100
CO_2	9364	213.685	19,870
CH_4	–	–	831,650

[a] From [12].
[b] From [18].

given, the HHV can be obtained by the following correlation [15] in MJ kg^{-1}:

$$\mathrm{HHV} = \mathrm{LHV} + 21.978\mathrm{H} \tag{9}$$

Here, H is the weight fraction of element H in the ultimate analysis.

The heating value of dry gas can be estimated from the following [16]:

$$\mathrm{HHV} = 12.75\mathrm{H_2} + 12.63\mathrm{CO} + 39.82\mathrm{CH_4} + 63.43\mathrm{C_2H_4} + \cdots \tag{10}$$

Here, H_2, CO, CH_4 and C_2H_4 indicate the volume or molar fractions of H_2, CO, CH_4 and C_2H_4 in the dry gas in %, respectively.

2.3. Exergy analysis

Unlike mass and energy, exergy does not obey conservation law for the unavoidable irreversibility of reaction processes. If the irreversibility is considered to the lost part, an exergy balance can also take shape. The exergy balance for Fig. 1 can be written as:

$$\dot{E}x_{\mathrm{biomass}} + \dot{E}x_{\mathrm{air}} = \dot{E}x_{\mathrm{gas}} + \dot{E}x_{\mathrm{tar}} + \dot{E}x_{\mathrm{uc}} + \dot{E}x_{\mathrm{loss}} \tag{11}$$

where $\dot{E}x_{\mathrm{biomass}}$, $\dot{E}x_{\mathrm{air}}$, $\dot{E}x_{\mathrm{gas}}$, $\dot{E}x_{\mathrm{tar}}$ and $\dot{E}x_{\mathrm{uc}}$ represent the exergy rates of biomass, air, product gas, tar and unreacted carbon, respectively. $\dot{E}x_{\mathrm{loss}}$ denotes the exergy rate lost from this system, and it includes the exergy from ash, lost heat and irreversibility of the process.

Being similar to energy, the total exergy of a stream can be simplified when neglecting the kinetic and potential exergy:

$$\dot{E}x = \dot{E}x^{\mathrm{ph}} + \dot{E}x^{\mathrm{ch}} \tag{12}$$

Here, $\dot{E}x^{\mathrm{ph}}$ and $\dot{E}x^{\mathrm{ch}}$ represent the physical and chemical exergy rates of the stream, respectively. The physical exergy rate is defined as:

$$\dot{E}x^{\mathrm{ph}} = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{13}$$

where $\dot{m}$ is mass flow rate of the stream in kmol s^{-1}. s and s_0 denote the specific entropy in kJ kmol^{-1} K^{-1} at the specified state (P and T) and the environmental condition (P_0 = 1 atm and T_0 = 298 K), respectively. The specific entropy values of some gases are in Table 1.

The physical exergy of biomass at environmental state is zero, then the exergy rate input by biomass can be calculated by a statistical correlation [17]:

$$\dot{E}x_{\mathrm{biomass}} = \beta\dot{m}\mathrm{LHV}_{\mathrm{biomass}} \tag{14}$$

Table 2
Coefficients of constant pressure specific heat capacity of some gases [12].

Gas	a	b ($\times 10^{-2}$)	c ($\times 10^{-5}$)	d ($\times 10^{-9}$)	Range (K)
N_2	28.90	−0.1571	0.8081	−2.873	273–1800
O_2	25.48	1.520	−0.7155	1.312	273–1800
H_2	29.11	−0.1916	0.4003	−0.8704	273–1800
CO	28.16	0.1675	0.5327	−2.222	273–1800
CO_2	22.26	5.981	−3.501	7.469	273–1800
CH_4	19.89	5.024	1.269	−11.01	273–1500

Table 3
β, LHV, HHV and exergy of fuels.

Fuel	β	LHV (MJ kg^{-1})	HHV (MJ kg^{-1})	Ex_{biomass} (MJ kg^{-1})
Wood chip	1.19	15.936	17.057	18.964
Pine sawdust	1.16	18.338	19.590	21.217
Rice husk	1.18	14.220	15.411	16.723
Polypropylene	1.05	42.001	44.700	43.962

Here, β is a correlation factor, and can be calculated from [17]:

$$\beta = \frac{1.044 + 0.0160\mathrm{H/C} - 0.3493\mathrm{O/C}(1 + 0.0531\mathrm{H/C}) + 0.0493\mathrm{N/C}}{1 - 0.4124\mathrm{O/C}} \quad (\mathrm{N/C} < 2) \tag{15}$$

where C, H, O and N are the weight fractions of carbon, hydrogen, oxygen and nitrogen in the ultimate analysis of biomass, respectively.

The chemical exergy rate is defined as:

$$\dot{E}x^{\mathrm{ch}} = \dot{m}ex^{\mathrm{ch}} \tag{16}$$

where ex^{ch} is the standard chemical exergy of the material. The standard chemical exergy values of some components are given in Table 1.

2.4. Energy and exergy efficiencies

To comprehensively evaluate biomass gasification, both energy and exergy efficiencies are introduced. η_1 is the gas energy divided by the total input energy. η_2 is the gas exergy divided by the total input exergy. They are defined:

$$\eta_1 = \frac{\dot{E}n_{\mathrm{gas}}}{\dot{E}n_{\mathrm{biomass}} + \dot{E}n_{\mathrm{air}}} \times 100\% \tag{17}$$

$$\eta_2 = \frac{\dot{E}x_{\mathrm{gas}}}{\dot{E}x_{\mathrm{biomass}} + \dot{E}x_{\mathrm{air}}} \times 100\% \tag{18}$$

3. Results and discussion

To study biomass gasification with air in autothermal gasifiers from thermodynamic aspect, some cases are selected. Data of wood chip, pine sawdust, rice husk and polypropylene are respectively from early literatures [2–4,19]. Polypropylene is gasified in a fluidized bed gasifier, wood chip and pine sawdust are in bubbling fluidized bed gasifiers, and rice husk is in a dual distributor type fluidized bed gasifier. The gasification agents are air. Polypropylene is the main and typical composition of waste (municipal refuse). It is not real biomass, and has significant difference in composition. In this paper, we compare it with biomass to get some conclusions.

3.1. Calculation

The HHVs of wood chip and polypropylene are directly from the corresponding references, while literatures [3,4] respectively mentioned the LHVs of pine sawdust and rice husk. The transformation between HHV and LHV follows the correlation Eq. (9). β is calculated from Eq. (15), and the exergy values of biomass (Ex_{biomass}) are from Eq. (14). β, LHV, HHV and exergy of the fuels are displayed in Table 3.

Table 4 displays the specific enthalpy, specific entropy and air energy on the base of one kilogram of fuel. The values of specific enthalpy and entropy of H_2, CO, CO_2, and N_2 are looked up according to the corresponding temperatures in Ref. [12], while that of CH_4 are calculated from Eqs. (7) and (8). Here, we neglect the other product gases such as acetylene (C_2H_2) and ethylene (C_2H_4), for they are very small in quantity. Gas yields and the HHVs are also presented in Table 4. The energy values of product gases (En_{gas}) and air (En_{air})

Table 4
Specific enthalpy and entropy, gas yield, gas HHV and air energy.

Fuel	ER	Specific enthalpy ($kJ\,kmol^{-1}$) Specific entropy ($kJ\,kmol^{-1}\,K^{-1}$)					Gas ($N\,m^3\,kg^{-1}$)	HHV ($MJ\,N\,m^{-3}$)	En_{air} (kJ)
		H_2	CO	CO_2	N_2	CH_4[c]			
A	0.32	20,013	20,378	26,631	20,297	18,867	1.97	4.90	501.4
		155.19	222.51	249.95	216.31	39.25			
	0.36	21,191	21,628	28,622	21,529	21,198	2.22	4.92	564.1
		156.85	224.27	252.76	218.06	42.51			
	0.38	20,807	21,472	28,372	21,375	20,680	2.31	4.94	595.5
		156.33	224.05	252.41	217.84	41.86			
	0.41	20,454	21,002	27,622	20,912	19,733	2.40	4.66	642.5
		155.82	223.40	251.37	217.19	40.47			
	0.43	22,757	23,367	31,410	23,242	24,406	2.53	3.97	673.8
		158.91	226.56	256.44	220.31	46.74			
B	0.26	25,342	26,091	35,821	25,928	29,477	2.1	4.60	452.7
		162.03	229.86	261.77	223.56	52.20			
	0.32	23,557	24,164	32,694	24,027	25,598	2.3	4.30	557.2
		159.91	227.56	258.05	221.30	47.20			
	0.36	24,151	24,803	33,730	24,658	26,872	2.4	4.60	626.8
		160.64	228.34	259.31	222.07	49.15			
	0.47	22,372	22,890	30,644	22,772	23,109	2.5	3.70	818.3
		158.42	225.95	255.45	219.71	44.45			
C	0.25	24,359	25,124	34,251	24,974	27,516	1.49	4.38	306.0
		160.89	228.72	259.93	222.45	49.91			
	0.30	27,197	28,211	39,268	28,016	34,163	1.71	3.54	415.3
		164.09	232.20	265.59	225.87	58.08			
	0.35	29,608	30,854	43,587	30,620	39,324	1.97	3.15	484.5
		166.56	234.92	270.02	228.54	62.63			
D	0.20	28,430	29,528	41,415	29,314	36,530	1.99	11.38	1930
		165.38	233.92	267.84	227.23	59.83			
	0.25	30,364	31,855	45,228	31,607	41,590	2.50	9.10	2412
		167.30	235.89	271.62	229.50	64.83			
	0.30	32,008	33,534	47,982	33,260	45,175	2.89	7.94	2896
		168.84	237.46	279.07	231.05	68.18			
	0.35	32,802	34,546	49,648	34,259	47,615	3.26	6.97	3378
		169.56	238.37	275.69	231.95	70.39			
	0.40	34,028	35,733	51,602	35,430	50,327	3.54	6.05	3860
		170.64	239.41	277.40	232.97	72.75			
	0.45	34,954	36,751	53,286	36,441	52,607	3.88	5.16	4342
		171.42	240.33	278.83	233.83	74.68			

A–D denote wood chip, pine sawdust, rice husk and polypropylene, respectively.

[c] Represents $h - h_0$ and $s - s_0$.

are computed from Eq. (5), while the exergy values of product gases (Ex_{gas}) are from Eqs. (12), (13) and (16).

3.2. Energy and exergy distribution

Fig. 2 exhibits the energy distribution of product gases for wood chip, pine sawdust, rice husk and polypropylene. On the whole, the chemical energy values (dense grid) of product gases are much higher than the corresponding physical energy values (sparse grid). Specifically, the chemical energy values are 2.16 (rice husk, ER = 0.35)–5.20 (wood chip, ER = 0.32) times as the corresponding physical energy values for biomass, while 2.91 (ER = 0.45)–8.26 (ER = 0.20) for polypropylene. This relationship is mainly resulted from the fact that product gases have much higher heating values than the corresponding enthalpy values. For example, the high heating value of H_2 at the environmental condition (1 atm, 25 °C) is 141,800 $kJ\,kg^{-1}$ [12], while the corresponding enthalpy is about 3829 $kJ\,kg^{-1}$ (calculated from the datum in Ref. [12]). Additionally, C_nH_m is included in energy calculation (while neglected in exergy calculation), also contributes. Based on 1 kg fuel, the total energy values (physical and chemical) of product gases are between 8253.49 kJ (rice husk, ER = 0.25) and 13,791.31 kJ (pine sawdust, ER = 0.36) for biomass, being much lower than the 25,390.38–28,089.31 kJ for polypropylene. This is because polypropylene has much higher carbon and hydrogen in the ultimate analysis than that of biomass. The carbon and hydrogen weight percentages (dry ash-free basis) in polypropylene are respectively 86.42% and 12.28% [19], while that in biomass respectively range in 46.4–50.0% and 5.7–6.775% [2–4]. Hence, polypropylene needs more oxygen or air (higher ER) to be gasified [1].

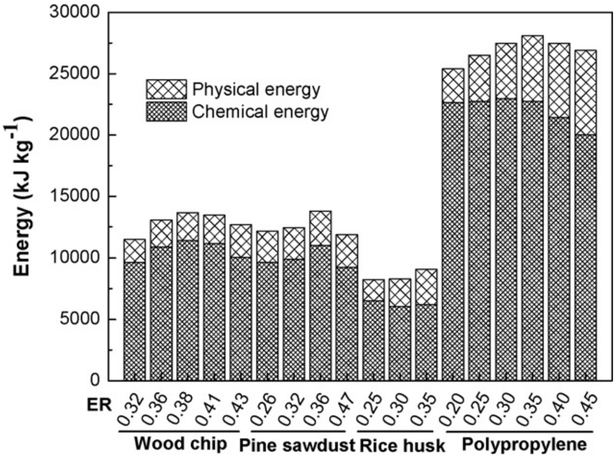

Fig. 2. Energy distribution of product gases.

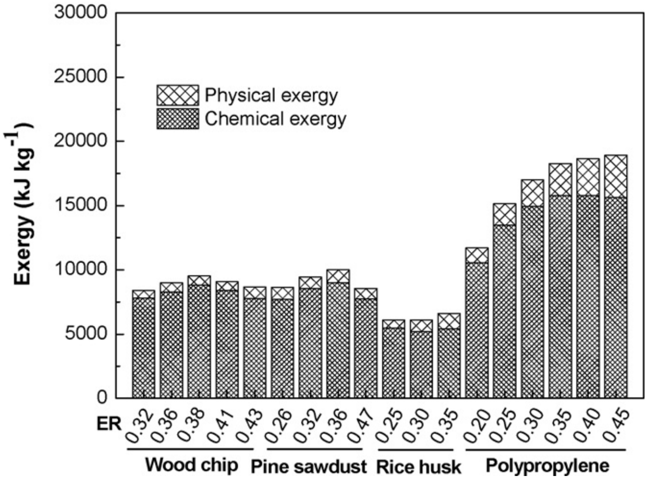

Fig. 3. Exergy distribution of product gases.

Rice husk shows lower total energy values (Fig. 2) than wood chip and pine sawdust, for it has higher ash content. The ash content of rice husk is 20% [4], while that of wood chip and pine sawdust are about 1% [2,3].

In Fig. 3, the chemical exergy values of product gases are 4.50 (rice husk, ER = 0.35)–13.45 (wood chip, ER = 0.32) times as the corresponding physical exergy values for biomass, while 4.73 (ER = 0.45)–9.28 (ER = 0.20) for polypropylene. On the whole, the physical, chemical and total exergy values of product gases are much lower than the corresponding energy values (Fig. 2). This is in agreement with the other researches [1,8]. The trend of exergy value is nearly the same as that of energy value except for polypropylene. The energy value of polypropylene increases first and then declines (Fig. 2), while the exergy value increases monotonously (Fig. 3). This is because C_nH_m is included in the energy value, while neglected in the exergy value.

3.3. The influence of ER on energy and exergy efficiencies

Fig. 4 exhibits the influence of ER on energy and exergy efficiencies of product gases for wood chip (a), pine sawdust (b), rice husk (c) and polypropylene (d). It is obvious that the energy efficiencies are much higher than the corresponding exergy efficiencies, this accords with the simulation results in Ref. [1]. The energy efficiencies of biomass gasification are between 52.38% (rice husk, ER = 0.25) and 77.41% (wood chip, ER = 0.38), while that of polypropylene gasification are from 54.45% (ER = 0.20) to 58.43% (ER = 0.35). The exergy efficiencies of biomass gasification are between 36.5% (rice husk, ER = 0.25) and 50.19% (wood chip, ER = 0.38), this is higher than the 31–35% of coal and biomass co-combustion in an atmospheric bubbling fluidized bed chamber [20] and in agreement with the 37% of a power plant [21]. The exergy efficiencies of polypropylene gasification are from 26.62% (ER = 0.20) to 43.06% (ER = 0.45). Although polypropylene has much higher energy (Fig. 2) and exergy (Fig. 3) values than biomass, the energy and exergy efficiencies are lower.

Air exergy ($\dot{E}x_{\mathrm{air}}$) is zero at the environmental condition, and the energy values (Table 4) of air are relatively very low, the energy and exergy efficiencies are hence mainly determined by the energy and exergy values of product gases, respectively. The energy values of product gases (Fig. 2) are much higher than the corresponding exergy (Fig. 3) values, while the denominators of the two efficiencies in definitions (17) and (18) are equal or approaching to each other, this makes the energy efficiencies be much higher than the corresponding exergy efficiencies.

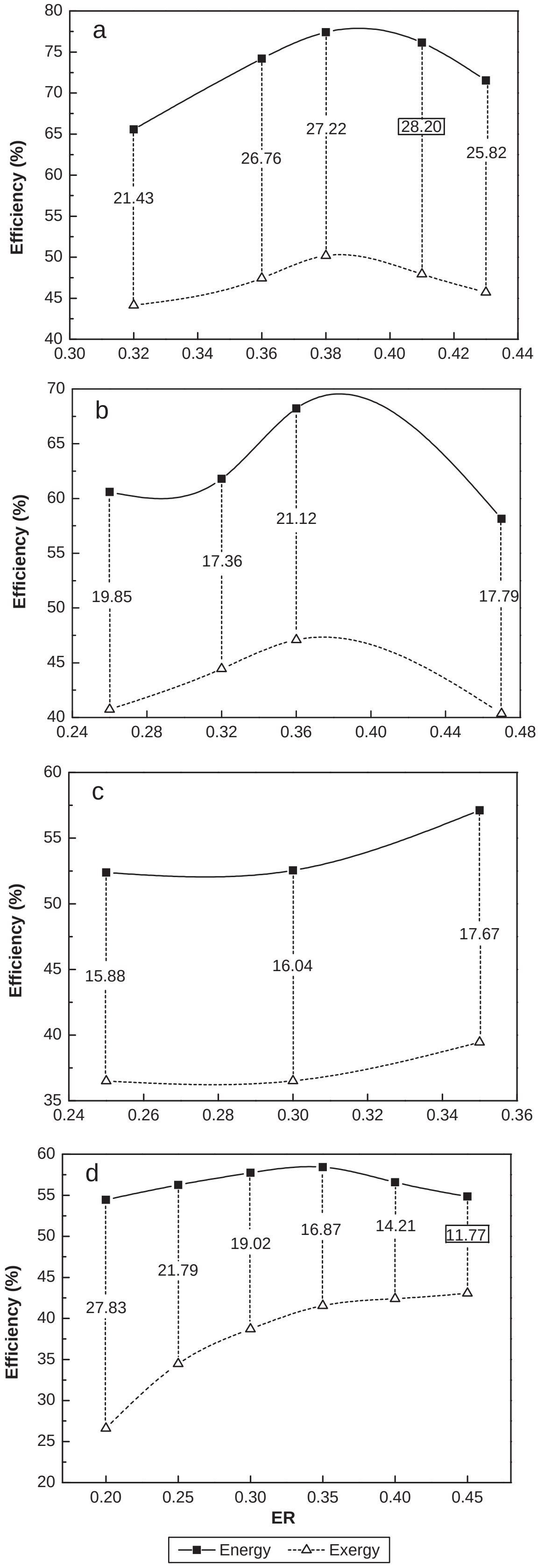

Fig. 4. Influence of ER on energy and exergy efficiencies of product gases for wood chip (a), pine sawdust (b), rice husk (c) and polypropylene (d).

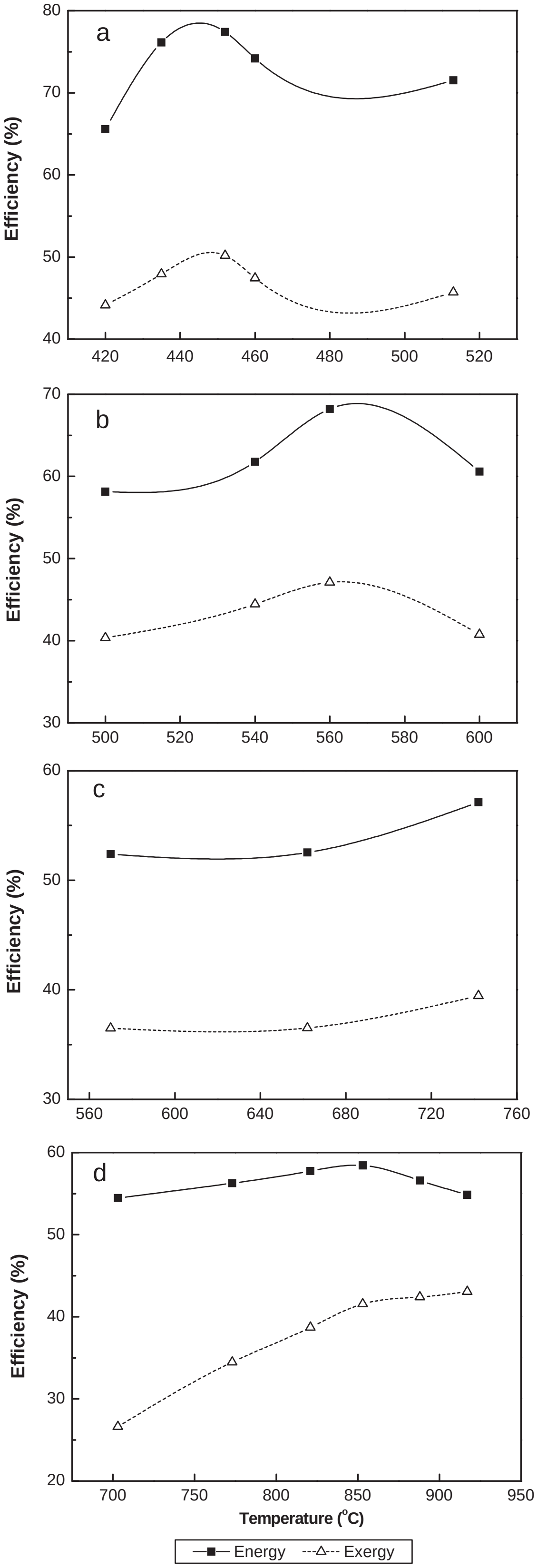

Fig. 5. Influence of gasification temperature on energy and exergy efficiencies of product gases for wood chip (a), pine sawdust (b), rice husk (c) and polypropylene (d).

In Fig. 4(a) and (b), the energy and exergy efficiencies increase first and then decline when ER increases, and the critical points are between 0.36 and 0.40. This is because the total energy (Fig. 2) and exergy (Fig. 3) values increase first and then reduce when ER increases.

In Fig. 4(c), when ER increases from 0.25 to 0.35, both the energy and exergy efficiencies rise monotonously. We can foresee that these two efficiencies will be reduced by the increasing N_2 which has low energy and exergy values (Table 1), and perhaps the critical ERs are in the range of 0.36–0.40.

For polypropylene (Fig. 4(d)), the energy efficiency rises first and then declines in the discussed ER of 0.20–0.45, while the exergy efficiency increases monotonously. They are mainly determined by the energy values (Fig. 2) and exergy values (Fig. 3), respectively. In fact, if C_nH_m which can get to 8.37 vol% of the dry gas yield is neglected from the calculation of HHV or energy value of the product gas, the energy efficiency will keep pace with the exergy efficiency, and both of these two efficiencies will rise when ER increases from 0.20 to 0.45. Additionally, resulting from the dilution of N_2 [22], both the energy and exergy efficiencies will definitely decline when ER is high enough.

Generally speaking, the typical trend is that the exergy efficiency keeps pace with the energy efficiency, and both of them increase first and then reduce when ER increases. Hence, a proper ER should be employed to get higher energy and exergy efficiencies. In this paper, the optimum ER for biomass gasification in autothermal gasifiers seems to be in 0.36–0.40.

3.4. The influence of gasification temperature on energy and exergy efficiencies

Fig. 5 shows the influence of gasification temperature on energy and exergy efficiencies of product gases for wood chip (a), pine sawdust (b), rice husk (c) and polypropylene (d). This is very similar to the situation in Fig. 4. We should mention that from 460 °C to 513 °C in Fig. 5(a), it seems that both the energy and exergy efficiencies decrease and then increase, this is not the same as the monotonous decrease after the first critical points in Fig. 4(a). In fact, if we chose the straight pattern when drew the figures, the trend will be harmonious for Figs. 4(a) and 5(a). Therefore, gasification temperature and ER have similar influence on the energy and exergy efficiencies of biomass gasification. In fact, gasification temperature in autothermal gasifiers is determined by ER.

4. Conclusions

Based on the gasification of wood chip, pine sawdust and rice husk, the chemical energy values of product gases are 2.16–5.20 times as the corresponding physical energy values, while the chemical exergy values are 4.50–13.45 times as the corresponding physical exergy values. Polypropylene has higher carbon and hydrogen content in the ultimate analysis, and generates higher gaseous energy and exergy values (while has lower energy and exergy efficiencies). The higher ash content makes rice husk produce lower energy and exergy values/efficiencies.

The energy efficiencies of biomass gasification are between 52.38% and 77.41%, while the exergy efficiencies range in 36.5–50.19%. The energy values of product gases are much higher than the corresponding exergy values, this results in higher energy efficiencies.

The energy and exergy efficiencies are mainly in accordance, and increase first and then decline when ER increases. In autothermal gasifiers, gasification temperature is determined by ER, so its influence on energy and exergy efficiencies is similar to that of ER.

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References

[1] K.J. Ptasinski, M.J. Prins, A. Pierik, Exergetic evaluation of biomass gasification, Energy 32 (2007) 568–574.
[2] S. Kaewluan, S. Pipatmanomai, Potential of synthesis gas production from rubber wood chip gasification in a bubbling fluidised bed gasifier, Energy Convers. Manag. 52 (2011) 75–84.
[3] I. Narváez, A. Orío, M.P. Aznar, J. Corella, Biomass gasification with air in an atmospheric bubbling fluidized bed: effect of six operational variables on the quality of the produced raw gas, Ind. Eng. Chem. Res. 35 (1996) 2110–2120.
[4] K.G. Mansaray, A.E. Ghaly, A.M. Al-Taweel, F. Hamdullahpur, V.I. Ugursal, Air gasification of rice husk in a dual distributor type fluidized bed gasifier, Biomass Bioenergy 17 (1999) 315–332.
[5] A. Abuadala, I. Dincer, Efficiency evaluation of dry hydrogen production from biomass gasification, Thermochim. Acta 507–508 (2010) 127–134.
[6] M.S. Rao, S.P. Singh, M.S. Sodha, A.K. Dubey, M. Shyam, Stoichiometric, mass, energy and exergy balance analysis of countercurrent fixed-bed gasification of post-consumer residues, Biomass Bioenergy 27 (2004) 155–171.
[7] M.J. Prins, K.J. Ptasinski, F.J.J.G. Janssen, From coal to biomass gasification: comparison of thermodynamic efficiency, Energy 32 (2007) 1248–1259.
[8] R. Karamarkovic, V. Karamarkovic, Energy and exergy analysis of biomass gasification at different temperatures, Energy 35 (2010) 537–549.
[9] M.J. Prins, K.J. Ptasinski, F.J.J.G. Janssen, Thermodynamics of gas-char reactions: first and second law analysis, Chem. Eng. Sci. 58 (2003) 1003–1011.
[10] L.F. Pellegrini, S. de Oliveira Jr., Exergy analysis of sugarcane bagasse gasification, Energy 32 (2007) 314–327.
[11] Y. Kalinci, A. Hepbasli, I. Dincer, Efficiency assessment of an integrated gasifier/boiler system for hydrogen production with different biomass types, Int. J. Hydrogen Energy 35 (2010) 4991–5000.
[12] Y.A. Cengel, M.A. Boles, Thermodynamics: An Engineering Approach, McGraw-Hill, Inc., New York, 1994.
[13] J. Parikh, S.A. Channiwala, G.K. Ghosal, A correlation for calculating HHV from proximate analysis of solid fuels, Fuel 84 (2005) 487–494.
[14] S.A. Channiwala, P.P. Parikh, A unified correlation for estimating HHV of solid, liquid and gaseous fuels, Fuel 81 (2002) 1051–1063.
[15] S. Bilgen, K. Kaygusuz, A. Sari, Second law analysis of various types of coal and woody biomass in Turkey, Energy Sources 26 (2004) 1083–1094.
[16] X.T. Li, J.R. Grace, C.J. Lim, A.P. Watkinson, H.P. Chen, J.R. Kim, Biomass gasification in a circulating fluidized bed, Biomass Bioenergy 26 (2004) 171–193.
[17] J. Szargut, Exergy Method: Technical and Ecological Applications, WIT Press, Boston, 2005.
[18] M.J. Moran, H.N. Shapiro, Fundamentals of Engineering Thermodynamics, John Wiley & Sons, Inc., New York, 2000.
[19] R. Xiao, B. Jin, H. Zhou, Z. Zhong, M. Zhang, Air gasification of polypropylene plastic waste in fluidized bed gasifier, Energy Convers. Manag. 48 (2007) 778–786.
[20] C. Martín, M.A. Villamañán, C.R. Chamorro, J. Otero, A. Cabanillas, J.J. Segovia, Low-grade coal and biomass co-combustion on fluidized bed: exergy analysis, Energy 31 (2006) 330–344.
[21] S.C. Kamate, P.B. Gangavati, Exergy analysis of cogeneration power plants in sugar industries, Appl. Therm. Eng. 29 (2009) 1187–1194.
[22] M.R. Mahishi, D.Y. Goswami, Thermodynamic optimization of biomass gasifier for hydrogen production, Int. J. Hydrogen Energy 32 (2007) 3831–3840.