EXERGY CHARACTERISTICS OF RICE HUSKS

by

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The comprehensive exergy characteristics of thirty two rice husk samples including exergy values (moisture related, S related, ash related, and LHV related) and exergy percentages (moisture related, S related, ash related, and LHV related) were investigated in this study. The results show that the moisture related exergy, S related exergy, ash related exergy, and LHV related exergy are in the ranges of 0-327.93, 0-67.78, 17.88-131.97, and 10577.05-19297.54 KJ/kg, respectively, for the rice husks. The exergy values of rice husks are in the range of 10918.01-19445.76 KJ/kg, and they are mainly determined by the LHV related exergy (96.81-99.70%), followed by moisture related exergy (0-2.66%), ash related exergy (0.11-0.78%), and S related exergy (0-0.43%).

Key words: *exergy characteristics, rice husk, distribution, percentage*

Introduction

The global production of rice husk in 2016 was estimated to be 123.81 million tones [1, 2]. This abundantly available rice husk makes itself a very important renewable energy source on the Earth. Due to the advantages of abundant availability and natural renewability, rice husk has extensive applications in our daily life. The raw rice husk can be used as pillow stuffing material and enzyme immobilization substrate. The ground rice husk can be used as material source for animal feeding and power generation, and it can also be used for production of hydrogen, biogas, biochar, carbon, acid, nanomaterial, *etc*. The physical, thermal, and chemical properties of rice husk were therefore widely and comprehensively studied [2, 3].

Exergy refers to the maximum obtainable work of a material at a given specific condition as regard to a given environmental reference and it is a measurement of how far a certain material deviates from a state of equilibrium with its environment [4]. Exergy is now widely used to evaluate energy sources, agricultural products, drying processes, thermal cycles, energy systems, *etc*.

Rice husk related exergy was also ever studied. Srinivas *et al*. [5] studied the exergy efficiency of syngas production from rice husk gasification in a pressurized circulating fluidized bed through using a thermodynamic equilibrium model. Zhang *et al*. [6] studied the exergy values and efficiencies of syngas produced from air gasification of rice husk in an autothermal

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gasifier. Zhang *et al*. [7] investigated the exergy distributions of syngas producted from rice husk gasification in an entrained flow reactor. For the previous investigations, the exergy of rice husk is of significant importance because determination of the exergy of rice husk is the first step for investigating and evaluating the material characteristics, transfer processes, and utilization systems of the rice husk from exergy aspect [8]. Zhang *et al*. [3] comprehensively investigated the exergy of six rice husks. These included the values and percentages of moisture related exergy, S related exergy, and ash related exergy. They also observed a relationship between exergy and LHV, a relationship between exergy and moisture content, a relationship between exergy and ash content for the rice husks. However, the exergy characteristics and relationships are strongly dependent on the fuel types and properties [9-13]. A comprehensive investigation of the exergy characteristics of extensive rice husk samples is therefore significantly necessary and these extensive data can: provide comprehensive exergy characteristics of rice husk and set solid foundation for estimation of the exergy of rice husk.

The main objective of this study is to investigate the comprehensive exergy characteristics of extensive rice husk samples. The specific objectives are: to collect the comprehensive basic data of extensive rice husk samples and to detail the exergy characteristics of rice husks.

Materials and methods

Materials

The rice husks which have comprehensive basic data including approximate analysis (moisture content and ash content), ultimate analysis (C, H, O, N, and S), heating values (HHV and LHV), and ash compositions (Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, MnO, Na_2O, P_2O_5, SO_3, SiO_2, TiO_2, *etc.*) were used in this study. Table 1 shows the approximate analysis, ultimate analysis, and heating values of the thirty two rice husk samples and tab. 2 shows the corresponding ash compositions.

Exergy of rice husk

The statistical method proposed by Szargut *et al*. [15] can be used for calculating the exergy of rice husk:

$$ex \quad \beta(\text{LHV} \quad \eta_w h_w) \quad 9683\eta_s \quad ex_{ash}\eta_{ash} \quad ex_w \eta_w \tag{1}$$

where ex [kJkg^{-1}] is the exergy of rice husk on wet basis, β – the correlation factor for rice husk, h_w – the evaporation enthalpy of moisture (= 2442 kJ/kg, [15]), η_w [%] – the moisture content of rice husk, η_S [%] – the weight percentage of sulfur on wet basis, η_{ash} [%] – the weight percentage of ash on wet basis, ex_{ash} [kJkg^{-1}] – the exergy of ash, ex_w – the exergy of water (= 900 kJkmol^{-1}, [16]), and LHV [kJkg^{-1}] – the lower heating value of rice husk on wet basis

Equation (1) can be reorganized to:

$$ex \quad \beta\text{LHV} \quad \eta_w(\beta h_w \quad ex_w) \quad 9683\eta_s \quad ex_{ash}\eta_{ash} \tag{2}$$

The first, second, third, and fourth terms on the right side of eq. (2) are defined in this study as LHV related exergy, moisture related exergy, S related exergy, and ash related exergy, respectively. The ash related exergy, $ex_{ash}\eta_{ash}$, can be calculated from the chemical exergy of ash components through a linear mixing method [13]:

$$ex_{ash}\eta_{ash} \quad \Sigma ex_{ash \quad i} m_{ash \quad i} \tag{3}$$

where $ex_{ash\text{-}i}$ [kJmol^{-1}] is the exergy of ash component i, $m_{ash\text{-}i}$ [molkg^{-1}] – the mass of ash component i

Table 1. Moisture contents, ash contents, element contents, and HV of rice husks on wet basis [14]

No.	Origin	Approximate analysis [%]		Ultimate analysis [%]					HV [MJkg^{-1}]
		Moisture	Ash	C	H	O	N	S	
1	N	0	20.26	38.83	4.75	35.47	0.52	0.05	H: 15.84
2	Japan	0	17.10	40.70	5.40	36.20	0.60	0.12	N
3	Japan	0	22.00	37.20	4.90	34.80	0.40	0.70	N
4	Japan	0	12.70	41.10	5.40	39.70	0.40	0.70	N
5	Japan	0	18.60	37.80	4.90	37.60	0.40	0.70	N
6	Japan	0	17.10	35.20	4.60	42.10	0.40	0.60	N
7	Japan	0	15.00	41.20	5.30	37.40	0.40	0.70	N
8	N	0	18.50	49.30^{b}	6.10^{b}	43.60^{b}	0.80^{b}	0.08^{b}	N
9	China	0	15.90	37.62	4.91	40.92	0.53	0.12	N
10	China	0	18.16	38.45	5.08	37.83	0.15	0.23	L: 14.49
11	Spain	1.10	12.90	42.00^{a}	5.40^{a}	39.30^{a}	0.40^{a}	0.00	H: 16.80^{a}
12	N	5.73	10.55	38.82	5.73	38.39	0.66	0.12	L: 13.85
13	N	6.70	13.00^{a}	39.30^{a}	5.70^{a}	41.10^{a}	0.90^{a}	0.00	N
14	China	6.73	17.09	50.47^{b}	6.85^{b}	42.09^{b}	0.59^{b}	0.00	N
15	Spain	7.27	13.70	26.69^{b}	2.88^{b}	70.05^{b}	0.21^{b}	0.17^{b}	H: 15.90^{a}
16	Canada	8.68	17.17	38.45	4.55	30.78	0.37	0.02	L: 13.24
17	Canada	9.00	22.39	35.22	4.28	28.67	0.46	0.01	L: 13.40
18	Canada	9.08	21.28	34.19	4.93	30.19	0.35	0.03	L: 14.22
19	Indian	9.20	25.40^{a}	34.70^{a}	5.00^{a}	34.50^{a}	0.20^{a}	0.05^{a}	L: 11.86
20	Spain	9.37	8.93	43.01^{a}	5.80^{a}	40.61^{a}	0.73^{a}	0.00	N
21	N	9.40	12.80^{a}	42.30^{a}	6.10^{a}	37.50^{a}	1.10^{a}	0.04^{a}	L: 15.00
22	Finland	9.40	19.70^{a}	40.10^{b}	4.70^{b}	54.50^{b}	0.50^{b}	0.05^{b}	L: 15.50^{a}
23	Portugal	9.40	10.50	40.70	6.00	32.90	0.50	0.00	L: 14.40
24	China	9.68	15.57	37.24	5.07	31.56	0.45	0.43	L: 14.49
25	Thailand	9.80	20.50	37.90^{b}	6.30^{b}	55.30^{b}	0.40^{b}	0.10^{b}	N
26	India	9.80	17.40^{a}	39.80^{a}	5.70^{a}	36.40^{a}	0.50^{a}	0.20^{a}	H: 15.50^{a}
27	China	10.07	15.61	36.73^{a}	4.13^{a}	41.30^{a}	0.41^{a}	0.07^{a}	H: 14.76^{a}
28	Canada	10.16	16.35	38.27	4.58	30.19	0.46	0.02	L: 14.12
29	Canada	10.20	16.79	37.99	4.45	30.17	0.41	0.01	L: 14.60
30	Thailand	10.30	14.00	38.00	4.55	32.40	0.69	0.06	H: 14.98
31	Canada	10.44	13.70	39.85	4.94	31.53	0.41	0.02	L: 16.20
32	Turkey	11.20	20.60	39.60^{b}	6.00^{b}	53.70^{b}	0.70^{b}	0.00	H: 13.40^{a}

N – indicates not detailed or not known, H – indicates high, L – indicates low, a – dry basis, b – dry ash-free basis

Table 2. Mineral oxidizes of ashes (%, [14])

No.	Origin	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	SO_3	SiO_2	TiO_2
1	N	0.78	3.21	0.14	3.71	0.01		0.21	0.43	0.72	91.42	0.02
2	Japan		1.60		5.30				0.60		91.10	
3	Japan		1.20		4.30				1.10		91.50	
4	Japan		2.50		5.80				1.00		88.90	
5	Japan		1.70		6.60				1.00		89.10	
6	Japan		1.50		4.40				1.40		91.20	
7	Japan		2.00		8.00				1.10		86.80	
8	N	1.04	1.40	0.41	4.16	0.49	0.27	0.23	0.60	1.31	89.86	0.02
9	China[a]	0.43	2.25	0.13	3.89	0.74	0.01	0.21	0.64	0.47	6.89	0.03
10	China	1.27	0.45	0.56	0.62	0.19		0.12	1.49		94.80	0.00
11	Spain	0.52	0.23	0.11	0.38	0.11	0.01	0.10	0.08		98.02	0.02
12	N[a]	0.01	0.07				0.01		0.06	0.03	10.37	0.00
13	N	0.30	2.80	0.20	3.70	1.30			1.60	0.80	88.20	0.00
14	China	0.91	1.15	0.12	4.68	0.47		1.78	0.93		87.83	0.04
15	Spain	1.30	1.80	3.30	4.90	1.10	0.3	0.40	1.70		88.20	0.00
16	Canada	0.11	0.59	0.10	2.30	0.41		0.23	0.57	0.88	94.00	0.04
17	Canada	0.09	0.34	0.09	2.00	0.30		0.03	0.60	1.12	90.00	0.06
18	Canada	0.05	0.48	0.09	2.10	0.44		0.08	0.59	0.10	96.00	0.04
19	Indian	0.56	0.81	0.48	1.03	0.05	0.08	0.22	0.44		96.26	0.07
20	Spain		1.37		4.02	1.06		0.31			89.81	
21	N	0.00	1.30	0.10	5.40	0.80		0.20	3.70		87.70	0.00
22	Finland	0.10	0.60	0.10	1.90	0.30	0.1	0.01	0.60		95.90	0.01
23	Portugal	0.30	2.80	0.20	3.70	1.30		0.70	1.60	0.80	88.20	0.00
24	China	1.23	1.57	2.46	3.50	0.76		2.05	2.62		83.15	0.78
25	Thailand	0.06	1.88	0.23	0.58	0.96		0.39			94.60	
26	India[a]	0.26	0.21	0.08	0.09	0.18		0.05	0.18		16.30	0.01
27	China	0.16	0.56	0.08	2.44	0.62	0.15	0.10	1.17		94.71	0.00
28	Canada	0.13	0.33	0.16	1.80	0.30		0.08	0.03	0.11	97.00	0.02
29	Canada	0.13	0.45	0.13	2.80	0.45		0.23	0.89	1.10	90.00	0.05
30	Thailand	0.17	0.49	0.22	2.68	0.34		0.03	0.54	0.34	90.30	0.01
31	Canada	0.25	2.00	0.27	2.50	0.40		0.09	1.20	1.08	92.00	0.04
32	Turkey	0.30	2.80	0.20	3.70	1.30			1.60	0.80	88.20	0.00

N – indicates not detailed or not known; a – of biomass

Szargut *et al*. [15] also gave the following equations for obtaining the correlation factor:

$$\beta \quad 1.0437 \quad 0.0140\frac{H}{C} \quad 0.0968\frac{O}{C} \quad 0.0467\frac{N}{C} \qquad (O/C \quad 0.5) \tag{4}$$

$$\beta \quad \frac{1.044 \quad 0.0160\frac{H}{C} \quad 0.3493\frac{O}{C} \;\; 1 \quad 0.0531\frac{H}{C} \quad 0.04931\frac{N}{C}}{1 \quad 0.41241\frac{O}{C}} \qquad (O/C \quad 2) \tag{5}$$

where C is the number of carbon in the molecular formula of rice husk, H – the number of hydrogen in the molecular formula of rice husk, O – the number of oxygen in the molecular formula of rice husk, and N – the number of nitrogen in the molecular formula of rice husk.

The HHV of rice husk can be measured directly, and the LHV can then be calculated through the following eq. [15]:

$$\text{HHV} \quad \text{LHV} \quad 21.978\eta_{\text{H}} \tag{6}$$

where HHV [MJkg^{-1}] is the higher heating value of rice husk, LHV [MJkg^{-1}] – the lower heating value of rice husk, ηH [%] – the weight percentage of hydrogen in rice husk.

If the HHV or LHV of the rice husk sample is not reported, the following equation can be used to estimate the HHV of the rice husk sample [17, 18]:

$$\text{HHV} \quad 0.3491\eta_C \quad 1.1783\eta_{\text{H}} \quad 0.1005\eta_{\text{S}} \quad 0.1034\eta_{\text{O}} \quad 0.0151\eta_{\text{N}} \quad 0.0211\eta_{\text{ash}} \tag{7}$$

where HHV [MJkg^{-1}] is the higher heating value of rice husk on dry basis, η_{C} [%] – the weight percentage of carbon in rice husk on dry basis, η_{H} [%] – the weight percentage of hydrogen in rice husk on dry basis, η_{S} [%] – the weight percentage of sulfur in rice husk on dry basis, η_{O} [%] – the weight percentage of oxygen in rice husk on dry basis, η_{N} [%] – the weight percentage of nitrogen in rice husk on dry basis, η_{ash} [%] – the weight percentage of ash in rice husk on dry basis.

Results and discussion

Moisture related exergy of rice husk

Figure 1 shows the moisture related exergy values for the 32 rice husk samples (tabs. 1 and 2). The moisture related exergy values are in the range of 0-327.93 kJ/kg. Zhang *et al.* [10-12] stated that the moisture related exergy of a fuel is proportional to the moisture content of the fuel. The results that the first ten rice husk samples have the lowest moisture related exergy values (0 kJ/kg) whereas the last rice husk sample (No. 32) shows the highest moisture related exergy value (327.93 kJ/kg) are due to the facts that the first ten rice husk samples have the lowest moisture content (0%) whereas the last rice husk sample has the highest moisture content (11.20%). However, the No. 15 rice husk sample has the eighteenth highest moisture content (7.27%) whereas it shows the second highest moisture related exergy value (315.07 kJ/kg). This is because as it was defined in eq. (2) that the moisture related exergy of rice husk is not only determined by the moisture content but also the correlation factor. It is observed that the No. 15 rice husk sample has the highest correlation factor (1.754) than all the other rice husk samples (1.119-1.258), contributing significantly to its second highest moisture related exergy value (315.07 kJ/kg).

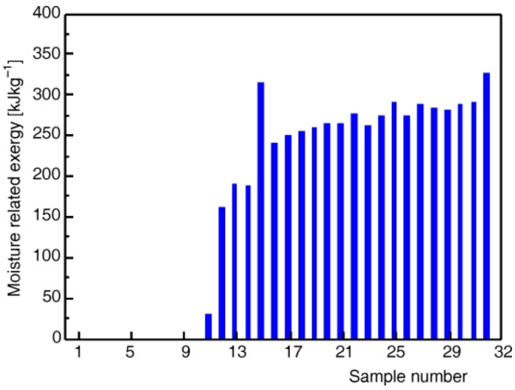

Figure 1. Moisture related exergy values

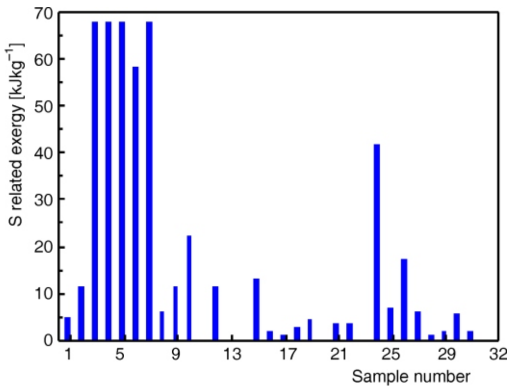

Figure 2. The S related exergy values

The S related exergy of rice husk

Figure 2 shows the S related exergy values for the 32 rice husk samples. The S related exergy values are in the range of 0-67.78 kJ/kg. Zhang *et al*. [3, 9-12] stated that the S related exergy value of fuel is directly determined by the S content of the fuel, and it is shown in eq. (2) that the S related exergy of a fuel is proportional to the S content of the fuel. The results that the No. 11, No. 13, No. 14, No. 20, No. 23, and No. 32 rice husk samples have the lowest S related exergy values (0 kJ/kg) whereas the No. 3, No. 4, No. 5, and No. 7 rice husk samples show the highest S related exergy values (67.78 kJ/kg) are due to the lowest S content (0%) and the highest S content (0.70%), respectively.

Ash related exergy of rice husk

Figure 3 shows the ash related exergy values for the 32 rice husk samples. The ash related exergy values are in the range of 17.88-341.03 kJ/kg. Zhang *et al*. [9-11] stated that the ash related exergy of a fuel is proportional to the ash content of the fuel. However, it is observed that the No.12 rice husk sample has the lowest ash related exergy value (17.88 kJ/kg) whereas it has the second lowest ash content (10.55%). The No. 9 rice husk sample has the highest ash related exergy value (341.03 kJ/kg) whereas it has the nineteenth lowest ash content (15.90%). This indicates that the ash related exergy of rice husk is not only determined by the ash content but also the ash compositions [3, 12].

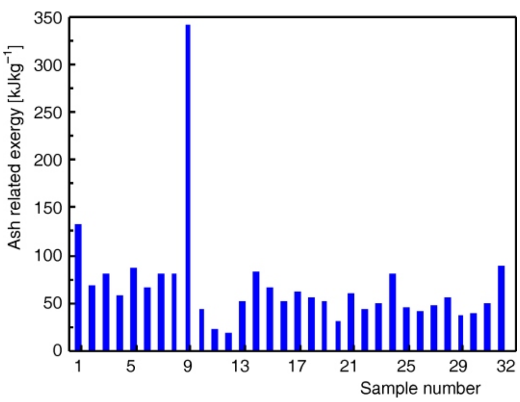

Figure 3. Ash related exergy values

The LHV related exergy of rice husk

Figure 4 shows the LHV related exergy values for the 32 rice husk samples. The LHV related exergy values are in the range of 10577.05-24675.63 kJ/kg. Zhang *et al*. [12] stated that the LHV related exergy of a fuel is proportional to the LHV of the fuel. The No. 25 rice husk sample has the lowest LHV related exergy value (10577.05 kJ/kg) is mainly due to its lowest LHV (calculated to be 8879.12 kJ/kg). However, the No. 15 rice husk sample has the highest LHV related exergy value (24675.63 kJ/kg) whereas it has the fifteenth highest LHV (calculated to be 14065.38 kJ/kg). As it was defined in eq. (2) that LHV related exergy value is also determined by the correlation factor. The No. 15 rice husk sample has the highest β value (=1.754) among all the rice husks (1.118-1.754), mainly contributing to the highest LHV related exergy value (24675.63 kJ/kg).

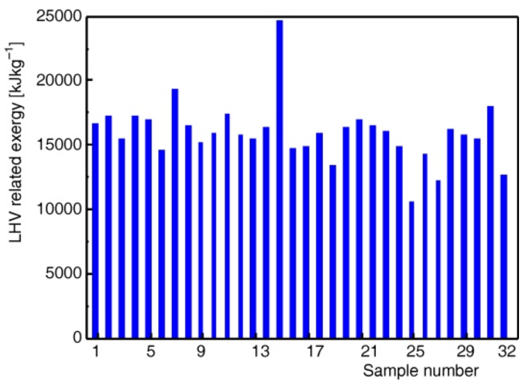

Figure 4. The LHV related exergy values

Exergy of rice husk

Figure 5 shows the exergy values of the 32 rice husk samples. The exergy values are in the range of 10918.01-25070.43 kJ/kg. Nilsson [19] and Zhang *et al*. [3, 9-11] stated that the exergy of a fuel is proportional to the LHV of the fuel. The No. 25 rice husk sample has the lowest exergy value (10918.01 kJ/kg) is mainly due to its lowest LHV (calculated to be 8879.12 kJ/kg). However, the No. 15 rice husk sample has the highest exergy value (25070.43 kJ/kg) whereas it has he fifteenth highest LHV (calculated to be 14065.38 kJ/kg). Zhang *et al*. [6, 20] stated that the exergy of a fuel is proportional to its correlation factor β. The No. 15 rice husk sample has the highest β value (=1.754), mainly contributing to the result that it has the highest exergy value (25070.43 kJ/kg). The results that the No. 25 rice husk sample has the lowest exergy value (10918.01 kJ/kg) whereas the No. 15 rice husk sample has the highest exergy value (25070.43 kJ/kg) are similar to the results that the No. 25 rice husk sample has the lowest LHV related exergy value (10577.05 kJ/kg) whereas the No. 15 rice husk sample has the highest LHV related exergy value (24675.63 kJ/kg). This is because the exergy value of rice husk is mainly determined by the LHV related exergy value of rice husk [12].

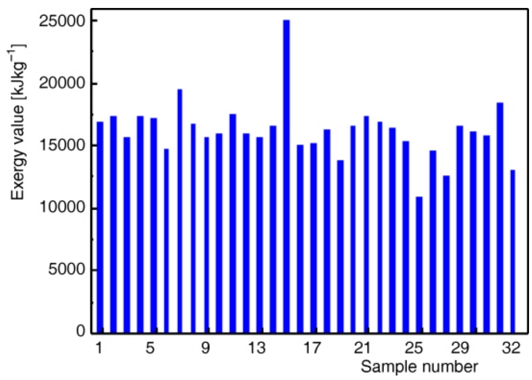

Figure 5. Exergy values of rice husks

Exergy distribution of rice husk

The percentages of moisture related exergy for the 32 rice husk samples are shown in fig. 6. The percentages of moisture related exergy are in the range of 0-2.66%. The first ten rice husk samples have the lowest percentages of moisture related exergy (0%) are due to the facts that they have the lowest moisture related exergy values (0 kJ/kg, in fig. 1). However, the No. 25 rice husk has the highest percentage of moisture related exergy (2.66%) whereas it has the fourth highest moisture related exergy value (289.95 kJ/kg, in fig. 1). This is due to the fact that the No. 25 rice husk has the fourth highest moisture related exergy value (289.95 kJ/kg, in fig. 1) and the lowest exergy value (10918.01 kJ/kg, in fig. 5) [3, 11].

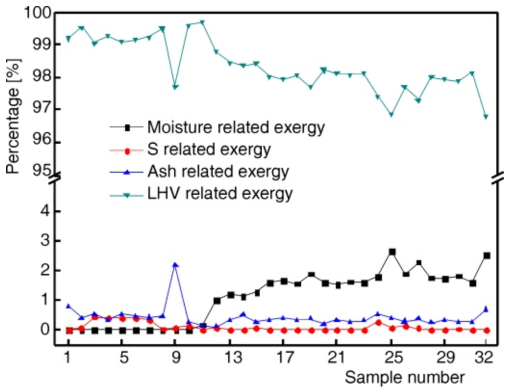

Figure 6. Exergy distribution of rice husk

The percentages of *S* related exergy for the 32 rice husk samples are in the range of 0-0.43%. The results that the No. 11, No. 13, No. 14, No. 20, No. 23, and No. 32 rice husk samples have the lowest percentages of S related exergy (0%) whereas the No. 3 rice husk sample shows the highest percentage of S related exergy (0.43%) are due to the facts that the No. 11, No. 13, No. 14, No. 20, No. 23, and No. 32 rice husk samples have the lowest S related exergy values (0 kJ/kg) whereas the No. 3 rice husk sample shows the highest moisture related exergy value (67.78 kJ/kg).

The percentages of ash related exergy for the rice husks are in the range of 0.11-2.19%. The results that the No. 12 rice husk sample has the lowest percentage of ash related exergy (0.11%) whereas the No. 9 rice husk sample has the highest percentage of ash related exergy (2.19%) are due to the facts that the No. 12 rice husk sample has the lowest ash related exergy value (17.88 kJ/kg) whereas the No. 9 rice husk sample has the highest ash related exergy value (341.03 kJ/kg).

The percentages of LHV related exergy for the 32 rice husk samples are in the range of 96.81-99.70%. The No. 32 rice husk sample has the lowest percentage of LHV related exergy (96.81%) is due to the fact that it has the third lowest LHV related exergy value (12642.55 kJ/kg, in fig. 4) and the third lowest exergy value (13059.54 kJ/kg, in fig. 5). The No. 11 rice husk sample has the highest percentage of LHV related exergy (99.70%) is due to the fact that it has the fourth highest LHV related exergy value (17438.27 kJ/kg, in fig. 4) and the fourth highest exergy value (17491.07 kJ/kg, in fig. 5).

It was observed in this study that the LHV related exergy contributes the most (96.81-99.70%) to the exergy of rice husk (10918.01-19445.76 kJ/kg), followed by the moisture related exergy (0-2.66%), ash related exergy (0.35-1.29%), and S related exergy (0-0.43%).

Conclusions

The moisture related exergy, S related exergy, ash related exergy, and LHV related exergy are in the ranges of 0-327.93, 0-67.78, 17.88-131.97, and 10577.05-19297.54 kJ/kg for the rice husks.

The exergy values are in the range of 10918.01-19445.76 kJ/kg for the rice husks, and they are mainly contributed by the LHV related exergy (96.81-99.70%), followed by the moisture related exergy (0-2.66%), ash related exergy (0-0.43%), and S related exergy (0.11-0.78%).

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