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ENERGY AND EXERGY ANALYSIS OF RICE STRAW GASIFICATION

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***Abstract*— In this study, energy and exergy analyzes were performed in the gasification of rice straw pellets prepared in 5 different blends: PRF (reference sample with no additives), PVA3 (rice straw + 3% PVA), PML5 (rice straw + 5% molasses), PC5 (rice straw + 5% coal dust), and PC15 (rice straw + 15% coal dust). The average mass flow rates was measured in the gasification process. The tar and gas flow rates varied between 5.30g/s and 5.70g/s, 0.063g/s and 0.069g/s and between 0.424mol/s and 0.464mol/s, respectively. The heating value (LHV) of the pellets ranged from 12.45MJ/kg to 12.93MJ/kg. The calorific values of the obtained syngas samples were between 3885.5MJ/Nm3 and 4427.7MJ/Nm3. The energy efficiency of the pellet samples in gasification ranged from 53.44% to 58.01% and exergy efficiency varied from 49.19% to 53.48%. The lowest irreversibility value in the gasification process was 36.74kW in PC5 pellet, the highest irreversibility value was 44.21kW in PRF pellet. As a result of the thermodynamic analysis of the pellet samples in gasification, it was concluded that there is no need to add any additives in the pelletization of the rice straw.**

***Keywords*— irreversibility, biomass blends, exergy analysis, rice straw, gasification.**

I. INTRODUCTION

Biomass gasification is the most reliable and promising method nowadays to generate electricity because this process provides a sustainable and affordable alternative to fossil fuel-based process plants at small and medium levels (Kayisoglu *et al.*, 2016; Khan, 2015, Parthasarathy *et al.*, 2021). Gasification is a thermochemical process that can convert the biomass in a partial oxidation process at elevated temperature into syngas which contains such as H_2, CO, CH_4, and CO_2 gases for thermal and power applications (Manatura *et al.*, 2017; Rezaiyan and Cheremisinoff, 2005). Gasification reactions can be defined as a combination of pyrolysis reactions, followed by high temperature tar and coal reactions, followed by other primary gaseous reactions to obtain simple gas products (Parthasarathy *et al.*, 2021). In the gasification process, the air is generally used due to its low cost. When the air is used in the gasification process of the biomass, a syngas with a heating value of 4-7MJ/Nm^3 is obtained depending on the raw material. The higher heating value (12-28MJ/Nm^3) can be obtained by using pure O_2, but the cost of syngas production increases due to the cost of O_2 production (Manatura *et al.*, 2017).

The potential use of existing natural gas infrastructure as an energy carrier is considered as the major advantage. Syngas can be used as a green alternative to natural gas in households and fuel in transportation. Currently, several research institutes, including the Energy Research Center of the Netherlands (ECN), Center for Solar Energy and Hydrogen Research (ZSW) Baden Würtenberg, and Paul-Sherrer Institute (PSI) in Switzerland, are working on developing biomass-to-SNG technology (Vitasari *et al.*, 2011).

Experimental and theoretical studies were conducted (Singh *et al.*, 2015) on a 50kWth downdraft gasifier with biomass blends of various quantities and qualities available in rural areas, in which the effective utilization of biomass materials as blends can meet the rural energy demand have shown by the experimental and theoretical studies. Xiang *et al.* (2021) attempted to find a gasifier that is most suitable for the gasification of village-level solid wastes through the exergy analysis method. The results showed that the updraft fixed bed gasifier had higher exergy efficiency, and the gas produced by the downdraft fixed bed gasifier has a higher heating value.

Rice is one of the most important cereals consumed in the world after wheat. In recent years, rice production has increased in Turkey. The straws remaining on the surface of the field after the rice harvest is a problem for farmers. The silica content of rice straw is higher than other cereals. Therefore, it is difficult to break down the rice straws and very hard to decompose. Therefore, farmers are banned, although the rice straws remaining in the field are burned every year. This causes loss of energy and adverse environmental conditions. Evaluations of rice straws with the proper techniques and different methods have made a significant contribution to the country's economy and also will help reduce the impact of adverse environmental conditions. The gasification process of rice straw is one of these methods. The gasification of rice straw will be able to gain 75x109 MJ of energy in our country every year (Kayisoglu et al., 2016).

The lack of consensus on the evaluation of the performance of different stages of energy systems is one of the difficulties of measuring energy efficiency. In practice, energy efficiency has various performance indicators, such as thermodynamics or economics. Based on the second law (exergy analysis), thermodynamic indicators of

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process performance are commonly accepted as the most natural way to measure the performance of different processes, including but not limited to energy technology, chemical engineering, transportation, agriculture, etc. (Vitasari *et al*., 2011). Nowadays, energy analysis and exergy analysis have been integrated and applied to thermal performance evaluation of various gasification processes by many researchers. The exergy analysis of hydrogen production from biomass steam gasification was reviewed by Zhang *et al*. (2019), but they did not distinguish the type of gasifiers. The results indicated that the exergy efficiency initially increased and was finally decreased by both the steam to biomass ratio and steam flow rate. Mehrpooya *et al*. (2018) investigated 23 different kinds of biomass sources and analyzed the modeling and simulation of the biomass gasification process. The results showed that the highest (about 90.0%) exergy efficiency is the drying stage in all cases. Echegaray *et al*. (2016) investigated the gasification of peach pits exergetic efficiency. They utilized that thermodynamic indicators of process performance based on the second law (exergy analysis) in order to evaluate the effect of different operational parameters (temperature, supply air/stoichiometric air, supply steam/carbon ratio and moisture feed). The experiments shown that exergetic efficiency of the gasification process were decreases when the all considered operational parameters increase. Rodriguez *et al*. (2018) presented studies about the gasification of the lignocellulosic winery wastes in fluidized bed to obtain energy. The exergetic improvement potential (IP) and sustainability index (SI) variations with different operational variables were analyzed based on the exergy analysis. Gonzalez *et al*. (2020) worked on the exergy balance of an integrated biomass gasification power plant. The total destroyed exergy of biomass gasification and power generation processes showed a higher contribution and reaching values of 42.4% and 45.5% of the total destroyed exergy. Some researchers have also investigated in terms of the waste of gasification reactions. Echegaray *et al.* (2019) presents a thermodynamic model for describing the five wastes gasification behavior with char and tar formation. They considered that influence of variables process on the exergetic efficiency and sustainability index and declareted that the main problem for biomass gasification process is the tar often do to it produces soiling and equipment erosion, and an effective energy loss between 5 and 15%.

In this study, rice straw pellets prepared with different additives have been gasified with a micro-scale gasifier which was developed in our department. The main purpose of this paper is to compare rice straw pellets for their gasification efficiency using energy and exergy analysis methods.

II. EXPERIMENTAL SETUP

A. The Gasifier System

Experimental setup of the gasifier system includes adiabatic downdraft gasifier reactor, cyclone, gas cooling unit and condensation tank, vacuum pump and its service water tank, flare unit, measurement and control components, gas chromatography device (GC), and its components. The schematic view of the gasification unit is shown in Fig. 1. The system has a fixed bed reactor with an upper air inlet. The capacity of the reactor is 25kg of biomass. The gasifier reactor is a throatless type and the reactor diameter is 350mm. The height of the main reactor body is 840mm and is made up of stainless steel (AISI 310) material. Inner walls of the body have a refractive layer (Hycast 70) that is applied as 50mm. 1.5kW powered vacuum pump was used to create a gas flow in the line. Ash removal helix and gas cooler fan have 0.55kW powered motors.

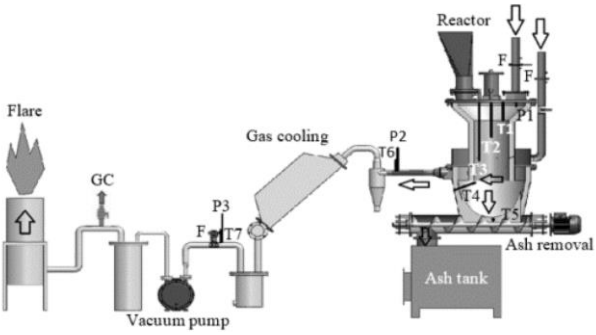

Figure 1: Schematic view of the gasification system.

Measurements were made from 7 points for temperature, 3 points for pressure, 2 points for flow rates. K-type thermocouples were used for temperature measurements. Air and gas flow rates were measured by orifice flow meters. Experimental data were collected and monitored by a Programmable Logic Controller (PLC) based moduler system. The control cabinet includes a 24VDC power supply, a 7-inch color touch-sensitive human-machine interface (HMI), a PLC CPU module, PLC expansion modules, relays and contactors. An USB flash drive plugged into HMI is used to save data. GC was used for the analysis of syngas produced in the gasifier operated at 0.2 Er ratio. The position of the GS was shown in Fig. 1.

B. Characteristics of Rice Straw Pellets

In this study, rice straws were chopped and blended with different additive materials like PVA, molasses, and coal dust. Five different samples were prepared and evaluated for the study. The proximate and ultimate analyses of the rice straw pellets were done in TUBITAK MAM Institute. The compositions of rice straw pellets used in this re-search are given in Table 1.

C. Syngas Analysis

The syngas sample with the help of a pipe from the main gas output line was taken and analyzed with Agilent 7890B GC model gas chromatography device. The device gives volumetric percentages weight of gas components (H_2, CO, CH_4, CO_2, and N_2) contained in the syngas.

III. ENERGY AND EXERGY ANALYSIS

The schematic view of the gasification process using rice straw pellets is shown in Fig. 2 for evaluation energy and exergy analysis. Inputs of the system are biomass, air, ash screw, cooling fan, and vacuum pump and outputs are

Table 1. Composition of rice straw pellets

Code	Pellet Composition
PRF	No additive, reference pellet
PVA3	Rice straw + PVA %3
PML5	Rice straw + Molasses %5
PC5	Rice straw + Coal dust %5
PC15	Rice straw + Coal dust %15

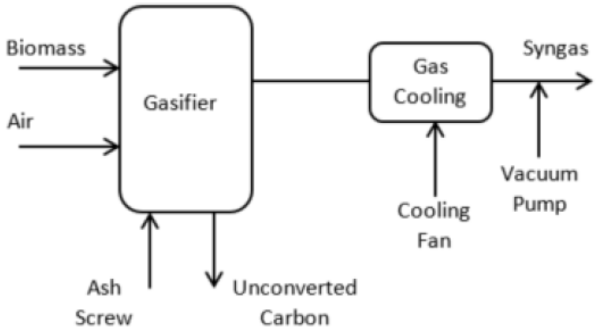

Figure 2: Schematic view of the inlet and outlet flows of the gasification system.

syngas, tar, ash, and char. The syngas leaving the reactor is subjected to a cooling process. During the gasification process, the temperature of the gasifier was kept at 800°C and ER was adjusted as 0.2. In the gasification of the rice straw, when the core region temperature exceeds 800°C, vitrification and agglomeration occur in the reactor (Tuğ, 2016).

Equivalence Ratio (ER):

The important parameter in gasification is the equivalence ratio (ER), which is defined as the actual air-fuel ratio to the stoichiometric air-fuel ratio (Manatura *et al.*, 2017):

$$ER = \frac{(\dot{m}_{air}/\dot{m}_{biomass})_{actual}}{(\dot{m}_{air}/\dot{m}_{biomass})_{stoichiometric}} = \frac{AF_{actual}}{AF_{stoichiometric}}, \quad (1)$$

where AF_{actual} and $AF_{stoichiometric}$ are actual air-fuel ratio and stoichiometric air-fuel ratio, respectively.

Energy Balance:

The energy balance of the gasifier can be written as (Manatura *et al.*, 2017):

$$\dot{Q}_{biomass} + \dot{Q}_{electricity} = \dot{Q}_{syngas} + \dot{Q}_{tar} + \dot{Q}_{ash} + \dot{Q}_{char} + \dot{Q}_{loss}, \quad (2)$$

where $\dot{Q}_{biomass}$, $\dot{Q}_{electricity}$, $\dot{Q}_{syngas}$, $\dot{Q}_{tar}$, $\dot{Q}_{ash}$, $\dot{Q}_{char}$ and $\dot{Q}_{loss}$ represent the energy flow rate of biomass, electricity, syngas, tar, ash, char, and loss part in kW, respectively. Electricity is the sum of the installed power of the electric motors that operate the vacuum pump, cooling fan, and ash screw used in the gasification system. $\dot{Q}_{electricity}$=2.60kW in the gasification system.

Total energy flow is;

$$\dot{Q} = \dot{Q}^{ki} + \dot{Q}^{po} + \dot{Q}^{ph} + \dot{Q}^{ch} \quad (3)$$

where $\dot{Q}^{ki}$, $\dot{Q}^{po}$, $\dot{Q}^{ph}$ and $\dot{Q}^{ch}$ represent the kinetic, potential, physical, and chemical energy rates in kW, respectively.

Neglecting $\dot{Q}^{ki}$ and $\dot{Q}^{po}$ Eq. (3) reduces to:

$$\dot{Q} = \dot{Q}^{ph} + \dot{Q}^{ch} \quad (4)$$

The physical (sensitive) energy is

$$\dot{Q}^{ph} = \dot{m}\Delta h = \dot{m}\int_{T_0}^{T} C_p dT \quad (5)$$

where; $\dot{m}$, Δh and C_p are gas flow rate in kmol/s, Enthalpy change in kJ/kmol, and constant pressure specific heat in kJ/kmolK, respectively.

Equaion (5) is suitable for air since it is heated before entering the gasifier. In this study, the air was not preheated, thus $\dot{Q}_{ash} = 0$.

Constant pressure specific heat (Cp) for each gas component can be calculated equations that are given in Table 2.

For the biomass and tar, their chemical energy can be evaluated as:

$$\dot{Q}_{b,t}^{ch} = \dot{m}_{b,t} LHV_{b,t} \quad (6)$$

where $LHV_{b,t}$ is the heating value of biomass and tar in kJ/kg and $\dot{m}_{b,t}$ is the mass flow rate in kg/s.

The LHV of syngas in kJ kmol^{-1} is (Manatura *et al.*, 2017):

$$LHV_{syngas} = 282993x_{CO} + 802303x_{CH_4} + 241827x_{H_2} \quad (7)$$

where x_{CO}, x_{CH_4} and x_{H_2} represent a molar fraction of these gases in syngas, respectively.

The energy efficiency of the gasification can be calculated by the following equation

$$\eta_{En} = \frac{\dot{Q}_{syngas}}{\dot{Q}_{biomass} + \dot{Q}_{electricity}}. \quad (8)$$

Exergy analysis:

Exergy analyzes of biomass gasification using rice straw pellets as a feedstock were performed by the method applied by Szargut *et al.* (1988) and was evaluated with the following assumptions (Lewandowski and Kicherer, 1996):

- The system is operated at a steady state.
- Potential and kinetic energies are negligible.
- Reference state (dead state) is set as $T_0 = 298.15$K and P_0 =1atm.
- Ash residue that remains behind the gasification process is negligible.
- Syngas is assumed to be an ideal gas.

The exergy balance of the gasification can be defined as:

$$\dot{E}x_{biomass} + \dot{E}x_{electricity} = \dot{E}x_{syngas} + \dot{E}x_{tar} + \dot{I}_{gassifier}, \quad (9)$$

where $\dot{E}x_{biomass}$, $\dot{E}x_{electricity}$, $\dot{E}x_{syngas}$ and $\dot{E}x_{tar}$ represent the exergy of the biomass, vacuum pump, cooling fan, syngas, tar in kW, respectively. $\dot{I}_{gassifier}$ is the irreversibility of the gasifier.

Chemical exergy ($\dot{E}x^{ch}$) and physical exergy ($\dot{E}x^{ph}$) are the sum of exergy ($\dot{E}x$) of syngas.

$$\dot{E}x = \dot{E}x^{ch} + \dot{E}x^{ph} \quad (10)$$

Only chemical exergy was considered for biomass. The exergy of biomass can be defined as (Szargut *et al.*, 1988):

$$\dot{E}x_{biomass} = \dot{m}_{biomass}\beta LHV_{biomass}, \quad (11)$$

where $LHV_{biomass}$ and β represent the lower heating value in kJ/kg and quality of fuel, respectively. $\dot{m}_{biomass}$ is the mass flow rate of biomass in kg/s.

The quality of fuel (β) can be expressed as:

$$\beta = \frac{1.0414+0.0177(\mathrm{H/C})-0.3328(\mathrm{O/C})[1+0.0537(\mathrm{H/C})]}{1-0.4021(\mathrm{O/C})} \quad (12)$$

Table 2. Constant pressure specific heat ideal gas and temperature relations (Karamarkovic and Karamarkovic, 2010).

Gas	$\boldsymbol{Cp(kJ/kmolK)}$, $\theta = \boldsymbol{T(Kelvin)/100}$	Range, K	Max. Error, %
N_2	$Cp = 39.060 - 512.79\theta^{-1.5} + 1072.7\theta^{-2} - 820.4\theta^{-3}$	300-3500	0.43
O_2	Cp=37.432+0.20102$\theta^{1.5}$−178.57$\theta^{-1.5}$+236.884θ^{-2}	300-3500	0.30
H_2	Cp=56.505−702.74$\theta^{-0.75}$+1165.0θ^{-1}−560.70$\theta^{-1.5}$	300-3500	0.60
CO	Cp=69.145−0.704634$\theta^{0.75}$−200.77$\theta^{-0.5}$+176.76$\theta^{-0.75}$	300-3500	0.42
H_2O	Cp=143.05+183.54$\theta^{0.25}$−82.751$\theta^{0.5}$−3.6989 θ	300-3500	0.43
CO_2	Cp=−3.7357+30.529$\theta^{0.5}$−4.1034 θ +0.024198θ^{2}	300-3500	0.19
CH_4	Cp=−672.87+439.74$\theta^{0.25}$−24.8754$\theta^{0.75}$+323.88$\theta^{-0.5}$	300-3500	0.15

Table 3. Specific absolute entropies of the syngas components

Substance	$\boldsymbol{s_o\ (kJ/kmolK)}$
N_2	191.610
H_2	130.684
CO	197.653
CO_2	213.795
CH_4	186.256

where C, H, and O are the molar fraction of carbon, hydrogen, and oxygen, respectively.

The physical exergy of syngas is determined as:

$$\dot{E}x^{ph} = \dot{m}_{syngas} \sum_i y_i ex_i^{ph} \tag{13}$$

For each gas component, the specific physical exergy in kJ/kmol is defined as:

$$ex^{ph} = \left(h - h_0^f\right) - T_o\left(s - s_0\right) \tag{14}$$

where h and s are the specific enthalpies in kJ/kmol and entropy in kJ/kmolK at the state (pressure, P (kPa) and temperature, T (K)). Moreover, h_0^f and s_0 represent the specific enthalpy of formation and entropy at the reference state. When the temperature of the syngas is known, the $\left(h - h_0^f\right)$ can be determined for each gas component as below:

$$\left(h - h_0^f\right)_i = \int_{T_0}^{T} C_{p.i} dT \tag{15}$$

The entropy of each gas component in the syngas at the state condition can be calculated by:

$$s_i = s_{0,i} + \int_{T_0}^{T} C_{p.i}(dT/T) - R\ln(P_i/P_0) \tag{16}$$

where R is the universal gas constant and its value is 8.314kJ/kmolK.

Molar-specific absolute entropies of the components of the syngas at the reference state are given in Table 3.

The chemical exergy of syngas can be determined by the composition analysis of syngas and the flow rate. Its value is obtained from the following equation,

$$\dot{E}x^{ch} = \dot{m}_{syngas}\left(\sum_i y_i ex_i^{ch} + RT_0 \sum_i y_i \ln y_i\right) \tag{17}$$

where ex_i^{ch} represents the standard chemical exergy of the syngas compositions i that can be obtained from any thermodynamics book.

The exergy efficiency of the gasification can be calculated by the following equation:

$$\eta_{Ex} = \frac{\dot{E}x_{syngas}}{\dot{E}x_{biomass} + \dot{E}x_{electricity}}. \tag{18}$$

IV. RESULT AND DISCUSSION

Characterisation of samples:

Analysis results of pellet samples are displayed in Table 4 and Table 5. The LHV values of the pellet samples ranged from 12.45MJ/kg to 12.93MJ/kg, and the HHV values ranged from 13.53 to 13.98MJ/kg. LHV and HHV values are close to each other in all samples. Manatura *et al.* (2017) reported that in the rice husk pellets the LHV value was 14.17MJ/kg and the HHV value was 15.49MJ/kg. The heating value of the rice husk pellets is higher than the rice straw pellets. This is because the O/C ratios of the rice husk are lower than the rice straw. In their study, the O/C value of the rice husk pellets was reported as 0.92. In this study, O/C value of the rice straw pellets was around 0.87 on average (Table 3). The heating value of fuels decreases nearly linearly with increasing O concentration (Lewandowski and Kicherer, 1996).

Gasification:

The tests were performed in triplicate and the calculations were made according to the average of the results. The average mass flow rates measured in the gasification process are given in Table 6 for each pellet sample. The mass, tar and gas flow rates varied between 5.30g/s and 5.70g/s, 0.063g/s and 0.069g/s and between 0.424mol/s and 0.464mol/s, respectively. In general, the tar flow rate was about 1.1% of the biomass flow rate. Similar results were found in the process of gasification with rice husks by Manatura *et al.* (2017). It was explained that updraft gasifiers produce more “tar” than downdrafts while “tar” production of fluidized beds was in between them. An average value of about 50g-tar/Nm3-syngas “tar” was measured in raw producer gases from updraft gasifiers which are higher than in any other gasifier. It was reported that an average “tar” loading of about 10g-tar/Nm3-syngas was measured in fluidized beds and CFBs (Graham and Bain, 1993). In this study, the tar production was about 6.6g-tar/Nm3-syngas on average.

The specific heat, enthalpy change, and entropy values of each gas component calculated as a function of gas temperature and pressure of syngas after cooling are given in Table 7.

Table 4. Proximate analysis of pellet samples

Pellet Samples	Moisture (wt%)	Ash (wt%)	Volatile matter (wt%)	Fixed Carbon (wt%)	LHV (MJ/kg)	HHV (MJ/kg)
PRF	7.01	17.21	61.61	14.18	12.77	13.85
PVA3	7.38	17.62	61.09	13.92	12.71	13.78
PML5	6.84	17.03	61.09	14.97	12.78	13.84
PC5	8.94	17.86	58.38	14.83	12.45	13.53
PC15	8.39	19.16	56.55	15.91	12.93	13.98

Table 5. Ultimate analysis of pellet samples (wt%)

Pellet Samples	C	H	N	S	O	H/C	O/C
PRF	39.90	4.89	1.24	0.20	35.27	0.12	0.88
PVA3	39.42	4.95	1.32	0.7	35.12	0.13	0.89
PML5	39.10	5.05	1.69	0.18	35.71	0.13	0.91
PC5	39.37	4.80	1.60	0.24	34.38	0.12	0.87
PC15	40.16	4.79	1.50	0.32	32.32	0.12	0.80

Table 7. Specific heat, enthalpy changes, and entropies of syngas components

Syngas components	Syngas Temperature (K)	Syngas Pressure (kPa)	Cp (kJ/kmolK)	Δh (kJ/kmol)	So (kJ/kmolK)	S (kJ/kmolK)
N_2	338	99	29.19	1196.7	191.61	195.56
H_2	339	99	29.05	1190.9	130.68	134.62
CO	340	99	29.09	1192.8	197.65	201.59
CO_2	342	99	38.75	1588.8	213.80	218.98
CH_4	345	99	37.58	1540.7	186.26	191.29

Table 8. Molar fraction (% dry basis) and LHV of syngas

	H_2	CO	CH_4	CO_2	N_2	LHV (kJ/Nm^3)
PRF	16.8	12.5	2.9	15.5	52.3	4427.7
PVA3	17.1	13	2.4	15.7	51.8	4344.0
PML5	15.2	12.4	2.8	15.8	53.8	4206.5
PC5	15.3	12.3	2.4	16.5	53.5	4061.5
PC15	14.4	11.9	2.6	16.2	54.9	3985.5

Table 9. Energy balance of gasifier system in kW

	PRF	PVA3	PML5	PC5	PC15
Biomass	78.95	73.03	78.89	71.71	78.29
Electricity	2.60	2.60	2.60	2.60	2.60
TOTAL INPUT	81.55	75.63	81.49	74.31	80.89
Chemical energy of syngas	43.17	41.27	43.70	42.53	42.62
Physical energy of syngas	0.55	0.54	0.59	0.57	0.61
Tar	2.34	2.27	2.48	2.41	2.56
Other loss	35.48	31.56	34.71	28.79	35.11
Energy efficiency (%)	53.62	55.27	54.35	58.01	53.44

Table 6. Mass flow rate biomass, tar, and syngas

Pellet	Biomass (g/s)	Tar (g/s)	Syngas (mol/s)
PRF	5.70	0.065	0.435
PVA3	5.30	0.063	0.424
PML5	5.70	0.069	0.464
PC5	5.30	0.067	0.451
PC15	5.60	0.071	0.477

Table 10. β and chemical exergy values of rice straw pellets

Pellet	LHV (kJ/kg)	β (-)	Exch (kJ/kg)
PRF	12770	1.1589	14799
PVA3	12710	1.1611	14758
PML5	12780	1.1657	14898
PC5	12450	1.1574	14410
PC15	12930	1.1442	14795

The molar fraction and LHV of syngas for each pellet sample are shown in Table 8. LHV of syngas samples varied between 3985.5kJ/Nm^3 and 4427.7kJ/Nm^3. The heating value is related to the molar fraction of hydrogen and nitrogen in syngas. As the hydrogen ratio increases, the heating value of the syngas also increases (Kartal and Ozveren, 2020). Conversely, if the nitrogen ratio increases, the heating value of syngas decreases. This situation is evident in Table 8.

Energy and exergy analyzes:

The energy balances of gasification of rice straw pellets are given in Table 9. The total energy input to the system ranged from 74.31kW to 81.55kW. Energy efficiencies of gasification of pellet samples varied between 53.44% and 58.01%. Manatura *et al.* (2017) found that the energy efficiency of the rice husk gasification was about 44%. They have externally applied heat energy to heat the air during the gasification process. So the efficiency was lower than our values. In the process of gasification of biomass, energy efficiency can vary widely depending on the type of biomass and the gasification process (Rodriguez, 2016). The gasifier was operated at optimum 0.2 ER ratio, excluding distribution, heat losses or other losses that result from operational activities (Onabanjo *et al.*, 2016). The energy efficiency values of the gasification of pellet samples are close to each other.

The β and the exergy values of each pellet sample are displayed in Table 10. The β values changed between 1.1442 and 1.1657. Zhang *et al.* (2011) reported that β values for biomass changed between fuels in the range of 1.05-1.19. The beta values found in this study are within the specified limits. Manatura *et al.* (2017) also founded β value for the rice husk as 1.17. The β and the exergy values of the rice straw pellets were very close to each other in this study. There was no significant difference in the chemical exergy values of rice straw pellets. Ptasinski *et al.* (2007) expressed that the chemical exergy values of different biomass vary between 14760kJ/kg and 17129 kJ/kg. In this study, the chemical exergy values of rice straw pellets were close to the bottom of these limits (Table 10).

Table 11. Exergy balance of gasifier system in kW

	PRF	PVA3	PML5	PC5	PC15
Biomass	84.41	78.15	84.58	76.38	82.85
Electricity	2.60	2.60	2.60	2.60	2.60
TOTAL INPUT	87.01	80.75	87.18	78.98	85.45
Chemical exergy of syngas	42.79	40.84	43.38	42.23	42.37
Physical exergy of syngas	0.01	0.01	0.01	0.01	0.01
Tar	2.34	2.27	2.48	2.41	2.56
Irreversibility	44.21	39.91	43.78	36.74	43.07
Exergy efficiency (%)	49.19	50.58	49.78	53.48	49.59

Chemical exergy contained in the biomass is larger than its LHV and the chemical exergy contained in the product gas is smaller than its chemical energy. Ptasinski *et al*. (2007) explained larger chemical exergies than LHVs for biomass by the fact that polymers such as cellulose and hemicellulose are highly ordered structures, and work can be delivered if these are decomposed. Physical exergy values were very low in all samples. This is caused by the syngas which are subjected to cooling while leaving the system. However, even though there is no syngas cooling process, physical exergy is always smaller than chemical exergy. The reason is that the chemical exergy of the biomass is the main constituent of the total exergy and the contribution of physical exergy is much smaller. The solid biofuels with high oxygen content are regarded as high-quality fuels, for which a penalty is paid when decomposing them into small gaseous components. Also, the gas produced from solid biomass gasification has a lower temperature so that it contains less physical exergy (Zhang *et al*., 2011).

In pellet samples, total exergy efficiencies varied between 49.19% and 53.48%. In all samples, the efficiency of exergy was lower than energy efficiency. The same results have been seen in researches related to biomass gasification. Zhang *et al*. (2011) have found that the energy efficiencies of biomass gasification are between 52.38% (rice husk, ER= 0.25) and 77.41% (wood chip, ER = 0.38), while those 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). The exergy efficiencies of dry refinery sludge gasification are from 31.93% (ER=0.24) to 50.38% (ER=0.195). Energy and exergy efficiencies will be reduced by the increasing N_2 which has low energy, and exergy values (Ahmed *et al*., 2014). The use of air in the gasification process results in high nitrogen content in the syngas. If pure oxygen is used, the gasification efficiency will be higher. However, the cost of gasification will also increase.

Irreversibility values of syngas samples were between 36.74kW and 44.21kW. The lowest irreversibility was in PC5 with 36.74kW and the highest irreversibility was in PRF with 44.21kW. The largest internal exergy losses (irreversibilities), the separation of carbon dioxide from methane, and drying of waste biomass take place in the methanation section in the gasifier (Vitasari *et al.*, 2011). Although it is insufficient to compensate losses due to high moisture content and/or thermal losses, pre-heating air and/or bagasse may reduce irreversibility (Pellegrini and Oliveira, 2007).

V. CONCLUSIONS

In this study, the energy and exergy analysis of rice straw pellets in five different compositions was performed. Results of experiments showed that physical exergy values of syngas samples were very small due to the application of syngas cooling. In all pellet samples, energy efficiency was higher than exergy efficiency. However, there is no significant difference between them in terms of energy and exergy efficiency. For this reason, PVR pellet sample which does not have any additives can be recommended for rice straw gasification. Exergy analysis gives results concerning only thermodynamic efficiency. The total energy input to the system ranged from 74.31kW to 81.55kW. Energy efficiencies of gasification of pellet samples varied between 53.44% and 58.01%. The presented results in this research will be helpful in further process development of rice straw gasification. Because the gasification of rice straw has important technical problems. The high silicon content requires continuous control of the core region temperature in the reactor. However, in order to make a final judgment about process feasibility, it is also necessary to perform economic analysis and should be evaluated together with technical analysis.

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REFERENCES

Ahmed, R., Sinnathambi, C.M., Eldmerdash, U. and Subbarao, D. (2014) Thermodynamics analysis of refinery sludge gasification in adiabatic updraft gasifier. *The Scientific World Journal*. **2014,** ID 758137.

Echegaray, M., García, D.Z., Mazza, G. and Rodriguez, R. (2019) Air-steam gasification of five regional lignocellulosic wastes: exergetic evaluation. *Sustainable Energy Technologies and Assessments*. **31**, 115-123.

González, A.M., Jaén, R.L. and Lora, E.E.S. (2020) Thermodynamic assessment of the integrated gasification-power plant operating in the sawmill industry: An energy and exergy analysis. *Renewable Energy*. **147**,1151-1163.

Graham, R.G. and Bain, R. (1993) *Biomass Gasification: Hot-Gas Clean-Up.* International Energy Agency, Biomass Gasification Working Group. December 21, 44.

Karamarkovic, R. and Karamarkovic, V. (2010) Energy and exergy analysis of biomass gasification at different temperatures. *Energy*. **35**, 537–549.

Kartal, F. and Özveren, U. (2020) A deep learning approach for prediction of syngas lower heating value from CFB gasifier in Aspen plus®. *Energy*. **209**, 118457.

Kayisoglu, B., Tug, S., Dalmis, I.S., Aktas, T., Durgut, M.R. and Durgut, F.T. (2016) Evaluation of a Micro-Scale Rice Straw Gasification Costs. *International Journal of Engineering Research and Development*. **10**, 10-15.

Khan, A. (2015) Economic Feasibility of Biomass Gasification for Electricity Generation in Pakistan. *Global Journal of Science Frontier Research: E Interdiciplinary*. **15**, 19-23.

Lewandowski, I. and Kicherer, A. (1996) Combustion quality of biomass: practical relevance and experiments to modify the biomass quality of Miscanthus x giganteus. *European Journal of Agronomy*. **6**, 163-177.

Manatura, K., Lu, J.H., Wu, K.T. and Hsu, H.T. (2017) Exergy analysis on torrefied rice husk pellet in fluidized bed gasification. *Applied Thermal Engineering*. **111,** 1016-1024.

Mehrpooya, M., Khalili, M. and Sharifzadeh, M.M.M. (2018) Model development and energy and exergy analysis of the biomass gasification process (Based on the various biomass sources). *Renewable and Sustainable Energy Reviews*. **91**, 869-887.

Onabanjo, T., Patchigolla, K., Wagland, S. T., Fidalgo, B., Kolios, A., McAdam, E. and Cartmell, E. (2016) Energy recovery from human faeces via gasification: a thermodynamic equilibrium modelling approach. *Energy conversion and management*. **118**, 364-376.

Parthasarathy, P., Fernandez, A., Al-Ansaria, T., Mackey, H., Rodriguez, R. and McKay, G. (2021) Thermal degradation characteristics and gasification kinetics of camel manure using thermogravimetric analysis. Journal of Environmental Management. **287**, 112345.

Pellegrini, L.F. and Oliveira, S. (2007) Exergy analysis of sugarcane bagasse gasification. *Energy*. **32**, 314–327.

Ptasinski, K.J., Prins, M.J. and Pierik, A. (2007) Exergetic evaluation of biomass gasification. *Energy*. **32**, 568–574.

Rezaiyan, J. and Cheremisinoff, N.P. (2005) *Gasification Technologies: A Primer for Engineers and Scientists*. CRC Press.

Rodriguez, R. (2016) Exergy analysis of syngas production via biomass thermal gasification. International *Journal of Thermodynamics*. **19**, 178-184.

Rodriguez, R., Mazza, G., Fernandez, A., Saffe, A. and Echegaray, M. (2018) Prediction of the lignocellulosic winery wastes behavior during gasification process in fluidized bed: experimental and theoretical study. *Journal of environmental chemical engineering*. **6**, 5570-5579.

Singh, V.C.J., Sekhar, S.J. and Thyagarajan, K. (2015) Analytical and experimental studies on a 50 kwth downdraft gasifier with biomass blends available in the hilly regions of south India. *Lat. Am. Appl. Res*. **45**, 145-155.

Szargut, J., Morris, D.R. and Stewart, F.R. (1988) *Exergy analysis of thermal, chemical, and metallurgical processes.* Edwards Brothers, Inc. Ann Arbor.

Tuğ, S. (2016) *A prototype downdraft gasifier design with mechanical stirrer for rice straw gasification*. PhD Thesis, Department of Biosystem Engineering, Tekirdag Namik Kemal University.

Vitasari,, C.R., Jurascik, M. and Ptasinski, K.J. (2011) Exergy analysis of biomass-to-synthetic natural gas (SNG) process via indirect gasification of various biomass feedstock. *Energy*. **36**, 3825-3837.

Xiang, X., Gong, G., Wang, C., Cai, N., Zhou, X. and Li, Y. (2021) Exergy analysis of updraft and downdraft fixed bed gasification of village-level solid waste. *International Journal of Hydrogen Energy*. **46**, 221-233.

Zhang, Y., Li, B., Li, H. and Liu, H. (2011) Thermodynamic evaluation of biomass gasification with air in autothermal gasifiers. *Thermochimica Acta*. **519**, 65–71.

Zhang, Y., Xu, P., Liang, S., Liu, B., Shuai, Y. and Li, B. (2019) Exergy analysis of hydrogen production from steam gasification of biomass: a review. *International Journal of Hydrogen Energy*. **44**, 14290-14302.

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