

## ENERGY, EXERGY, AND SUSTAINABILITY ANALYSIS OF RICE HUSK AIR GASIFICATION PROCESS

by

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*Biomass is one of the RES to produce power with zero CO<sub>2</sub> emission, biomass gasification process considered as a sustainable technology for energy conversion. This paper deals with rice husk air gasification simulation using non-stoichiometric equilibrium model based on Gibbs free energy minimisation. The FACTSAGE 6.3 software used to calculate gas composition at temperature range 600-1000 °C and equivalence ratio range 0.15-0.55. Maximum gas mixture exergy of 9551.7 kJ per kg of rice husk is obtained at  $\phi = 0.25$  and 725 °C. Chemical exergy contributes 89.90-94.85% of total gas mixture exergy, cold gas efficiency and exergetic efficiency varies in the range of 25.19-70.71% and 23.11-62.24%, respectively, in operating condition. Rice husk gasification process analysed by evaluating, sustainability index and environmental destruction factor.*

**Key words:** *rice husk, gasification, simulation, FACTSAGE 6.3 software, exergy analysis, sustainability*

### Introduction

Increase in demand for energy, depletion of fossil fuel and pollution problem necessitates the development of sustainable energy technology. Biomass replacement over fossil fuel reduces GHG emission and dependency on imported coal and oil [1]. Biomass considered as a renewable source of energy and carbon neutral, it can be regenerated quickly and CO<sub>2</sub> released on burning utilised during photosynthesis [2]. Biomass gasification process is a thermochemical conversion of biomass into gaseous fuel, common gasifying mediums are air, oxygen, and steam. Gasification takes place between 600 and 1000 °C in two steps, pyrolysis and gasification. Thermal decomposition of biomass occurs at pyrolysis step and biomass converted into volatile and char. Pyrolysed products converted into producer gas in gasification step [3-6]. Syngas mixture mainly consists of CO, H<sub>2</sub>, N<sub>2</sub>, CO<sub>2</sub>, HC, and traces of NH<sub>3</sub>, H<sub>2</sub>S [7]. Global paddy production in 2015 estimated as 749.8 million tonnes, (499.9 million tonnes milled basis) indicates rice husk potential for power generation [7, 8]. Syngas produced during gasification process used for electricity production, heat generation and used as feedstock in the production of ammonia, methanol, hydrogen, and diesel [3].

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Melgar *et al.* [9] developed a mathematical model for downdraft biomass gasifier, the model combines chemical and thermodynamic equilibrium to find producer gas composition. In this model effect of relative fuel/air ratio and moisture content of biomass are included. Shweta and Pratik [10] developed equilibrium model to predict the composition of producer gas and cold gas efficiency for biomass. Developed model includes water gas shift reaction, steam reforming, methanation reactions, energy balance, and component balance. Effect of moisture content, equivalence ratio and steam to biomass ratio are predicted. Good agreement of  $H_2$ , CO, and  $CO_2$  composition with experiment and slight overprediction of  $CH_4$ ,  $N_2$ . The equilibrium constant of chemical reactions is needed for the model to find the gas composition. Altafini *et al.* [6] simulated gasification of sawdust using equilibrium model based on Gibbs energy minimisation and also studied the effect of fuel moisture on gas composition. Equilibrium modelling for downdraft gasifier developed by Zainal *et al.* [11] to study the effect of temperature on gasifier zone and effect of moisture content in different fuels-wood, paddy husk, paper and municipal waste. Azzone *et al.* [12] developed equilibrium model for downdraft gasifier and used corn stalk, rapeseed straw and sunflower stalk as fuel, final gas composition calculated by many independent reactions. Non-stoichiometric equilibrium model based on free energy minimisation for circulating fluidised bed gasifier developed by Li *et al.* [13] with 44 major chemical species (liquid and gas phase). Effect of fuel moisture and steam injection is analysed, experimental carbon conversion values are added to the model for better gas composition prediction. Agostino *et al.* [14] developed non-stoichiometric equilibrium model for forest waste downdraft gasification. The model finds gas composition and lower heating value by Gibbs energy minimisation with Lagrange multiplier. In the simulation, elements – C, H, O, N, S, and 16 products are considered. The  $H_2$  overestimated, CO and  $CH_4$  are underestimated which leads to an error of 18.5% in lower heating value (LHV) of producer gas. Nuno *et al.* [15] developed a numerical model for gasification of miscanthus, based on the Eulerian-Eulerian approach using FLUENT for 2-D and multi-phase. Influence of gasifying agent mixtures, equivalence ratio, steam to biomass ratio,  $CO_2$  to biomass ratio on syngas composition, and cold gas efficiency are studied.

Angelo *et al.* [16] studied gas composition, yield and gasification performance of high temperature steam gasification and solar-assisted steam gasification by multi-phase, multi-physics 1-D steady-state model. The model includes reaction kinetics of drying, devolatilisation, and ad hoc kinetics. The 1-D models used for simulation of cylindrical shaped fixed bed reactor and time factor not considered. Marco *et al.* [17] developed new steady-state, a zero-dimensional model for fixed bed woody biomass downdraft gasifier using ASPEN PLUS. Gasification product calculated by Gibbs free energy minimisation. Effect of equivalence ratio, moisture content and gasification temperature on gas composition analysed. In simulation  $H_2$  over-estimated and  $CH_4$  under-estimated. Estimated LHV and cold gas efficiency (CGE) has an average percentage of error less than 7. Chanchun *et al.* [18] studied avoidable exergy destruction of a biomass boiler, total exergy loss calculated by finding unburned carbon loss, radiation loss, stack gas loss, and miscellaneous loss. Maximum exergy destruction occurs in the combustion process. Increase in biomass moisture from 33-50% decreases  $\psi$  from 37.28-32.78% and increase in excess air from 21-33% decreases  $\psi$  from 34.39-34.08%. Increase in steam temperature from 755-839 K increases  $\psi$  from 33.99-34.72%. Jiang *et al.* [19] studied energy and exergy analysis of combined cooling-heating and power system, contains biomass gasifier, heat pipe heat exchanger, and an internal combustion engine. Energy efficiency for summer, winter and transitional seasons are 50, 37.77, and 36.95% and corresponding exergy efficiency are 6.23, 12.51, and 13.79%. Highest exergy destruction occurs at gasification system. Rovas and Zabaniotou [20] studied exergy analysis of combined heat and power system uses fluidised bed gasifier

for olive kernel, peach kernel, and grape wastes at 750-850 °C and  $\phi = 0.3$ . Exergy analysis carried out for producer gas, tar, ash, and system components. Exergy efficiency of olive, peach and grape waste are 74.65, 68.75, and 61.35%, respectively. Exergy efficiency for rice husk is found to be 23.11-62.24% in the present study. Exergy loss depends on pressure, temperature, and composition change and exergy of tar and ash considered as exergy loss. Kanit *et al.* [21] studied exergy analysis of torrefied rice husk pellets in a bubbling fluidised bed gasifier. Rice husk pellets torrefied at 250 °C (RHP-250) and 350 °C (RHP-350), exergy efficiency of RHP-250 and RHP-350 are 30 and 21%, respectively. The RHP-250 and RHP-350 has 7% and 21% higher exergy than raw rice husk and specific chemical energy of RHP-350 syngas is 32% higher than RHP-250. In the present study, exergetic efficiency of rice husk is in the range of 23.11-62.24% for the selected operating condition.

Exergy analysis used as tool for process design and optimisation of thermal systems to find magnitude and location of irreversibility and to provide opportunity for energy efficiency improvement [2, 6, 7]. Exergy is measure of usefulness of an energy form, it is the maximum work obtained when system is in thermodynamic equilibrium with surrounding [22]. Exergy consumed or destroyed in any real process, exergy consumption in any process is proportional to entropy created in the process [23]. In present situation, it is necessary to understand energy distribution in systems for sustainable development. Gasification simulation is done by non-stoichiometric equilibrium modelling to study effect of temperature, equivalence ratio on gas composition and to find out energy efficiency,  $\eta$ , and exergetic efficiency,  $\psi$ . Gibbs energy minimisation method is used to find the equilibrium composition of multi-phase system. Products with negative Gibbs free energy from possible products are found from objective function, by subjecting the model to elemental mass balance constraint and non-negativity of the number of moles. Lagrange multiplier – iterative method used to solve set of simultaneous equations. The objective function is given by eq. (1):

$$\frac{G}{RT} = \sum_{j=1}^n n_j \left[ \frac{G^0}{RT} \ln \frac{n_j}{\sum n_j} \right] \quad (1)$$

where  $G$  [kJ] is the total Gibbs energy,  $G^0$  [kJ] – the Gibbs energy of pure component,  $R$  [8.314 kJ/kmolK] – the universal gas constant, and  $n_j$  – the number of moles of component  $j$ .

Exergy distribution of gas mixture and individual gases are evaluated and sustainability of gasification process analysed.

### Energy and exergy analysis

Efficient use of energy is required to meet growing energy demand, it is necessary to evaluate energy and exergetic efficiency of rice husk gasification to find energy loss. Energy and exergetic efficiencies are useful tools for energy conversion assessment and energy improvement [2]. Energy balance represented by eq. (2).

$$E_{\text{rice husk}} + E_{\text{air}} = E_{\text{gas}} + E_{\text{char}} + E_{\text{loss}} \quad (2)$$

where  $E_{\text{rice husk}}$ ,  $E_{\text{air}}$ ,  $E_{\text{gas}}$ ,  $E_{\text{char}}$ , and  $E_{\text{loss}}$  represents energy present in rice husk, air, product gas, unreacted carbon, and energy loss, respectively. Unequal distribution of air inside the gasifier is responsible for localised pyrolysis, pyrolysis ends at 600 °C. At higher temperatures, thermal cracking reduces the tar content. In equilibrium modelling production of tar is neglected [14]. As no tar formation is predicted in simulation, it is not accounted for energy and exergy balance. Cold gas efficiency represented by eq. (3).

$$\eta = (\text{LHV}_{\text{gas}} / \text{LHV}_{\text{rice husk}}) Y \times 100\% \quad (3)$$

where  $LHV_{\text{gas}}$  [kJ/Nm<sup>3</sup>] is the lower heating value of gas mixture,  $LHV_{\text{rice husk}}$  [kJ/kg] – the lower heating value of rice husk, and  $Y$  [Nm<sup>3</sup>/kg] – the gas yield.

Lower heating value of gas, rice husk and gas yield are calculated by eqs. (4)-(6).

$$LHV_{\text{gas}} = (\text{CO}\% \times 126.36 + \text{H}_2\% \times 107.98 + \text{CH}_4\% \times 358.18) \quad (4)$$

where CO, H<sub>2</sub>, CH<sub>4</sub> represents CO, hydrogen and CH<sub>4</sub> in mole percentage.

$$LHV_{\text{rice husk}} = (34835 \text{ C} + 93870 \text{ H} - 10800 \text{ O} + 6280 \text{ N} + 10465 \text{ S}) \quad (5)$$

where C, H, O, N, S represents fuel bound carbon, hydrogen, oxygen, nitrogen, and sulphur in mass fraction.

$$Y = \text{volume}_{\text{gas}} / \text{mass}_{\text{rice husk}} \quad (6)$$

Exergy analysis is a thermodynamic technique uses conservation of mass and energy principles to design thermal systems with maximum efficiency and it is based on First and Second law of thermodynamics. Magnitude and location of energy degradation in a process identified by exergy analysis, energy consumption minimisation leads to better utilisation of available energy, environmental impact reduction and gasifier design improvement [2]. The thermodynamic inefficiency of thermal system or process referred in terms of destruction or exergy loss, exergy never conserves in irreversible process, irreversibility in process considered as exergy loss to make exergy balance. Conservation of energy indicates  $\eta$  is always higher than  $\psi$  [2]. Exergy balance of gasification process given by eq. (7):

$$Ex_{\text{rice husk}} + Ex_{\text{air}} = Ex_{\text{gas}} + Ex_{\text{char}} + Ex_{\text{loss}} \quad (7)$$

where  $Ex_{\text{rice husk}}$ ,  $Ex_{\text{air}}$ ,  $Ex_{\text{gas}}$ ,  $Ex_{\text{char}}$ , and  $Ex_{\text{loss}}$  represents the exergy of rice husk, air, product gas, unreacted carbon, and exergy lost, respectively.

Total exergy of gas mixture calculated by eq. (8):

$$Ex_{\text{total}} = Ex^{\text{ch}} + Ex^{\text{ph}} + Ex^{\text{mixing}} \quad (8)$$

where  $Ex^{\text{ch}}$ ,  $Ex^{\text{ph}}$ ,  $Ex^{\text{mixing}}$  are chemical exergy, physical exergy, and exergy lost due to mixing of gas.

Chemical exergy of a substance is the maximum possible useful work done by the process when the substance brought from environment state to dead state. Chemical exergy of substances obtained from standard chemical exergy tables, specific chemical exergy of substance shown in tab. 1.

Specific physical exergy calculated by eq. (9):

$$Ex^{\text{ph}} = (h - h_0) - T_0(s - s_0) \quad (9)$$

where  $h$ ,  $s$ ,  $h_0$ , and  $s_0$  represent specific enthalpy, specific entropy, standard specific enthalpy, and entropy,  $T_0$  is atmospheric temperature.

**Table 1. Specific chemical exergy of gases [5]**

Gas component	Specific chemical exergy [kJkmol <sup>-1</sup> ]
N <sub>2</sub>	720
O <sub>2</sub>	3970
H <sub>2</sub>	236100
CO	275100
CO <sub>2</sub>	19870
CH <sub>4</sub>	831650

Specific enthalpy and entropy of gases are calculated as function of temperature given in tabs. 2 and 3.

**Table 2. Specific enthalpy of gases [24]**

Gases	Enthalpy as a function of temperature [kJkmol <sup>-1</sup> ]	Temperature range [K]
H <sub>2</sub>	$h = -13779.82 + 19.83 T + 1.54 \cdot 10^{-3} T^2 + 295179.9 T^{-1} + 4.77 \cdot 10^{-7} T^3 + 389.72 T^{0.5}$	298 < T < 1200
CO	$h = -235743.85 + 90.75 T - 3.12 \cdot 10^{-3} T^2 + 1541255.33 T^{-1} + 32063.32 \ln(T) - 5178.51 T^{0.5}$	298 < T < 1700
CO <sub>2</sub>	$h = -426583.55 + 103.34 T - 2.37 \cdot 10^{-3} T^2 + 40249.04 T^{-1} - 3496.57 T^{0.5} + 11004.74 \ln(T)$	298 < T < 1900
N <sub>2</sub>	$h = -23347.54 + 17.08 T + 8.69 \cdot 10^{-3} T^2 + 230154.97 T^{-1} - 1.51 \cdot 10^{-6} T^3 + 2939.81 \ln(T)$	298 < T < 1600
CH <sub>4</sub>	$h = -458850.73 + 304.93 T - 9.39 \cdot 10^{-3} T^2 + 4193372.13 T^{-1} + 110598.4 \ln(T) - 20287.96 T^{0.5}$	298 < T < 1300

**Table 3. Specific entropy of gases [24]**

Gases	Entropy as a function of temperature [kJkmol <sup>-1</sup> K <sup>-1</sup> ]	Temperature range [K]
H <sub>2</sub>	$s = 37.54 + 19.83 \ln(T) - 8.02 \cdot 10^{-3} T + 3.08 \cdot 10^{-3} T + 147589.95 T^{-2} + 7.15 \cdot 10^{-7} T^2 - 389.72 T^{-0.5}$	298 < T < 1200
CO	$s = -518.71 + 90.75 \ln(T) - 6.24 \cdot 10^{-3} T + 770627.67 T^{-2} - 32063.32 T^{-1} + 5178.51 T^{-0.5}$	298 < T < 1700
CO <sub>2</sub>	$s = -539.42 + 103.34 \ln(T) - 4.74 \cdot 10^{-3} T + 20124.52 T^{-2} + 3496.57 T^{-0.5} - 11004.74 T^{-1}$	298 < T < 1900
N <sub>2</sub>	$s = 97.76 + 17.08 \ln(T) + 1.74 \cdot 10^{-2} T + 115077.48 T^{-2} - 2.26 \cdot 10^{-6} T^2 - 2939.81 T^{-1}$	298 < T < 1600
CH <sub>4</sub>	$s = -2373.23 + 304.93 \ln(T) - 1.88 \cdot 10^{-2} T + 2096686.07 T^{-2} - 110598.4 T^{-1} + 2087.96 T^{-0.5}$	298 < T < 1300

Exergy lost due to gas mixing calculated from eq. (10):

$$Ex_{\text{mixing}} = RT_0 \ln(x) \quad (10)$$

where  $x$  is the mole fraction of gas component.

Exergetic efficiency of gasification process is defined as ratio of chemical exergy of gas produced to the exergy of biomass and air. Gas formation takes place at elevated temperature other than environmental condition to overcome this situation, physical exergy added in exergy calculation [2]. Exergetic efficiency calculated by eq. (11):

$$\Psi = \left( \frac{Ex_{\text{gas}}}{Ex_{\text{rice husk}} + Ex_{\text{air}}} \right) 100 \quad (11)$$

where  $Ex_{\text{gas}}$  [kJ] is the exergy of gas mixture,  $Ex_{\text{rice husk}}$  [kJ] – the exergy of rice husk, and  $Ex_{\text{air}}$  [kJ] – the exergy of air, calculated by eq. (12):

$$Ex_{\text{rice husk}} = m \beta LHV_{\text{rice husk}} \quad (12)$$

where  $m$  [kg] is the mass of rice husk and  $\beta$  – the exergy coefficient, it is given by eq. (13):

$$\beta = 1.044 + 0.016 \frac{H}{C} - \left[ 0.3493 \frac{O}{C} \left( 1 + 0.0531 \frac{H}{C} \right) \right] + \frac{0.0493 \frac{N}{C}}{1 - 0.4124 \frac{O}{C}} \quad (13)$$

Exergy destruction factor,  $F_{ed}$ , is the ratio of exergy destruction and exergy input, it is used to find process deviation from maximum benefit. It is given by eq. (14):

$$F_{ed} = \frac{I}{Ex_{input}} \quad (14)$$

where  $I$  [kJ] is the irreversibility in the process,  $Ex_{input}$  [kJ] – the exergy input:

$$\text{Irreversibility} = T_0 S_{gen} \quad (15)$$

where  $S_{gen}$  [kJ/K] is the entropy generated.

Environmental destruction factor,  $C_{ed}$ , used to quantify sustainability potential of gasification process and it is inverse of exergetic efficiency given by eq. (16):

$$C_{ed} = \frac{1}{\psi} \quad (16)$$

Sustainable development not only requires sustainable supply of clean and inexpensive energy source but also efficient use of them [25]. Exergy-based sustainability evaluation is useful to improve efficiency, minimise the payback period and pollution level [2]. Sustainability index (SI) is inverse of exergy destruction factor:

$$SI = \frac{1}{F_{ed}} \quad (17)$$

Relationship between  $\psi$  and SI given by eq. (18):

$$\psi = 1 - \frac{1}{SI} \quad (18)$$

## Methodology

Non-stoichiometric equilibrium modelling with Gibbs free energy minimisation used in rice husk air gasification simulation. Rice husk elemental composition values are given by ultimate and proximate analysis, shown in tab. 4. The stoichiometric air-fuel ratio calculated from elemental composition and operating conditions are taken from Karmakar *et al.* [26] to validate simulation. Three equivalence ratios 0.25, 0.35, and 0.45 with temperature range 600-800 °C has been adapted to find the effect of temperature and equivalence ratio on gas composition. Gas composition, gas yield and gas lower heating value are calculated shown in tab. 5, root mean square (RMS) value calculated by eq. (19) and simulation has average RMS value of 3.59, indicates simulation is in agreement with experiment. To study cold gas efficiency and exergetic efficiency, temperature and equivalence ratio varied from 600-1000 °C and 0.15-0.55 °C, respectively.

$$RMS = \sqrt{\frac{\sum_{j=1}^N (\text{experiment} - \text{simulation})^2}{N}} \quad (19)$$

where  $N$  is the number of gas components.

**Table 4. Proximate and ultimate analysis of rice husk [26]**

Ultimate analysis	Mass percentage	Proximate Analysis	Mass Percentage
Carbon	38.43	Volatile matter	55.54
Hydrogen	2.97	Fixed carbon	14.99
Nitrogen	0.49	Moisture	9.95
Sulphur	0.07	Ash	19.52
Oxygen	36.36		
Ash	21.68		

**Table 5. Simulation and experimental result of rice husk air gasification**

S. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
$\phi$	0.25				0.35					0.45				
$T$	650	675	700	725	600	650	700	725	750	600	650	700	725	800
Karmakar <i>et al.</i> [26] experimental gas composition [%]														
H <sub>2</sub>	17.22	17.93	18.12	18.49	14.13	14.22	14.63	15.88	16.08	8.92	9.32	10.15	10.27	10.22
CO	24.84	25.06	25.31	26.59	17.48	20.63	22.47	22.89	23.24	11.72	13.47	15.13	16.61	17.78
CO <sub>2</sub>	14.92	14.26	13.56	12.61	19.93	17.64	16.67	14.21	13.83	22.93	21.99	21.42	21.07	20.9
N <sub>2</sub>	40.4	40.29	40.63	40.35	45.67	45.59	44.91	46.18	46.12	54.15	53.41	52.09	51.16	50.33
CH <sub>4</sub>	2.62	2.46	2.38	1.96	2.79	1.92	1.32	0.84	0.73	2.28	1.81	1.21	0.89	0.77
Simulation gas composition [%]														
H <sub>2</sub>	16.97	17.43	17.76	17.97	12.6	13.86	14.53	14.55	14.47	10.63	11.69	11.63	11.46	10.87
CO	22.71	27.29	31.66	35.53	13.51	21.77	28.9	29.32	29.66	13.11	20.57	21.59	21.95	22.85
CO <sub>2</sub>	15.85	12.86	10.01	7.49	19.96	14.72	10.16	9.84	9.59	18.99	14.31	13.55	13.29	12.64
N <sub>2</sub>	43.82	41.9	40.17	38.7	53.24	49.2	46.2	46.18	46.23	56.78	53.13	53.17	53.27	53.63
CH <sub>4</sub>	0.65	0.51	0.4	0.31	0.68	0.44	0.22	0.1	0.05	0.49	0.29	0.06	0.03	0
LHV	4.93	5.51	6.06	6.54	3.31	4.4	5.3	5.31	5.33	2.98	3.97	4	4.02	4.06
Gas yield	1.24	1.3	1.35	1.4	1.43	1.54	1.64	1.64	1.64	1.72	1.84	1.83	1.83	1.82
RMS	2.05	1.65	3.38	4.73	4	2.24	4.16	3.55	3.53	2.47	4.85	4.65	4.37	4.6

## Results and discussion

### *Exergy distribution of individual gases and gas mixture*

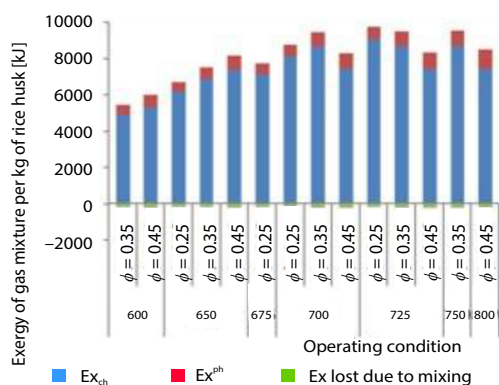
Chemical exergy of gases mainly depends on chemical exergy of carbon CO and its variation in the product gas composition influence the chemical exergy of gas mixture. The CO contributes 48.3-68.9% and H<sub>2</sub> contributes 28.06-38.64% of  $Ex^{ch}$  of gas mixture. The N<sub>2</sub> is the major contributor for  $Ex^{ph}$ , it contributes 37.08-51.13% of gas mixture physical exergy. The CO<sub>2</sub> and CO contribute next to N<sub>2</sub>, below 675 °C CO<sub>2</sub> contribution is more, increase in temperature decreases CO<sub>2</sub> content and physical exergy of CO<sub>2</sub> decreases. Except for N<sub>2</sub>,  $Ex^{ch}$  of individual gases are greater than corresponding  $Ex^{ph}$ . The ratio of chemical exergy to physical exergy for H<sub>2</sub>, CO, CO<sub>2</sub>, N<sub>2</sub>, and CH<sub>4</sub> and gas mixture are in the range of 20.23-31.49, 22.12-34.99, 1.01-1.62, 0.06-0.09, 35.05-59.68, and 6.93-13.16, respectively.



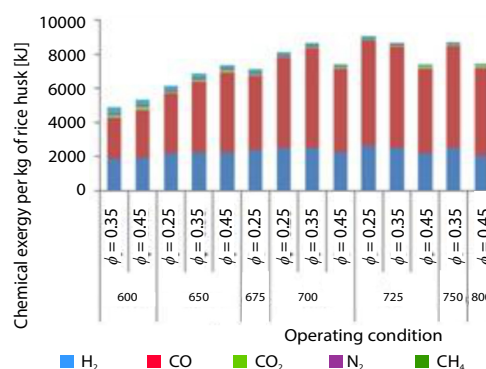
### Effect of temperature and equivalence ratio on exergy

Effect of temperature on chemical exergy and physical exergy analysed for  $\phi$  values 0.25, 0.35, and 0.45. For specific  $\phi$  value increase in temperature increases exergy of gas mixture due to increase in  $Ex^{ch}$  and  $Ex^{ph}$ , exergy lost due to mixing is lower than increase of  $Ex^{ch}$  and  $Ex^{ph}$ . Chemical exergy is the major contributor to exergy of gas mixture. Rice husk product gas exergy distribution at different operating conditions shown in fig. 1, maximum chemical exergy of 9058.33 kJ obtained per kg of rice husk at 725 °C for  $\phi = 0.25$  and lowest value of 4899.24 kJ is obtained at 600 °C for  $\phi = 0.35$ . Maximum physical exergy of 1070.51 kJ obtained at 800 °C for  $\phi = 0.45$  and lowest value of 535.45 kJ corresponds to 650 °C and  $\phi = 0.25$ . Chemical, physical exergy distribution of individual gases and exergy loss is shown in figs. 2-4. For  $\phi = 0.25$  chemical exergy of  $H_2$  increases with temperature rise, at  $\phi = 0.35$   $Ex^{ch}$  decreases after 725 °C and for  $\phi = 0.45$   $Ex^{ch}$  decreases after 650 °C. Physical exergy of  $H_2$  and  $N_2$  increases with increase in temperature for all  $\phi$  values. The  $Ex^{ch}$  and  $Ex^{ph}$  of CO increases but  $CH_4$  decreases with increase in temperature. The  $CO_2$  chemical exergy decreases with increase in temperature, for  $\phi = 0.25$  physical exergy of  $CO_2$  decreases with temperature, for  $\phi = 0.35$  and 0.45  $Ex^{ph}$  increases after 700 and 650 °C, respectively.

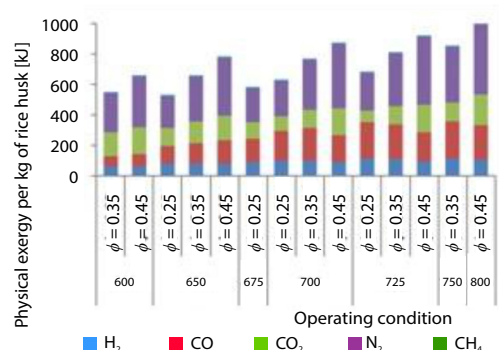
Effect of equivalence ratio analysed for temperatures 650, 700, and 725 °C. At 650 °C increase in equivalence ratio from 0.25 to 0.45 increases  $Ex^{ch}$  of gas mixture. At 700 °C it increases initially and then decreases for  $\phi$  value rise and at 725 °C chemical exergy of gas mixture



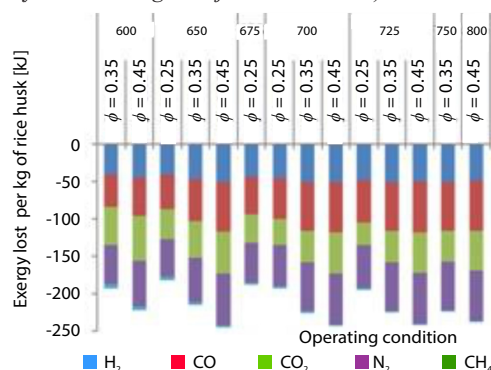
**Figure 1. Exergy distribution of gas mixture**  
(for color image see journal web site)



**Figure 2. Chemical exergy of individual gases**  
(for color image see journal web site)



**Figure 3. Physical exergy of individual gases**  
(for color image see journal web site)



**Figure 4. Exergy lost due to mixing of gases**  
(for color image see journal web site)

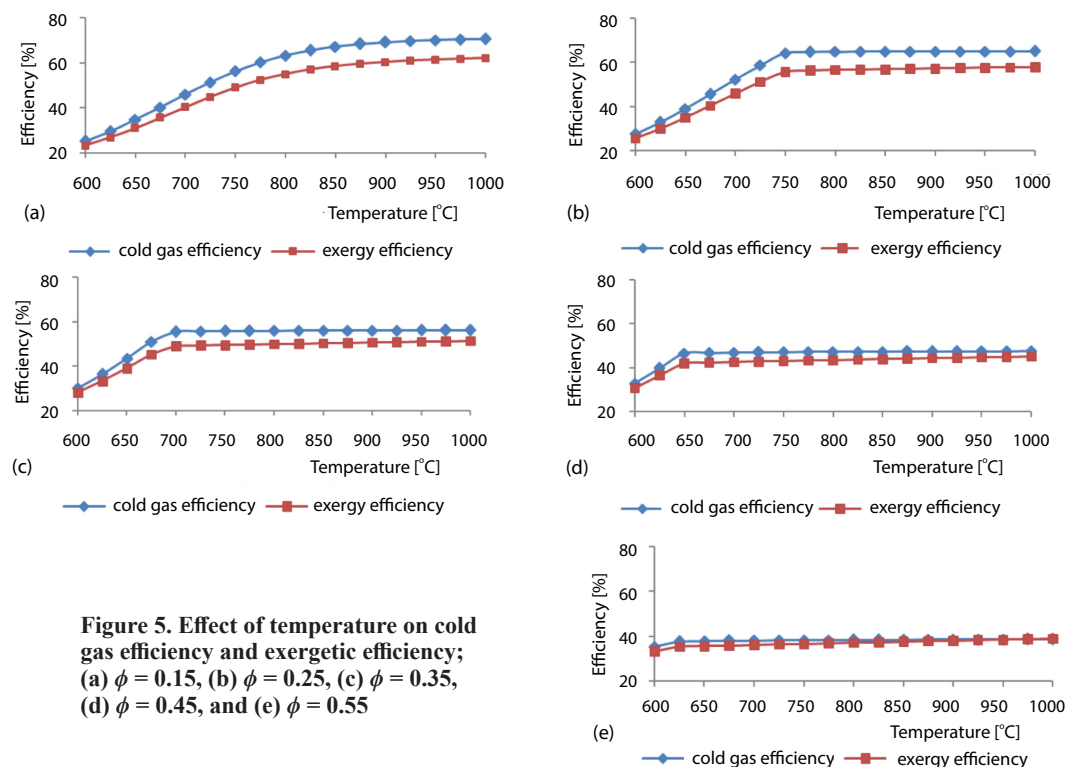


ture decreases with  $\phi$  value rise. Physical exergy of gas mixture increases with  $\phi$  value rise for temperatures. At 650 °C except CH<sub>4</sub> chemical exergy of gases increases with  $\phi$  value, at 700 °C H<sub>2</sub> and CH<sub>4</sub> chemical exergy decreases, non-combustible gases (CO<sub>2</sub> and N<sub>2</sub>) exergy values increases. The CO chemical exergy increases for  $\phi$  value change from 0.25-0.35 and then decreases. At 725 °C combustible gases chemical exergy decreases and non-combustible gases exergy increases with increase in  $\phi$  value, chemical exergy variation trend with  $\phi$  value rise at different temperatures followed by physical exergy of individual gases.

#### *Effect of temperature and equivalence ratio on energy and exergetic efficiency*

The efficiency of gasification becomes almost constant after certain temperature due to CH<sub>4</sub> and H<sub>2</sub> reduction and CO formation stabilisation. Efficiency stabilisation temperature decreases with increase in equivalence ratio. From fig. 5 efficiency stables at 900, 750, 700, 650, and 625 °C for  $\phi = 0.15, 0.25, 0.35, 0.45$ , and  $0.55$ , respectively. Stabilisation temperature indicates further increase in temperature of gasification has no remarkable increase in gasifier output. Exergetic efficiency follows the same trend of cold gas efficiency.

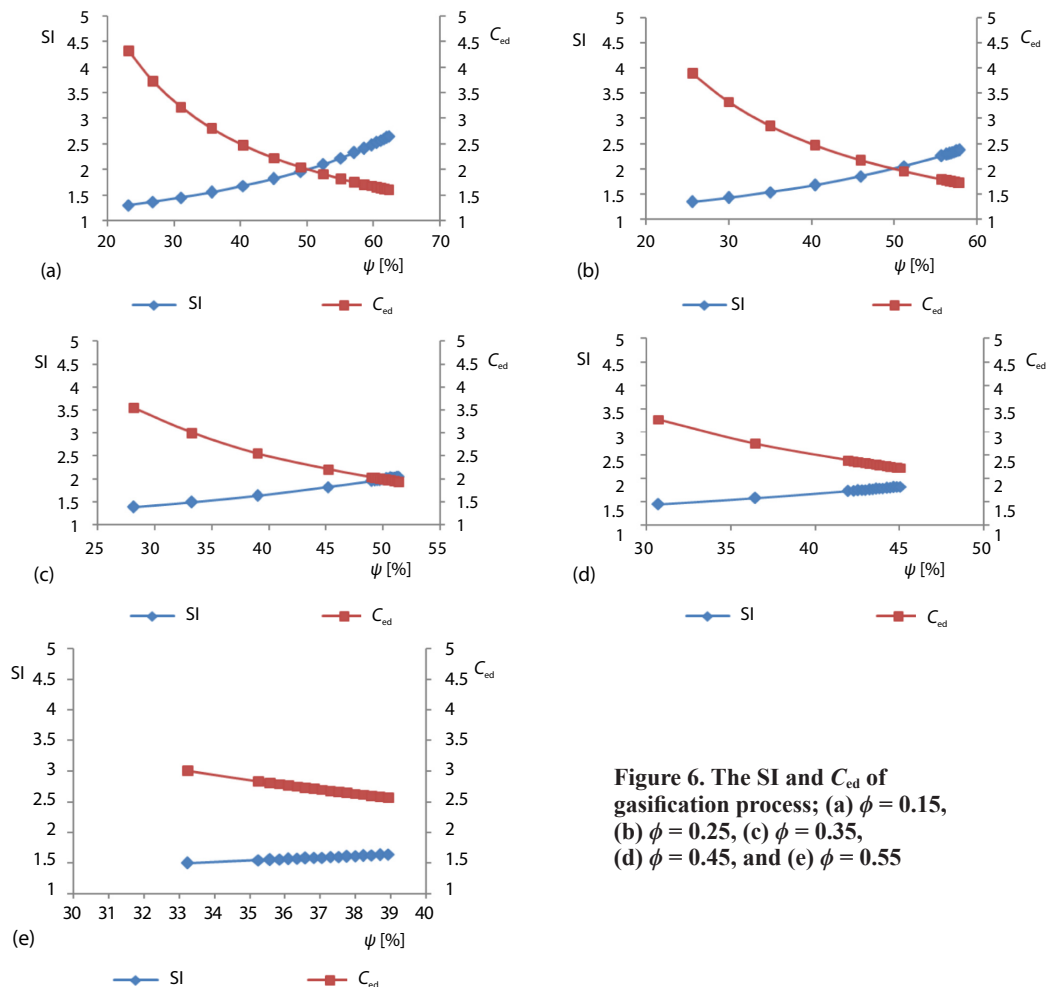
Equivalence ratio has strong influence on gasification, it affects bed temperature, gas composition and thermal efficiency. Gasifier temperature increases with increase in equivalence ratio because of increase in exothermic reactions [2]. At 600 °C increase in  $\phi$  value from 0.15-0.55 increases cold gas efficiency. For 625 °C and 650 °C,  $\eta$  value increases up to  $\phi = 0.45$ , for 675 °C, and 700 °C  $\eta$  value increases up to  $\phi = 0.35$  and 725-800 °C,  $\eta$  value increases up to  $\phi = 0.25$ . After 800 °C increase in  $\phi$  value decreases cold gas efficiency. Exergetic efficiency follows the same trend. increase in  $\phi$  value decreases LHV<sub>gas</sub> but it increases gas yield.



**Figure 5. Effect of temperature on cold gas efficiency and exergetic efficiency; (a)  $\phi = 0.15$ , (b)  $\phi = 0.25$ , (c)  $\phi = 0.35$ , (d)  $\phi = 0.45$ , and (e)  $\phi = 0.55$**

### Gasification process sustainability analysis

The high value of SI, low exergy destruction fraction,  $F_{ed}$ , and environment degradation factor,  $C_{ed}$ , for a system or process is preferred. The increase of  $\psi$  value indicates the effective utilisation of energy, reduced consumption of feed material and its corresponding pollution. Increase in temperature increases SI value and decreases  $C_{ed}$  and environmental degradation factor is inverse of exergetic efficiency. The SI and  $C_{ed}$  values coincide at  $\psi = 50\%$ , the condition at which useful work produced is equal to energy lost. For  $\phi = 0.15$ , 50% exergetic efficiency achieved at 750 °C. Operating below this temperature is not advisable, similarly for  $\phi = 0.25$  and 0.35 725 and 825 °C are respective temperatures. For  $\phi = 0.45$  and 0.55 maximum exergetic efficiency of 45.06 and 38.93 are achieved at 1000 °C.



**Figure 6.** The SI and  $C_{ed}$  of gasification process; (a)  $\phi = 0.15$ , (b)  $\phi = 0.25$ , (c)  $\phi = 0.35$ , (d)  $\phi = 0.45$ , and (e)  $\phi = 0.55$

### Conclusion

The main combustible gases CO, H<sub>2</sub>, and CH<sub>4</sub> are formed during gasification of rice husk. The CO and hydrogen play a crucial role in gas heating value contribution due to its high formation. Increase in temperature increases CO content from 0.15 to 0.55 equivalence ratios, H<sub>2</sub>

increases with temperature at low  $\phi$  value, increase in  $\phi$  value reduces hydrogen content. The  $H_2$  and CO content increase with the increase in equivalence ratio at 600 °C, at 625 °C and 650 °C increase in equivalence ratio decreases  $H_2$  and CO content after  $\phi = 0.45$ . Further increase in temperature reduces  $H_2$  and CO formation. Based on gasification simulation results of rice husk, chemical exergy value of gas mixture is 6.93-13.16 times greater than corresponding physical exergy values. The CO is the main contributor to chemical exergy of gas, it provides 48.3-68.9% of chemical exergy of the gas mixture. The  $N_2$  is major contributor for physical exergy, it provides 37.08-51.13 % of physical exergy of gas mixture. Energy efficiency is in the range of 25.19-70.71% and exergetic efficiency in the range of 23.11-62.24%. Increase in temperature increases energy and exergetic efficiency, influence of CO is predominant on energy and exergetic efficiency.

## Nomenclature

$C_{ed}$	– environmental destruction factor
$E_{air}$	– energy present in air, [kJ]
$E_{char}$	– energy present in char, [kJ]
$E_{gas}$	– energy present in gas, [kJ]
$E_{loss}$	– energy lost, [kJ]
$E_{rice\ husk}$	– energy present in rice husk, [kJ]
$Ex_{air}$	– exergy of air, [kJ]
$Ex_{char}$	– exergy of char, [kJ]
$Ex_{gas}$	– exergy of gas, [kJ]
$Ex_{loss}$	– exergy lost, [kJ]
$Ex_{rice\ husk}$	– exergy of rice husk, [kJ]
$Ex^{ch}$	– chemical exergy, [kJ]
$Ex^{mixing}$	– exergy lost due to mixing, [kJ]
$Ex^{ph}$	– physical exergy, [kJ]
$Ex_{total}$	– total exergy of gas mixture, [kJ]
$Ex_{input}$	– exergy input, [kJ]
$F_{ed}$	– exergy destruction factor
$G$	– total Gibbs energy, [kJ]
$G^0$	– Gibbs energy of pure component, [kJ]
$h$	– specific enthalpy, [kJkg <sup>-1</sup> ]
$h_0$	– standard specific enthalpy, [kJkg <sup>-1</sup> ]
$I$	– irreversibility in the process, [kJ]
$LHV_{gas}$	– lower heating value of gas mixture, [kJNm <sup>-3</sup> ]
$LHV_{rice\ husk}$	– lower heating value of rice husk, [kJkg <sup>-1</sup> ]

$n_j$	– number of moles of component
$N$	– number of gas components
$R$	– universal gas constant, [kJkmol <sup>-1</sup> K <sup>-1</sup> ]
$s$	– specific entropy, [kJ kg <sup>-1</sup> K <sup>-1</sup> ]
$s_0$	– standard specific entropy, [kJ kg <sup>-1</sup> K <sup>-1</sup> ]
$S_{gen}$	– entropy generated, [kJK <sup>-1</sup> ]
$T$	– temperatur, [K]
$T_0$	– atmospheric temperature, [K]
$x$	– mole fraction of gas component
$Y$	– gas yield, [Nm <sup>3</sup> kg <sup>-1</sup> ]

## Greek symbols

$\beta$	– exergy coefficient
$\phi$	– equivalence ratio
$\eta$	– energy efficiency, [%]
$\psi$	– exergetic efficiency, [%]

## Acronyms

LHV	– lower heating value
RHP -250	– rice husk pellet torrefied at 250 °C
RHP -350	– rice husk pellet torrefied at 350° C
RMS	– root mean square
SI	– sustainability index

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