

1 **ENERGY, EXERGY AND SUSTAINABILITY ANALYSIS OF RICE HUSK AIR**
2 **GASIFICATION PROCESS**

3 by

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10 *Biomass is one of the renewable energy sources to produce power with zero*
11 *carbon dioxide emission, biomass gasification process considered as a*
12 *sustainable technology for energy conversion. This paper deals with rice husk*
13 *air gasification simulation using non- stoichiometric equilibrium model based*
14 *on Gibbs free energy minimisation. FACTSAGE 6.3 software used to calculate*
15 *gas composition at temperature range 600 - 1000°C and equivalence ratio (ϕ)*
16 *range 0.15 - 0.55. Maximum gas mixture exergy of 9551.7 kJ per kg of rice husk*
17 *is obtained at $\phi=0.25$ and 725°C. Chemical exergy contributes 89.90 - 94.85%*
18 *of total gas mixture exergy, cold gas efficiency and exergetic efficiency varies in*
19 *the range of 25.19 - 70.71% and 23.11 - 62.24% respectively in operating*
20 *condition. Rice husk gasification process analysed by evaluating, sustainability*
21 *index (SI) and environmental destruction factor (C_{ed}).*

22 **Keywords:** *Rice husk, Gasification, Simulation, FACTSAGE, Exergy analysis,*
23 *Sustainability.*

24 **1. Introduction**

25 Increase in demand for energy, depletion of fossil fuel and pollution problem necessitates the
26 development of sustainable energy technology. Biomass replacement over fossil fuel reduces greenhouse
27 gas emission and dependency on imported coal and oil [1]. Biomass considered as a renewable source of
28 energy and carbon neutral, it can be regenerated quickly and carbon dioxide released on burning utilised
29 during photosynthesis [2]. Biomass gasification process is a thermo-chemical conversion of biomass into
30 gaseous fuel, common gasifying mediums are air, oxygen and steam. Gasification takes place between
31 600 and 1000°C in two steps, pyrolysis and gasification. Thermal decomposition of biomass occurs at
32 pyrolysis step; biomass converted into volatile and char. Pyrolysed products converted into producer gas
33 in gasification step [3 - 6]. Syngas mixture mainly consists of CO, H₂, N₂, CO₂, hydrocarbons and traces
34 of NH₃, H₂S [7]. Global paddy production in 2015 estimated as 749.8 million tonnes, (499.9 million
35 tonnes milled basis) indicates rice husk potential for power generation [7,8]. Syngas produced during
36 gasification process used for electricity production, heat generation and used as feedstock in the
37 production of ammonia, methanol, hydrogen and diesel [3].

38 Melgar et al [9] developed a mathematical model for downdraft biomass gasifier, the model
39 combines chemical and thermodynamic equilibrium to find producer gas composition. In this model
40 effect of relative fuel/air ratio and moisture content of biomass are included. Shweta and Pratik [10]
41 developed equilibrium model to predict the composition of producer gas and cold gas efficiency for

42 biomass. Developed model includes water gas shift reaction, steam reforming, methanation reactions,
43 energy balance and component balance. Effect of moisture content, equivalence ratio and steam to
44 biomass ratio are predicted. Good agreement of H₂, CO and CO₂ composition with experiment and slight
45 overprediction of CH₄, N₂. The equilibrium constant of chemical reactions is needed for the model to find
46 the gas composition. Altafini et al [6] simulated gasification of sawdust using equilibrium model based on
47 Gibbs energy minimisation and also studied the effect of fuel moisture on gas composition. Equilibrium
48 modelling for downdraft gasifier developed by Zainal et al [11] to study the effect of temperature on
49 gasifier zone and effect of moisture content in different fuels-wood, paddy husk, paper and municipal
50 waste. Azzone [12] et al developed equilibrium model for downdraft gasifier and used corn stalk,
51 rapeseed straw and sunflower stalk as fuel, final gas composition calculated by many independent
52 reactions. Non-stoichiometric equilibrium model based on free energy minimisation for circulating
53 fluidised bed gasifier developed by Li et al [13] with 44 major chemical species (liquid and gas phase).
54 Effect of fuel moisture and steam injection is analysed, experimental carbon conversion values are added
55 to the model for better gas composition prediction. Agostino et al [14] developed non-stoichiometric
56 equilibrium model for forest waste downdraft gasification. The model finds gas composition and lower
57 heating value by Gibbs energy minimisation with Lagrange multiplier. In the simulation, elements - C, H,
58 O, N, S and 16 products are considered. H₂ overestimated, CO and CH₄ are underestimated which leads
59 to an error of 18.5% in LHV of producer gas. Nuno et al [15] developed a numerical model for
60 gasification of miscanthus, based on the Eulerian-Eulerian approach using FLUENT for two dimensional
61 and multi-phase. Influence of gasifying agent mixtures, equivalence ratio, steam to biomass ratio, CO₂ to
62 biomass ratio on syngas composition and cold gas efficiency are studied.

63 Angelo et al [16] studied gas composition, yield and gasification performance of high-
64 temperature steam gasification and solar-assisted steam gasification by Multi-phase, multi-physics 1-D
65 steady-state model. The model includes reaction kinetics of drying, devolatilisation and ad hoc kinetics. 1-
66 D models used for simulation of cylindrical shaped fixed bed reactor and time factor not considered.
67 Marco et al [17] developed new steady state, a zero-dimensional model for fixed bed woody biomass
68 downdraft gasifier using ASPEN PLUS; gasification product calculated by Gibbs free energy
69 minimisation. Effect of equivalence ratio, moisture content and gasification temperature on gas
70 composition analysed. In simulation H₂ over-estimated and CH₄ under-estimated. Estimated LHV and
71 CGE has an average percentage of error less than 7. Chanchun et al [18] studied avoidable exergy
72 destruction of a biomass boiler, total exergy loss calculated by finding unburned carbon loss, radiation
73 loss, stack gas loss and miscellaneous loss. Maximum exergy destruction occurs in the combustion
74 process. Increase in biomass moisture from 33 - 50% decreases ψ from 37.28 - 32.78% and Increase in
75 excess air from 21 - 33% decreases ψ from 34.39 - 34.08%. Increase in steam temperature from 755 - 839
76 K increases ψ from 33.99 - 34.72%. Jiang et al [19] studied energy and exergy analysis of combined
77 cooling-heating and power system, contains biomass gasifier, heat pipe heat exchanger and an Internal
78 combustion engine. Energy efficiency for summer, winter and transitional seasons are 50, 37.77 and
79 36.95% and corresponding exergy efficiency are 6.23, 12.51 and 13.79%. Highest exergy destruction
80 occurs at gasification system. Dimitrios Rovas and Anastasia Zabaniotou [20] studied exergy analysis of
81 combined heat and power system uses fluidised bed gasifier for olive kernel, peach kernel and grape
82 wastes at 750 - 850°C and $\phi = 0.3$. Exergy analysis carried out for producer gas, tar, ash and system
83 components. Exergy efficiency of olive, peach and grape waste are 74.65, 68.75, 61.35% respectively.
84 Exergy efficiency for rice husk is found to be 23.11 - 62.24% in the present study. Exergy loss depends

85 on pressure, temperature and composition change; exergy of tar and ash considered as exergy loss. Kanit
 86 et al [21] studied exergy analysis of torrefied rice husk pellets in a bubbling fluidised bed gasifier. Rice
 87 husk pellets torrefied at 250 (RHP - 250) and 350°C (RHP - 350), exergy efficiency of RHP - 250 and
 88 RHP - 350 are 30 and 21% respectively. RHP - 250 and RHP - 350 has 7 and 21% higher exergy than
 89 raw rice husk and specific chemical energy of RHP - 350 syngas is 32% higher than RHP - 250. In the
 90 present study, exergetic efficiency of rice husk is in the range of 23.11 – 62.24% for the selected
 91 operating condition.

92 Exergy analysis used as tool for process design and optimisation of thermal systems to find
 93 magnitude and location of irreversibility and to provide opportunity for energy efficiency improvement [2,
 94 6, 7]. Exergy is measure of usefulness of an energy form, it is the maximum work obtained when system
 95 is in thermodynamic equilibrium with surrounding [22]. Exergy consumed or destroyed in any real
 96 process, exergy consumption in any process is proportional to entropy created in the process [23]. In
 97 present situation, it is necessary to understand energy distribution in systems for sustainable development.
 98 Gasification simulation is done by non-stoichiometric equilibrium modelling to study effect of
 99 temperature, equivalence ratio on gas composition and to find out energy efficiency (η) and exergetic
 100 efficiency (ψ). Gibbs energy minimisation method is used to find the equilibrium composition of multi-
 101 phase system. Products with negative Gibbs free energy from possible products are found from objective
 102 function, by subjecting the model to elemental mass balance constraint and non-negativity of the number
 103 of moles. Lagrange multiplier – Iterative method used to solve set of simultaneous equations. The
 104 objective function is given by Eq. (1).

$$105 \quad G / RT = \sum_{j=1}^n n_j \left[\frac{G^0}{RT} + \ln \frac{n_j}{\sum n_j} \right] \quad (1)$$

106 Where, G – Total Gibbs energy kJ
 107 G^0 – Gibbs energy of pure component kJ
 108 R – Universal gas constant = 8.314 kJ/ kmol K
 109 n_j – Number of moles of component j

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

112 1.1. Energy and exergy analysis

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

$$117 \quad E_{\text{rice husk}} + E_{\text{air}} = E_{\text{gas}} + E_{\text{char}} + E_{\text{loss}} \quad (2)$$

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

123 represented by Eq. (3).

124

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

125 Where, LHV_{gas} – Lower heating value of gas mixture kJ/Nm^3

126 $\text{LHV}_{\text{rice husk}}$ – Lower heating value of rice husk kJ/kg

127 Y – Gas yield Nm^3/kg

128 Lower heating value of gas, rice husk and gas yield are calculated by Eq. (4), (5) and (6).

129

$$\text{LHV}_{\text{gas}} = (\text{CO}\% \times 126.36 + \text{H}_2\% \times 107.98 + \text{CH}_4\% \times 358.18) \text{ kJ/Nm}^3 \quad (4)$$

130 Where, CO, H₂, CH₄ represents carbon monoxide, hydrogen and methane in mole percentage.

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

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

$$Y = \text{Volume}_{\text{gas}} / \text{Mass}_{\text{rice husk}} \text{ Nm}^3/\text{kg} \quad (6)$$

133 Exergy analysis is a thermodynamic technique uses conservation of mass and energy principles
134 to design thermal systems with maximum efficiency and it is based on first and second law of
135 thermodynamics. Magnitude and location of energy degradation in a process identified by exergy
136 analysis, energy consumption minimisation leads to better utilisation of available energy, environmental
137 impact reduction and gasifier design improvement [2]. The thermodynamic inefficiency of thermal
138 system or process referred in terms of destruction or exergy loss, Exergy never conserves in irreversible
139 process, irreversibility in process considered as exergy loss to make exergy balance. Conservation of
140 energy indicates η is always higher than ψ [2]. Exergy balance of gasification process given by Eq. (7).

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

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

143 Total exergy of gas mixture calculated by Eq. (8)

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

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

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

148 Specific physical exergy calculated by Eq. (9),

$$e^{\text{ph}} = (h-h_0) - T_0 (s-s_0) \text{ kJ/kmol} \quad (9)$$

149 Where, h , s , h_0 and s_0 represent specific enthalpy, specific entropy, standard specific enthalpy and
 150 entropy, T_0 is atmospheric temperature.

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

S.No	Gas component	Specific chemical exergy (kJ/kmol)
1	N ₂	720
2	O ₂	3970
3	H ₂	236100
4	CO	275100
5	CO ₂	19870
6	CH ₄	831650

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

154 **Table 2. Specific enthalpy of gases [25]**

S.No	Gases	Enthalpy as a function of temperature (kJ/kmol)	Temperature range (K)
1	H ₂	$h = -13779.82 + 19.83 T + 1.54 \times 10^{-3} T^2 + 295179.9 T^{-1} + 4.77 \times 10^{-7} T^3 + 389.72 T^{0.5}$	298 < T < 1200
2	CO	$h = -235743.85 + 90.75 T - 3.12 \times 10^{-3} T^2 + 1541255.33 T^{-1} + 32063.32 \ln(T) - 5178.51 T^{0.5}$	298 < T < 1700
3	CO ₂	$h = -426583.55 + 103.34 T - 2.37 \times 10^{-3} T^2 + 40249.04 T^{-1} - 3496.57 T^{0.5} + 11004.74 \ln(T)$	298 < T < 1900
4	N ₂	$h = -23347.54 + 17.08 T + 8.69 \times 10^{-3} T^2 + 230154.97 T^{-1} - 1.51 \times 10^{-6} T^3 + 2939.81 \ln(T)$	298 < T < 1600
5	CH ₄	$h = -458850.73 + 304.93 T - 9.39 \times 10^{-3} T^2 + 4193372.13 T^{-1} + 110598.4 \ln(T) - 20287.96 T^{0.5}$	298 < T < 1300

155 Exergy lost due to gas mixing calculated from Eq. (10)

$$ex^{\text{mixing}} = RT_0 \ln(x) \text{ kJ/kmol} \quad (10)$$

156 Where, x – Mole fraction of gas component.

157 Exergetic efficiency of gasification process is defined as ratio of chemical exergy of gas
 158 produced to the exergy of biomass and air. Gas formation takes place at elevated temperature other
 159 than environmental condition to overcome this situation, physical exergy added in exergy calculation
 160 [2]. Exergetic efficiency calculated by Eq. (11)

$$\psi = Ex_{\text{gas}} / (Ex_{\text{rice husk}} + Ex_{\text{air}}) \times 100\% \quad (11)$$

161 Where, Ex_{gas} – Exergy of gas mixture kJ
 162 $Ex_{\text{rice husk}}$ – Exergy of rice husk kJ, calculated by Eq. (12).
 163 Ex_{air} – Exergy of air kJ

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

165 Where, m- mass of rice husk kg
 166 β – exergy coefficient, it is given by correlation (13)

$$\beta = 1.044 + 0.016 (H/C) - [0.3493 (O/C) (1 + 0.0531 (H/C))] + 0.0493 (N/C) / [1 - 0.4124 (O/C)] \quad (13)$$

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

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

169 Where, I – Irreversibility in the process kJ
 170 Ex_{input} – Exergy input in kJ

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

171 Where, S_{gen} – Entropy generated kJ/K

172 Environmental destruction factor (C_{ed}) used to quantify sustainability potential of gasification process
 173 and it is inverse of exergetic efficiency given by Eq. (16).

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

174 Sustainable development not only requires sustainable supply of clean and inexpensive energy source but
 175 also efficient use of them [24]. Exergy-based sustainability evaluation is useful to improve efficiency,
 176 minimise the payback period and pollution level [2]. Sustainability index is inverse of exergy destruction
 177 factor.

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

178 Relationship between ψ and SI given by Eq. (18)

$$\psi = 1 - (1 / SI) \quad (18)$$

179 2. Methodology

180 Non- stoichiometric equilibrium modelling with Gibbs free energy minimisation used in rice
 181 husk air gasification simulation. Rice husk elemental composition values are given by ultimate and
 182 proximate analysis, shown in Table 4. The stoichiometric air-fuel ratio calculated from elemental
 183 composition and operating conditions are taken from Karmakar et al [26] to validate simulation. Three
 184 equivalence ratios 0.25, 0.35 and 0.45 with temperature range 600 - 800°C has been adapted to find the
 185 effect of temperature and equivalence ratio on gas composition. Gas composition, gas yield and gas lower

186 heating value are calculated shown in Table 5, RMS value calculated by Eq. (19) and simulation has
 187 average RMS value of 3.59, indicates simulation is in agreement with experiment. To study cold gas
 188 efficiency and exergetic efficiency, temperature and equivalence ratio varied from 600 - 1000°C and 0.15
 189 - 0.55 respectively.

190

$$\text{RMS} = \sqrt{\frac{\sum_j^N (\text{Experiment} - \text{Simulation})^2}{N}} \quad (19)$$

191 Where, N is the number of gas components.

192

Table 3. Specific entropy of gases [25]

S.No	Gases	Entropy as a function of temperature (kJ /kmol K)	Temperature range (K)
1	H ₂	$s = 37.54 + 19.83 \ln(T) - 8.02 \times 10^{-3} T + 3.08 \times 10^{-3} T^2 + 147589.95 T^{-2} + 7.15 \times 10^{-7} T^2 - 389.72 T^{-0.5}$	298 < T < 1200
2	CO	$s = -518.71 + 90.75 \ln(T) - 6.24 \times 10^{-3} T + 770627.67 T^{-2} - 32063.32 T^{-1} + 5178.51 T^{-0.5}$	298 < T < 1700
3	CO ₂	$s = -539.42 + 103.34 \ln(T) - 4.74 \times 10^{-3} T + 20124.52 T^{-2} + 3496.57 T^{-0.5} - 11004.74 T^{-1}$	298 < T < 1900
4	N ₂	$s = 97.76 + 17.08 \ln(T) + 1.74 \times 10^{-2} T + 115077.48 T^{-2} - 2.26 \times 10^{-6} T^2 - 2939.81 T^{-1}$	298 < T < 1600
5	CH ₄	$s = -2373.23 + 304.93 \ln(T) - 1.88 \times 10^{-2} T + 2096686.07 T^{-2} - 110598.4 T^{-1} + 2087.96 T^{-0.5}$	298 < T < 1300

193

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

S.No	Ultimate Analysis	Mass Percentage	Proximate Analysis	Mass Percentage
1.	Carbon	38.43	Volatile matter	55.54
2.	Hydrogen	2.97	Fixed carbon	14.99
3.	Nitrogen	0.49	Moisture	9.95
4.	Sulphur	0.07	Ash	19.52
5.	Oxygen	36.36		
6.	Ash	21.68		

194 3. Results and discussion

195 3.1. Exergy distribution of individual gases and gas mixture

196 Chemical exergy of gases mainly depends on chemical exergy of carbon monoxide; it's variation
 197 in the product gas composition influence the chemical exergy of gas mixture. CO contributes 48.3 - 68.9%
 198 and H₂ contributes 28.06 - 38.64% of Ex^{ch} of gas mixture. N₂ is the major contributor for Ex^{ph}, it

199 contributes 37.08 - 51.13% of gas mixture physical exergy. CO₂ and CO contribute next to N₂, below
 200 675°C CO₂ contribution is more, increase in temperature decreases CO₂ content and physical exergy of
 201 CO₂ decreases. Except for N₂, Ex^{ch} of individual gases are greater than corresponding Ex^{ph}. The ratio of
 202 chemical exergy to physical exergy for H₂, CO, CO₂, N₂, CH₄ and gas mixture are in the range of 20.23 -
 203 31.49, 22.12 - 34.99, 1.01 - 1.62, 0.06 - 0.09, 35.05 - 59.68 and 6.93 -13.16 respectively.

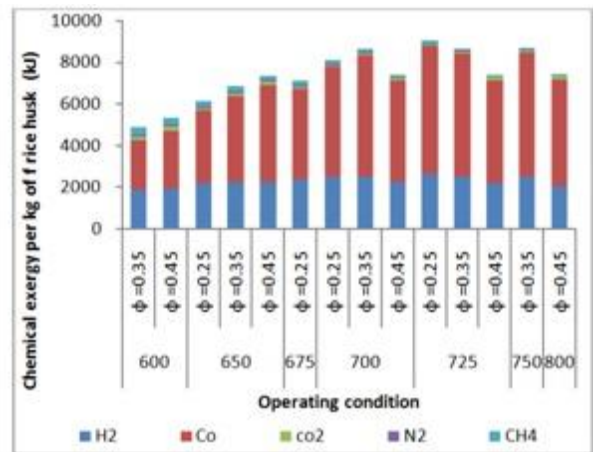
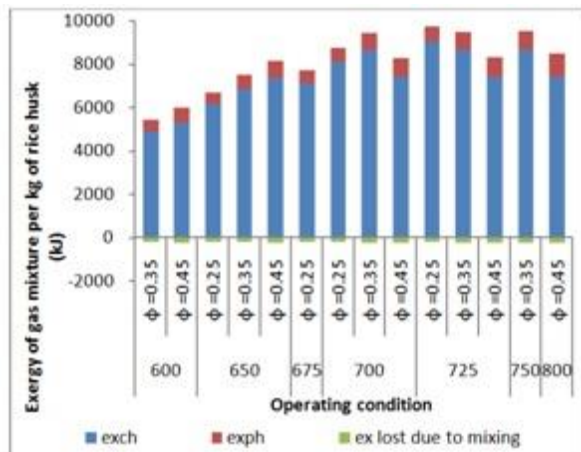
204 3.2. Effect of temperature and equivalence ratio on exergy

205 Effect of temperature on chemical exergy and physical exergy analysed for ϕ values 0.25, 0.35
 206 and 0.45. For specific ϕ value increase in temperature increases exergy of gas mixture due to increase in
 207 Ex^{ch} and Ex^{ph}, exergy lost due to mixing is lower than increase of Ex^{ch} and Ex^{ph}. Chemical exergy is the
 208 major contributor to exergy of gas mixture. Rice husk product gas exergy distribution at different
 209 operating conditions shown in Fig.1, maximum chemical exergy of 9058.33 kJ obtained per kg of rice
 210 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
 211 physical exergy of 1070.51 kJ obtained at 800°C for $\phi = 0.45$ and lowest value of 535.45 kJ corresponds
 212 to 650°C and $\phi = 0.25$. Chemical, physical exergy distribution of individual gases and exergy loss is
 213 shown in Fig. 2, 3 and 4. For $\phi = 0.25$ chemical exergy of H₂ increases with temperature rise, at $\phi = 0.35$
 214 Ex^{ch} decreases after 725°C and for $\phi = 0.45$ Ex^{ch} decreases after 650°C. Physical exergy of H₂ and N₂
 215 increases with increase in temperature for all ϕ values. Ex^{ch} and Ex^{ph} of CO increases but CH₄ decreases
 216 with increase in temperature. CO₂ chemical exergy decreases with increase in temperature, for $\phi = 0.25$
 217 physical exergy of CO₂ decreases with temperature, for $\phi = 0.35$ & 0.45 Ex^{ph} increases after 700 & 650°C
 218 respectively.

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

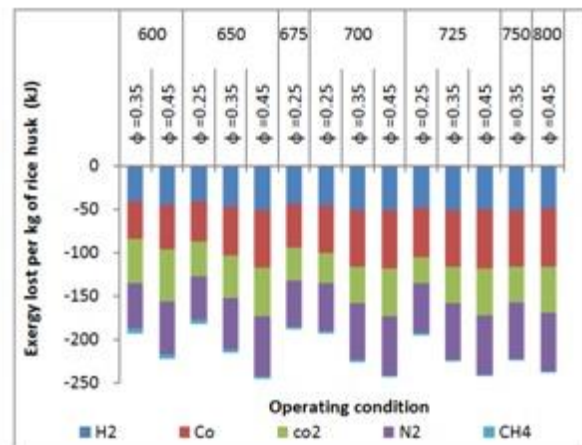
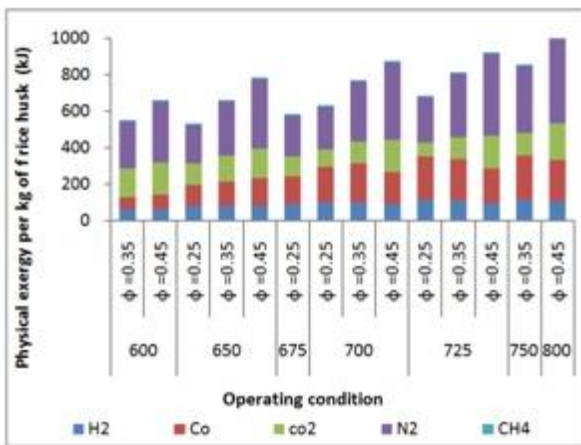
S.No	1	2	3	4	5	6	7	8	9	10	11	12	13	14
ϕ	0.25				0.35					0.45				
T	650	675	700	725	600	650	700	725	750	600	650	700	725	800
Karmakar et al [17] experimental gas composition (%)														
H ₂	17.22	17.93	18.12	18.49	14.13	14.22	14.63	15.88	16.08	8.92	9.32	10.15	10.27	10.22
CO	24.84	25.06	25.31	26.59	17.48	20.63	22.47	22.89	23.24	11.72	13.47	15.13	16.61	17.78
CO ₂	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 ₂	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 ₄	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 ₂	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 ₂	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 ₂	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 ₄	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

220 Effect of equivalence ratio analysed for temperatures 650, 700 and 725°C. At 650°C increase
 221 in equivalence ratio from 0.25 to 0.45 increases Ex^{ch} of gas mixture. At 700°C it increases initially
 222 and then decreases for ϕ value rise and at 725°C chemical exergy of gas mixture decreases with ϕ
 223 value rise. Physical exergy of gas mixture increases with ϕ value rise for temperatures. At 650°C
 224 except CH_4 chemical exergy of gases increases with ϕ value, at 700°C H_2 and CH_4 chemical exergy
 225 decreases, non-combustible gases (CO_2 and N_2) exergy values increases. CO chemical exergy
 226 increases for ϕ value change from 0.25 to 0.35 and then decreases. At 725°C combustible gases
 227 chemical exergy decreases and non-combustible gases exergy increases with increase in ϕ value,
 228 chemical exergy variation trend with ϕ value rise at different temperatures followed by physical
 229 exergy of individual gases.



230
231 **Figure 1. Exergy distribution of gas mixture**

Figure 2. Chemical exergy of Individual gases



232
233 **Figure 3. Physical exergy of individual gases**

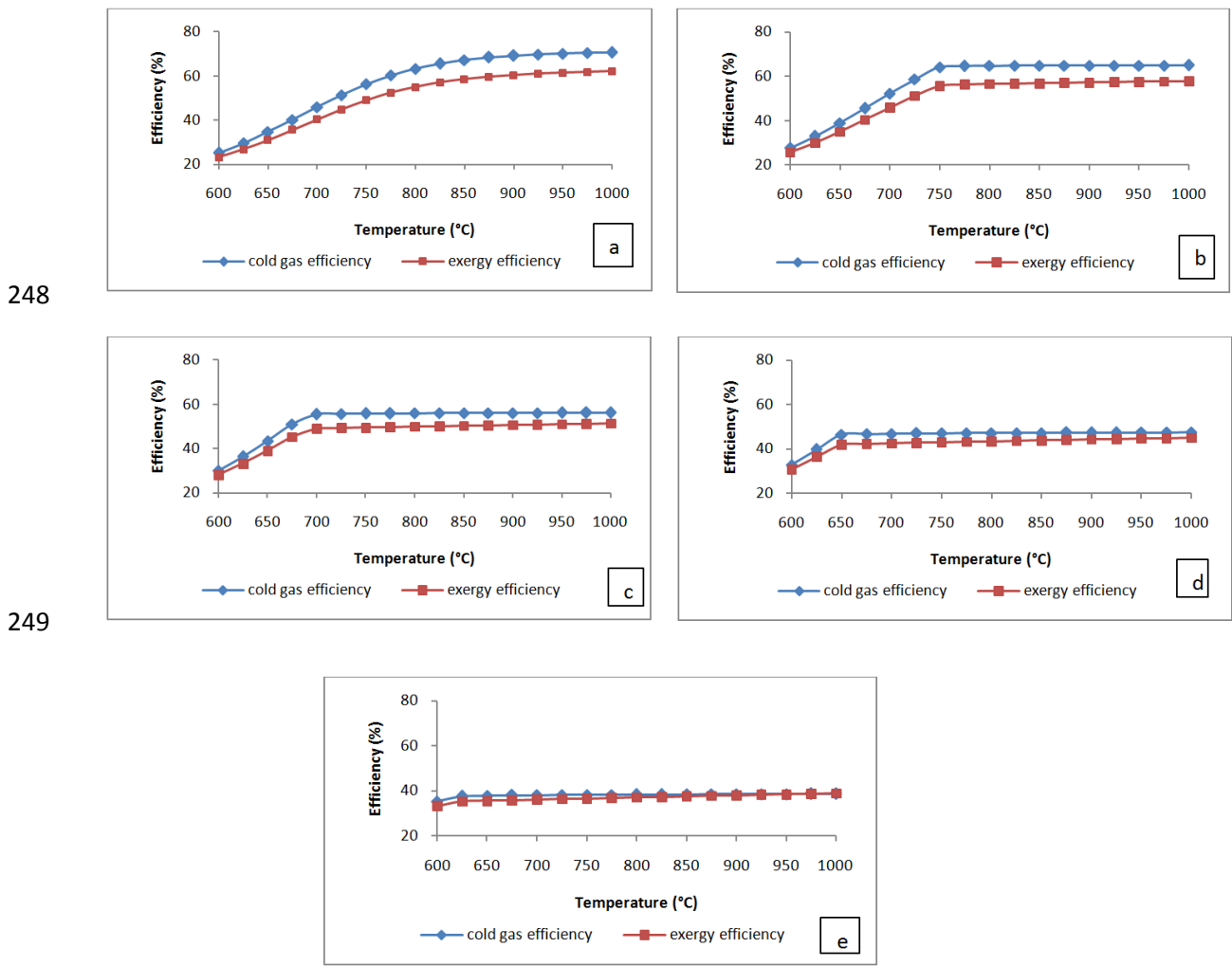
Figure 4. Exergy lost due to mixing of gases

234 **3.3. Effect of temperature and equivalence ratio on energy and exergetic efficiency**

235 The efficiency of gasification becomes almost constant after certain temperature due to CH_4
 236 and H_2 reduction and CO formation stabilisation. Efficiency stabilisation temperature decreases with
 237 increase in equivalence ratio, From Fig. 5 efficiency stables at 900,750,700,650 and 625°C for $\phi =$
 238 0.15, 0.25,0.35,0.45 and 0.55 respectively. Stabilisation temperature indicates further increase in

239 temperature of gasification has no remarkable increase in gasifier output. Exergetic efficiency follows
 240 the same trend of cold gas efficiency.

241 Equivalence ratio has strong influence on gasification, it affects bed temperature, gas
 242 composition and thermal efficiency. Gasifier temperature increases with increase in equivalence ratio
 243 because of increase in exothermic reactions [2]. At 600°C increase in ϕ value from 0.15 to 0.55
 244 increases cold gas efficiency. For 625 and 650°C, η value increases up to $\phi = 0.45$, for 675 and 700°C
 245 η value increases up to $\phi = 0.35$ and 725 - 800°C, η value increases up to $\phi = 0.25$. After 800°C
 246 increase in ϕ value decreases cold gas efficiency. Exergetic efficiency follows the same trend.
 247 increase in ϕ value decreases LHV_{gas} but it increases gas yield.

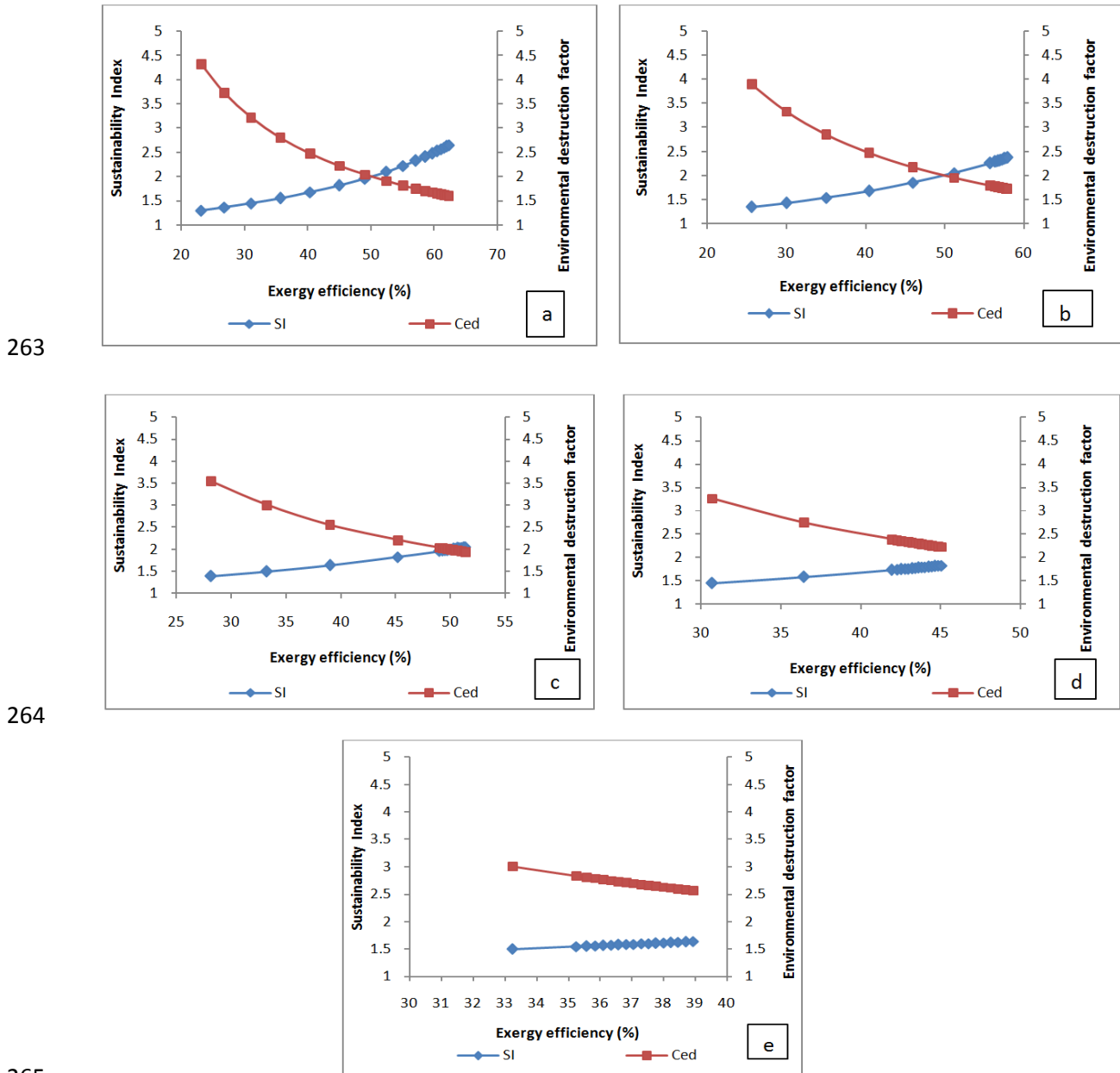


250
 251 **Figure 5. Effect of temperature on cold gas efficiency and exergetic efficiency (a) $\phi = 0.15$,**
 252 **(b) $\phi = 0.25$, (c) $\phi = 0.35$, (d) $\phi = 0.45$, (e) $\phi = 0.55$**

253 **3.4. Gasification process sustainability analysis**

254 The high value of sustainability index (SI), low exergy destruction fraction (F_{ed}) and
 255 environment degradation factor (C_{ed}) for a system or process is preferred. The increase of ψ value
 256 indicates the effective utilisation of energy, reduced consumption of feed material and its
 257 corresponding pollution. Increase in temperature increases SI value and decreases C_{ed} ; environmental

258 degradation factor is inverse of exergetic efficiency. SI and C_{ed} values coincide at $\psi = 50\%$, the
 259 condition at which useful work produced is equal to energy lost. For $\phi = 0.15$, 50% exergetic
 260 efficiency achieved at 750°C . Operating below this temperature is not advisable, similarly for $\phi =$
 261 0.25 and 0.35 725 and 825°C are respective temperatures. For $\phi = 0.45$ and 0.55 maximum exergetic
 262 efficiency of 45.06 and 38.93 are achieved at 1000°C .



265 **Figure 6. Sustainability index and environmental destruction factor of gasification process**
 266 **(a) $\phi = 0.15$, (b) $\phi = 0.25$, (c) $\phi = 0.35$, (d) $\phi = 0.45$, (e) $\phi = 0.55$**
 267

268 **4. Conclusions**

269 The main combustible gases- CO , H_2 and CH_4 are formed during gasification of rice husk.
 270 Carbon monoxide and hydrogen play a crucial role in gas heating value contribution due to its high
 271 formation. Increase in temperature increases CO content from 0.15 to 0.55 equivalence ratios, H_2
 272 increases with temperature at low ϕ value, increase in ϕ value reduces hydrogen content. H_2 and CO

273 content increase with the increase in equivalence ratio at 600°C, at 625 and 650°C increase in
 274 equivalence ratio decreases H₂ and CO content after $\phi = 0.45$. Further increase in temperature reduces
 275 H₂ and CO formation. Based on gasification simulation results of rice husk, chemical exergy value of
 276 gas mixture is 6.93 – 13.16 times greater than corresponding physical exergy values. CO is the main
 277 contributor to chemical exergy of gas, it provides 48.3 - 68.9% of chemical exergy of the gas mixture.
 278 Nitrogen is major contributor for physical exergy, it provides 37.08 - 51.13 % of physical exergy of
 279 gas mixture. Energy efficiency is in the range of 25.19 - 70.71% and exergetic efficiency in the range
 280 of 23.11 - 62.24%. Increase in temperature increases energy and exergetic efficiency, influence of CO
 281 is predominant on energy and exergetic efficiency.

282 Nomenclature

283	C_{ed}	– Environmental destruction factor	T_0	– Atmospheric temperature [K]
284	E_{char}	– Energy present in char, [kJ]	x	– Mole fraction of gas component
285	E_{gas}	– Energy present in gas, [kJ]	Y	– Gas yield [$Nm^3 kg^{-1}$]
286	E_{loss}	– Energy lost, [kJ]	Greek symbols	
287	$E_{rice\ husk}$	– Energy present in rice husk, [kJ]	β	– Exergy coefficient
288	EX_{air}	– Exergy of air, [kJ]	ϕ	– Equivalence ratio
289	EX_{char}	– Exergy of char, [kJ]	η	– Energy efficiency [%]
290	EX_{gas}	– Exergy of gas, [kJ]	ψ	– Exergetic efficiency [%]
291	EX_{loss}	– Exergy lost, [kJ]	Acronyms	
292	$EX_{rice\ husk}$	– Exergy of rice husk, [kJ]	E	– Energy
293	EX^{ch}	– Chemical exergy, [kJ]	Ex	– Exergy
294	EX^{mixing}	– Exergy lost due to mixing, [kJ]	LHV	– Lower heating value
295	EX^{ph}	– Physical exergy, [kJ]	RHP – 250	– Rice husk pellet torrefied at 250°C
296	EX_{total}	– Total exergy of gas mixture, [kJ]	RHP – 350	– Rice husk pellet torrefied at 350°C
297	EX_{input}	– Exergy input, [kJ]	RMS	– Root mean square
298	F_{ed}	– Exergy destruction factor	SI	– Sustainability index
299	G	– Total Gibbs energy, [kJ]		
300	G^0	– Gibbs energy of pure component, [kJ]		
301	h	– Specific enthalpy, [$kJ kg^{-1}$]		
302	h_0	– Standard specific enthalpy, [$kJ kg^{-1}$]		
303	I	– Irreversibility in the process, [kJ]		
304	LHV_{gas}	– Lower heating value of gas mixture [$kJ Nm^{-3}$]		
305	$LHV_{rice\ husk}$	– Lower heating value of rice husk [$kJ kg^{-1}$]		
306	n_j	– Number of moles of component		
307	N	– Number of gas components		
308	R	– Universal gas constant, [$kJ kmol^{-1} K^{-1}$]		
309	s	– Specific entropy, [$kJ kg^{-1} K^{-1}$]		
310	s_0	– Standard specific entropy, [$kJ kg^{-1} K^{-1}$]		
311	S_{gen}	– Entropy generated, [$kJ K^{-1}$]		

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