Exergy Analysis of Self-Bed Feedstock in Rice Husk Bubbling Fluidized Bed Gasifier

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Abstract. This study will use the result simulation of bubbling fluidized bed gasifier (BFBG) in CFD to know the value of producer gas (CO₂, CO, H₂, CH₄, O₂, and N₂). Commonly in BFBG silica sand is used as bed material in the gasification process but in this study silica sand or bed material is absented in the gasification process. The energy and exergy analysis will be evaluated in this study to indicate the performance of BFBG without bed material. In this study rice husk is used as a feedstock with feed rate 0.2 kg/s, and air is used as medium gasification in the range of ER (equivalence ratio) between 0.24 to 0.45. Variation of ER affect the value of energy and exergy, where the higher ER applied the higher exergy destruction that occur and decrease the efficiency of exergy. It was calculated that the best efficiency was obtained when the value of ER is 0.24, with the total value of energy and exergy are 2544 and 2335 kJ per kg biomass, sequentially.

1. Introduction
Biomass to energy through the process of thermochemical in gasification especially, become one of the solutions to fulfill the energy requirements, moreover biomass to energy will help us to maintain the produce of GHG (greenhouse gasses). According to the European Commission’s about the definition of biomass, there are several kind resources of biomass such as, residue from agriculture, biodegradable parts of industry and municipal solid waste (MSW), also forestry and relative industries [1]. Residue from agriculture, rice husk become one of the potential biomass to produce energy, because of the high calorific values (15.3 MJ/kg-biomass) [2]. From paddy rice we can get rice husk around 20 to 33% from the total wight of paddy rice [3]. Country like China, India, Indonesia and Bangladesh are the highest country that produce the paddy rice [4]. In 2019, Indonesia produce paddy rice around 54 million ton [5], then the wight of rice husk approximately about 10.8 million ton. So, Indonesia have a huge potential to produce energy through the rice husk.

Utilization biomass to energy can be done by the process of gasification. Gasification is a method to generate power from syngas by the process of thermochemical partial oxidation process where the carbonaceous materials (coal, biomass, plastics) are transformed to gas [6]. There are several kinds of reactors in the process of gasification to convert biomass to various products (syngas, tar, ash, and char) and quantities [7]. Bubbling fluidized bed gasifier (BFBG) is one of several kind of reactor which, usually use silica sand as bed material [8]. Mummayiz et.al [9] did simulation about BFBG but in unique condition where feedstock is being used as bed
material (self-bed feedstock). The reasons why rice husk is used as a feedstock already describe in the previous paragraph, and foremost because the composition of silica in rice husk itself [10]. The outcome from simulation consist data about syngas composition, cold gas efficiency, yield syngas, calorific value, and temperature distribution, which form those data we can use to do analysis energy and exergy.

Exergy is amount of the usefulness of energy form, as the system in the state of thermodynamic equilibrium with the surroundings then the maximum work is obtained [11]. The analysis of energy and exergy is carried out to evaluate the energy sources also, from exergy analysis we can do optimization of thermal system to make a chance to improve the energy efficiency from finding magnitude and location of irreversibility [12][13]. Kanit et. al [14] used fluidized bed gasification and torrefied rice husk pellet as feedstock to do the analysis of exergy, the experiments show that the process of torrefaction can enhance exergy but the overall energy efficiency is decline because the energy loss in volatile gas and energy input throughout the process of combined torrefaction-gasification. The overall exergy efficiency for the torrefied rice husk pellets are 30% and 21% at temperature 250 °C and 350 °C, sequentially. Yaning et. al [12] evaluate the energy and exergy analysis of rice husk gasification in an entrained flow reactor in the differences of ER and temperature reactor. The result of this study shown that temperature and ER affect the value of energy and exergy from syngas. The highest energy and exergy of syngas were obtained when temperature reactor is 1000 °C and ER 0.25, about 10,062 and 7990 kJ per kg biomass, sequentially. In this study, the energy and exergy analysis from simulation data by Mummyiz et. al [9], about self-bed feedstock in rice husk bubbling fluidized bed gasification will be performed.

2. Energy analysis

Fig. 1 present the schematic input and output form the flow of energy and exergy in FBG, the analysis of energy and exergy are evaluated by using some assumptions:

(i) The system was analyzed at steady state condition.
(ii) Reference state is set for pressure $P_o$ (101.324 kPa) and temperature $T_o$ (25°C).
(iii) Producer gas is assumed as ideal gas.
(iv) The remain residue ash and char form the process gasification was negligible
(v) The change of potential and kinetic energies and exergies between inlet and exit are negligible.
(vi) Heat loss through the reactor was neglected.

Energy from the biomass is converted by the process of gasification where the process of gasification will produce a producer gas that can be used as a fuel. Table 1 give the ultimate and proximate analysis from the biomass and Table 2 shown the value of converted biomass to the producer gas also the result calculation of energy and exergy. Evaluation the energy and exergy from the product of gasification is the important matter to know the best parameter for operation. The value of gaseous will convert to another unit using some formula.

Mass balance in gasifier reactor is defined as the total mass entering the inlet of reactor equal to the total mass exit from the reactor that write as,

$$\dot{m}_{\text{biomass}} + \dot{m}_{\text{air}} = \dot{m}_{\text{syngas}} + \dot{m}_{\text{tar}} + \dot{m}_{\text{char}} + \dot{m}_{\text{ash}}$$

$$\dot{E}_{\text{biomass}} + \dot{E}_{\text{air}} + \dot{E}_{\text{heat}} = \dot{E}_{\text{syngas}} + \dot{E}_{\text{tar}} + \dot{E}_{\text{char}} + \dot{E}_{\text{ash}} + \dot{E}_{\text{loss}}$$

In the process of gasification, the total of energy flow can be defined as,

$$\dot{E}_t = \dot{E}_{ph} + \dot{E}_{ch}$$
by ignoring the kinetic and potential energy rates, the total energy rate equation can be rewritten as,

\[ \dot{E}_t = \dot{m} (h + HHV) \]  

(4)

The value of HHV can be calculated by using equation,

\[ HHV = 33823 \, C + 144249 \left( H - \frac{O}{8} \right) + 9481 \, S \left( \frac{J}{kg} \right) \]  

(5)

where the value of C, O, S, H are shown in Table 1 with a calculated by difference and adb (air-dried base). To get the value of LHV we omit the moisture content from the biomass and can be predict using equation,

\[ LHV = HHV - 22604H - 2581M \left( \frac{kJ}{kg} \right) \]  

(6)

**Table 1: Analysis ultimate and proximate of rice husk [15]**

| Parameter                  | Value     |
|----------------------------|-----------|
| Proximate analysis (%) , adb |           |
| Volatile mater             | 61.78     |
| Fixed Carbon               | 8.04      |
| Moisture                   | 4.55      |
| Ash                        | 30.18     |
| Ultimate Analysis (%) , adb |           |
| Carbon (C)                 | 37.65     |
| Hydrogen (H)               | 5.13      |
| Nitrogen (N)               | 1.63      |
| Oxygen (O)\(^a\)           | 55.40     |
| Sulfur (S)                 | 0.18      |
| Heating value (MJ/kg)      |           |
| LHV                        | 12.85     |

3. **Exergy analysis**

Exergy calculation is one of ways to know the value of maximum work that can be used, its different from energy that cannot be destroyed, exergy can destroyed due to the irreversible process in the system, thus the exergy balance equation for this case can be written as,

\[ \dot{E}_{x_{\text{biomass}}} + \dot{E}_{x_{\text{air}}} + \dot{E}_{x_{\text{heat}}} = \dot{E}_{x_{\text{syngas}}} + \dot{E}_{x_{\text{tar}}} + \dot{E}_{x_{\text{char}}} + \dot{I}_g \]  

(7)

Total exergy rate entering and exit from reactor is defined as

\[ \dot{E}_{x_t} = \dot{E}_{x_{\text{char}}} + \dot{E}_{x_{\text{ph}}} \]  

(8)

The analysis exergy from biomass just consider the chemical exergy, corresponding to the empirical correlation that Szargut [16] proposed,

\[ \dot{E}_{x_{\text{biomass}}} = \dot{m}_{\text{biomass}} \beta LHV_{\text{biomass}} \]  

(9)

where \( \beta \) is the quality of fuel that could be defined as ratio between exergy to LHV of biomass and in equation expressed as [16],

3
\[ \beta = 1.0414 + 0.0177 \left( \frac{H}{L} \right) -0.3328 \left( \frac{O}{L} \right) \left[ 1 + 0.0537 \left( \frac{H}{L} \right) \right] \frac{1}{1 - 0.4021 \left( \frac{O}{L} \right)} \]  

(10)

C, H, and O are a molar fraction from biomass that shown on Table 1. Physical exergy of syngas is calculated as follows [17]:

\[ \dot{E}_{\text{ph}} = \dot{m}_{\text{syngas}} \times \sum_i y_i e_i^{\text{ph}} \]  

(11)

\[ e_i^{\text{ph}} = (h - h_i) - T_o (s - s_o) \]  

(12)

Chemical exergy can be calculated as follows [18]:

\[ \dot{E}_{\text{ch}} = \dot{m}_{\text{syngas}} \times \sum_i y_i \left( e_i^{\text{ch}} + RT_o \ln \frac{y_i}{\sum y_i} \right) \]  

(13)

The efficiency of exergy is ratio between exergy rate-out to exergy rate-in from the reactor, written as

\[ \eta_{\text{Ex}} = \frac{\dot{E}_{\text{syngas}}}{\dot{E}_{\text{air}} + \dot{E}_{\text{heat}}} \]  

(14)

The calculation of energy and exergy analysis from data simulation by Mummayiz et. al [9] shown on Table 2.

| ER (MJ/Nm³) | % Efficiency | Energy | Exergy |
|------------|--------------|--------|--------|
| 0.24       | 83.19%       | 60.01% |
| 0.31       | 71.9%        | 50.99% |
| 0.38       | 65.44%       | 45.05% |
| 0.45       | 49.68%       | 33.39% |

4. Result and discussion

ER is represented as the proportion between actual air fuel ratio to stochiometric air fuel ratio [18], from the data simulation, ER was used in the range of 0.24 to 0.45 which means only 24% to 45% of stochiometric air was given to reactor. The higher value of ER involves the more air intake to reactor. The effect of ER on energy and exergy of syngas shown in Table 2. The highest efficiency of energy and exergy of syngas occur in the value of ER 0.24, with the total value of efficiency is about 83.19% and 60.01%, sequentially. For ER 0.31 to 0.45 the value of total efficiency for energy and exergy of syngas decrease until the lowest value about 49.68% and 33.39%. Fig. 2 (a) and (b) show the total energy and exergy from syngas in difference of ER consist of chemical and physical energy and exergy at certain temperature, Fig.2 shows that chemical energy and exergy are the main contributor toward energy and exergy of gas mixture. Maximum chemical energy and exergy occur in the value of ER 0.24 at temperature 485 °C in value 2387 and 2186 kJ per kg biomass and the lowest happen when ER 0.45 in value 1303 and 1180 kJ per kg biomass at temperature 817 °C. The value of energy and exergy decrease significantly from ER 0.38 to 0.45 where the value of energy and exergy decrse 482 and 443 kJ/kg, respectively. ER 0.38 give the highest value of physical energy and exergy than the
others, where the value is 232.5 kJ/kg for energy and 222.7 kJ/kg for exergy at temperature 738 °C.

Table 1. show the heating value of biomass 12.85 MJ per kg biomass from the process of gasification the energy from biomass is converted to syngas in heating value around 5.96 to 7.77 MJ/Nm$^3$ as shown in Table 2. The differences heating value of syngas involved by operation condition for this work is ER. Nevertheless, not only the value of ER that give a different heating value but also variety of biomass, agent gasification, catalysts, reactors, feeding rate, feed stock size, gasification temperature and etc, will give a various of heating value and characteristic of syngas [19].

The increases value of the ER will increase the volume of O$_2$ and affect the production of gas producer. In the process of gasification, we perform a lower amount of air, in order to make a partial oxidation to produce a combustible gas like CO, H$_2$, and CH$_4$ [6]. The higher quantity of air will bring the reaction to the process of combustion and affect the number of combustible gas where the amount of it will decrease and the gases produced by combustion process like CO$_2$ and H$_2$O vapors will increase [20]. Thus, this is one of the reasons why the total value of energy and exergy decrease in the process of increasing ER.

Temperature gasification is affected by ER, where the rising ER will increase the temperature of gasification. The high temperature of gasification will lift the production of combustible gas [21]. Thus, there are contrary between the high ER and temperature to produce syngas. Increasing the value of energy and exergy syngas can be done by increasing temperature of gasification, but in the condition, a few amounts of air that in take to the reactor. To do this, we must find the optimum value of ER and temperature to get the highest value of combustible gas. Furthermore, rice husk as self-bed material utilizes a component of silica as medium of gasification, based on study which is done by Al-Farraji et. al [22] inform that, there is no change of value of $U_{mf}$ (minimum fluidizing velocity) by the variation height of the bed but the alteration of size material bed will vary the value of $U_{mf}$. During the process of gasification, the change size of rice husk is unavoidable because the process of decomposition. Thus, the value of $U_{mf}$ decrease in the process gasification of self-bed feedstock in rice husk bubbling fluidized bed.

5. Conclusion

In this work the lowest ER give the best value of efficiency for energy and exergy from self-bed feedstock in rice husk bubbling fluidized bed gasification at ER 0.24 with total energy and exergy by syngas about 2544 and 2335 kJ per kg biomass, respectively at temperature 484 °C. The value of best efficiency for energy and exergy from syngas are 83.19% and 60.01% , sequentially. ER has influence to the value of temperature, while increasing ER the value of temperature will rise due to the rising quantity of air (O$_2$). So, the reaction between biomass and air is going to the combustion process, and make the production of syngas decrease, in reverse the volume of gas CO$_2$ and H$_2$O are increases. Throughout, the process gasification of self-bed feedstock the value of $U_{mf}$ decrease, due to the decomposition of rice husk.
Nomenclature

\( \dot{m} \)  Mass flowrate  \( y \)  Molar fraction syngas  \( T \)  Temperature
\( \dot{E} \)  Energy flowrate  \( \eta_{Ex} \)  Efficiency of exergy  \( R \)  Gas constant
\( \dot{E}_{x} \)  Exergy flowrate  \( HHV \)  Higher heating value  \( e \)  Exergy
\( s \)  Entropy  \( LHV \)  Lower heating value  \( P \)  Pressure
\( I_{g} \)  Irreversibility of gasifier  \( h \)  Enthalpy

Subscript and Superscript

\( ch \)  Chemical  \( i \)  Specific component
\( ph \)  Physical  \( o \)  Initial condition
\( t \)  Total  \( f \)  formation

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