Research and Analysis on Gas Performance Index of Pine Particle Gasification

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Abstract. The gasification test was carried out with pine particle as raw material, how temperature and steam flow rate affect gas gasification performance index was studied by using self-made gasification test system platform. The results show that the volume fraction of hydrogen increases, the volume percentage of carbon monoxide decreases and CH₄ content decreases with the increase of temperature in steam flow rate of 0.3kg/h; Its the gas volume fraction of the trend is similar with the steam flow rate of 0.3kg/h, but the total gas energy with the temperature increased first and then reduced and the total gas increased by 28393.39KJ/Kg at 800 ℃; The steam flow from 0.3kg/h to 0.6kg/h, the low calorific value of gas varies from 10 to 14MJ/m³, the increase of the calorific value of gas is 2111.36KJ/m³.

1. Introduction
As a clean energy, biomass has two characteristics: the first, biomass containing sulfur, nitrogen content is low, Gases generated during the utilization and conversion of biomass have low fouling properties. The second, Biomass energy is formed by photosynthesis of green plants, it can effectively reduce the greenhouse gas CO₂, can improve the ecological environment because of releasing O₂ [1-2]. Biomass gasification converts low-grade biomass into clean gas, and replaces non-renewable fuels for human needs[3]. Therefore, biomass gasification technology, especially water vapor gasification technology, has received universal attention[4]. Kong Meng et al.[5] think that biomass utilization is
one of the most promising utilization methods in energy conversion, so it has become a hot spot for research. The heart of biomass gasification is the gasifier, which is also the least efficient system in gasification systems[6]. The traditional evaluation of gasification efficiency generally uses carbon conversion rate and cold gas efficiency, this method is theoretically deficient [7]. Dinner I et al.[8] showed that in an adiabatic system (ignoring heat loss), the energy efficiency can reach 100% while the exergy efficiency is only 79%. Therefore, many scholars recommend using exergy performance indicators instead of the traditional energy analysis in order to achieve a more reasonable evaluation. Through the research on the characteristics of high-yield gas produced by gasification of biomass and the analysis of gasification process performance indexes (low calorific value of syngas, exergy efficiency and gas exergy), the quality of gas is improved[9].

2. Method

2.1. Experimental Materials

The gasification test was carried out with waste pine sawdust material of a wood processing plant in Baotou (Figure1(a)) by using self-made high temperature steam gasification of biomass to produce hydrogen gas test system platformFigure1(b). Pine sawdust elemental analysis and industrial analysis as shown in Table 1. Pine shredded pellets were passed through a pellet mill (model K120 manufactured by Xiaoyi Mingyang Machinery Factory, Figure1(b)) before the test. Pellets with a grain size of about 10 mm and 10 mm long were selected as the test material (Figure1(c)). Exhaust air from the system through nitrogen injection and check its air tightness before experiment. And then the water and gasifier were heated to a predetermined temperature by the control system and tested. Then different steam flow rates and temperatures were selected as variables to test. At the same time, 160 mg particles were weighed, and the nitrogen purity of 99.99% and 100 ml / min of flow rate was used as a carrier. Thermal gravimetric analysis was carried out by heating to a predetermined temperature of 800°C, at a heating rate of 10K/min. The weight loss was measured at different times. The different stages in the gasification and pyrolysis process are studied.

![Figure 1](image1.png)

**Figure 1.** Experimental raw materials and equipment.

| Table 1. Proximate and ultimate analysis of pine wood shavings. |
|----------------------|------|-------|------|------|------|
| Elemental Analysis   | Element mass fraction/% | C_{ad} | H_{ad} | O_{ad} | N_{ad} | S_{ad} |
| Industry Analysis    | Compositio mass fraction/% | V^a | F_C^b | A^c | Q_{LHV}^dMJ/kg |
| Elemental Analysis   | 50.54 | 7.08 | 41.11 | 0.15 | 0.57 |
| Industry Analysis    | 82.29 | 17.16 | 0.55 | 16.89 |
2.2. Determination of gasification components and component content

Gas chromatography (Agilen 7890B) manufactured by Agilent Technologies Inc. was used to detect and analyze pine gas at different flow rates and temperatures, and gas analysis was performed using a thermal conductivity detector (TCD) such as H₂, CO and CH₄.

2.3. Analysis of Gasification Process Performance Indexes

For the gasification system, the input of exergy to the gasifier include biomass exergy flow rate and steam exergy flow rate, the output of exergy are gas exergy flow rate, tar exergy flow rate, and ash exergy flow rate. For gasifiers exergy balance equation is

\[ \dot{E}_{\text{steam}} + \dot{E}_{\text{biomass}} - \dot{E}_{\text{fuel}} - \dot{E}_{\text{ash}} - \dot{E}_{\text{tar}} = \dot{E}_{\text{dest}} \]  

(1)

Where \( \dot{E}_{\text{steam}} \) is steam exergy flow rate, KW; \( \dot{E}_{\text{biomass}} \) is biomass exergy flow rate, KW; \( \dot{E}_{\text{fuel}} \) is gas exergy flow rate, KW; \( \dot{E}_{\text{ash}} \) is ash exergy flow rate, KW; \( \dot{E}_{\text{tar}} \) is tar exergy flow rate, KW; \( \dot{E}_{\text{dest}} \) is gasifier exergy loss.

2.3.1. Gas exergy flow rate. Gas exergy flow rate includes physical exergy flow rate and chemical exergy flow rate, which are calculated as:

\[ \dot{E}_{\text{fuel}} = \dot{E}_{\text{ph}} + \dot{E}_{\text{ch}} \]  

(2)

in this equation, \( \dot{E}_{\text{ph}} \) is gas physical exergy flow rate, KW; \( \dot{E}_{\text{ch}} \) is gas chemical exergy flow rate, KW.

Chemical exergy flow rate is calculated as:
\[ \dot{E}_{ch} = n \left( \sum_i x_i E_{0i} + RT_0 \sum_i x_i \ln x_i \right) \]  

in this equation, \( \dot{E}_{ch} \) is gas chemical exergy flow rate, KW; \( \dot{n} \) is molar flow rate, kmol/s; \( E_{0i} \) is standard chemistry exergy of component i, KW; as shown in Table 2; \( R \) is the ideal gas constant 8.314KJ/(Kmol·K); \( T_0 \) is the temperature in the reference state, K; \( x_i \) is the volume fraction or mole fraction of component i, %.

**Table 2.** Specific enthalpy, entropy and standard chemical exergy of components[10].

| Gas | \( h_0 \) kJ · kmol\(^{-1} \) | \( s_0 \) kJ · kmol\(^{-1} \) · K\(^{-1} \) | \( E_{x0} \) kJ · kmol\(^{-1} \) |
|-----|-------------------------------|---------------------------------|-------------------|
| H\(_2\) | 8468.00 | 130.57 | 236100 |
| CO | 8669.00 | 197.54 | 275100 |
| CH\(_4\) | 186.16 | | 831650 |

The gas physical exergy flow rate is calculated as:

\[ \dot{E}_{ph} = \dot{n} \left[ \left( h - h_0 \right) - T_0 \left( s - s_0 \right) \right] \]  

Where \( h \) is the specific entropy, kJ/ (mol·K) and \( s \) is the specific enthalpy at the given temperature and pressure, kJ/mol; \( h_0 \) is the standard specific enthalpy and \( s_0 \) is the standard specific entropy under the reference, its value is shown in Table 2; assuming that the gas is an ideal gas, the specific enthalpy difference and the specific entropy difference are calculated as follows:

\[ \Delta h = h - h_0 = \int_{h_0}^{T} c_p dT \]  

\[ \Delta s = s - s_0 = \int_{s_0}^{T} \frac{c_p}{T} dT - R \ln \frac{P}{P_0} \]

Where \( p \) is the given pressure, pa; \( T \) is the given temperature, K; \( P_0 \) is the pressure under the reference state, pa; \( c_p \) is the specific constant pressure heat capacity; the specific constant pressure heat capacity is calculated as follows:

\[ C_p = a' + b'T + c'T^2 + d'T^3 \]  

The type of proportional coefficient according to Table 3.

**Table 3.** Coefficients used in constant specific heat empirical equation[11].

| Gas | \( a' \) | \( b' \) | \( c' \) | \( d' \) |
|-----|---------|---------|--------|--------|
| H\(_2\) | 29.11 | -1.916×10\(^{-3} \) | 4.003×10\(^{-6} \) | -8.704×10\(^{-10} \) |
| CO | 28.16 | 1.675×10\(^{-3} \) | 5.372×10\(^{6} \) | -2.222×10\(^{-9} \) |
2.3.2. Gas energy efficiency. Gas is the main product of gasifier, so the effective use of gas energy is the gas exergy, exergy efficiency is calculated as

\[
\eta_{\text{fuel}} = \frac{\dot{E}_{\text{fuel}}}{\dot{E}_{\text{biomass}} + \dot{E}_{\text{steam}}} \times 100\%
\]

in this equation, \( \eta_{\text{fuel}} \) is gas efficiency, \( \% \); \( \dot{E}_{\text{fuel}} \) is gas exergy flow rate, KW; \( \dot{E}_{\text{biomass}} \) is exergy flow rate of biomass, KW; \( \dot{E}_{\text{steam}} \) is exergy flow rate of steam, KW.

2.3.3. Calculation of low gas calorific value. Come to its calculation formula[12]:

\[
Q_{\text{LHV}} = 126CO + 108H_2 + 359C_4
\]

in the formula, \( Q_{\text{LHV}} \) is the gas calorific value, MJ/m³; CO, H₂ and CH₄ are the volume fraction of gas, %.

2.3.4. Calculation formula of biomass exergy flow rate.

\[
\dot{E}_{\text{biomass}} = m \beta_{\text{biomass}} L_{\text{biomass}}
\]

Where \( \beta \) is the correlation factor; \( L_{\text{biomass}} \) is the low-grade heat value of biomass MJ/m³; \( m \) is the mass flow rate, kg/s; based on the literature [13-14], \( \beta \) is calculated as:

\[
\beta_{\text{biomass}} = \frac{1.044 + 0.016H/C + 0.3493O/C(1 + 0.0531H/C) + 0.0493N/C}{1 - 0.04124O/C}
\]

in the equation, C, H, O and N are the volume fraction of elemental analysis in biomass, %.

3. Results and discussion

3.1. Influence of temperature

Figure 3 shows the TG curve at a heating rate of 10 K/min. From Fig. 3, it can be seen that the pyrolysis of the particles can be roughly divided into three stages. (1) At about 100°C, Differential thermogravimetry curve shows the first peak, at this point is mainly pine particles moisture evaporation stage. (2) It is obvious that the second peak at 340 °C is the pyrolysis stage of pine pellet, and the weight loss rate reaches the maximum at this time. It is the main phase of pyrolysis reaction and also the volatile release stage. (3) After the temperature is higher than 500 °C, the ash is mainly the further decomposition of the solid residue, finally reaching the weight loss rate of 19.06%. The result is consistent with the previous study of Niu [15]. The results show that the production of gasification gas is mainly determined by one reaction, which mainly includes the reaction of volatilization and water vapor conversion[16-22].
Figure 3. The pyrolysis weight loss curve of pine sawdust.

Figure 4 (a) and (b), respectively, at the steam flow of 0.3kg/h and 0.6kg/h, the gas volume fraction changes with temperature. It can be seen from Fig.4(a) that as the temperature increases, the volume fraction of H\textsubscript{2} increases from 27.45% to 38.38% with an increase of 10.93%, while the volume fraction of CO decreases and the minimum volume fraction reaches 22.21% at 800°C. On the one hand this is because more biomass and tar are cleaved by the elevated temperature and release more gas molecules, and on the other hand the water vapor reduction reaction (C+2H\textsubscript{2}O→CO+2H\textsubscript{2}) is endothermic, increasing the temperature favors the forward reaction. With the increase of CO concentration, promoting the CO shift reaction (CO+H\textsubscript{2}O→H\textsubscript{2}+CO\textsubscript{2}) to the forward direction, which leads to the increase of H\textsubscript{2} volume fraction and the decrease of CO volume fraction. Franco et al. [23]. concluded that the steam reduction reaction (C+2H\textsubscript{2}O→CO\textsubscript{2}+2H\textsubscript{2}) became more dominant at a temperature higher than 830°C, similar to our experimental results. With a gradually increasing temperature, the rate of CO\textsubscript{2} reduction (C+CO\textsubscript{2}→2CO) begins to dominate, and the reaction is endothermic, resulting in an increase in the CO content of the gas. As the reaction of CH\textsubscript{4} with steam reforming is endothermic, with the increase of temperature, the reaction rate of methane (CH\textsubscript{4}+H\textsubscript{2}O→3H\textsubscript{2}+CO) increases, and the volume fraction decreases from 17.29% to 11.98%. The trend of curves in Figure 4(a) are similar to Figure 4(b). When the temperature is 950 °C, the volume fractions of H\textsubscript{2} and CO increase from 38.38% and 27.67% of 0.3kg / h to 44.79% and 30.61% of 0.6kg / h, respectively, while CH\textsubscript{4} increases from 11.98 % to 9.94%, indicating that the appropriate increase in steam flow can get hydrogen-rich gas.
Figure 4. Gas volume fraction changes with temperature with the different steam flow rate.

Figure 5(a) and Figure 5(b) respectively show the change of the total gas temperature with the steam flow rates of 0.3 kg/h and 0.6 kg/h. It can be seen from Figure 3 that with the increase of temperature, the gas total exergy increases from 10564.76KJ/kg at 700℃ to 12483.38KJ/kg at 800℃ and then decreases to 11026.82KJ/kg at 950℃, while the value gas group exergy are similar to the rules of Figure 4(a). The reason is that with the increase of temperature, the output of gas also increases, which leads to the increase of gas total exergy and gas group exergy. Figure 5(b) is similar to Figure 5(a) for the changing gas total exergy with temperature. At 800℃, the steam flow rate increases from 0.3kg/h to 0.6kg/h and the gas group exergy increases from 12483.38KJ/Kg to 40876.77KJ/Kg, with an increase of 28393.39KJ/Kg. Therefore, gasification effect at this temperature.

Figure 5. The change of the total exergy of the gas at different temperature with the different steam flow rate.

Figure 6 shows the change of low gas calorific value with temperature at different steam flow rates. With different steam flow rates and temperatures, the low gas calorific value varies from 10 to 14MJ/m³, similar to that of Li [24].With a steam flow rate of 0.3kg/h, the low gas calorific value decreases with temperature, which is due to due to the relatively low calorific value of H₂. Although the volume fraction of H₂ is large, its increased calorific value can not make up for the decrease of calorific value of other hydrocarbon gases, so the caloric value of the gas is reduced. Figure 4(a) verifies this result. Steam flow increased from 0.3kg/h to 0.6kg/h, which enhanced the reforming reaction between water gas and CH₄, which resulted in the increase of gas production, which led to the
increase of low gas calorific value at the corresponding temperature. [25-29]. At the temperature of 800°C, the low gas calorific value increased from 11965.36KJ/m³ of steam flow rate of 0.3kg/h to 14076.72KJ/m³ of 0.6kg/h, with an increase of 2111.36KJ/m³, showing a positive impact on an increase of steam flow rate of gasification.

![Figure 6](image1.png) ![Figure 7](image2.png)

Figure 6. Low calorific value of gas changes with temperature in different steam flow rate.  
Figure 7. The change of gas exergy efficiency with temperature in different steam flow rate.

Figure 7 shows the change of gas exergy efficiency with temperature at different steam flow rates. It can be seen from the figure that as the temperature increases, the efficiency increases first and then decreases, and the change trend is similar to that in Figure 5(a) and Figure 5(b). With the increase of steam flow rate from 0.3kg/h to 0.6kg/h at 800°C, the gas exergy efficiency increased from 28.90\% to 35.55\%, an increase of 6.65\% due to the increase of steam flow, the output of gas increases, so the efficiency of gas increases.

4. Conclusions

This article from the view of exergy about temperature and steam flow on the gas characteristics and gasification process performance indicators come to the following conclusions:

1. At the steam flow rate of 0.3kg/h, the volume fraction of H₂ increases with the increase of temperature, the volume fraction of CO increases first and then decreases to 20.21 \% at 800°C, the volume fraction of CH₄ decreases with temperature. When the steam flow rate increases to 0.6kg/h, the trend of the curves is similar to that of 0.3kg / h. Appropriately increasing the steam flow rate can produce hydrogen-rich gas. However, due to the change of gas volume fraction, the gas total exergy increased first and then decreased, increasing by 28393.39KJ / Kg at 800°C.

2. At different steam flow rates, the low calorific value of gas varies from 10 to 14MJ/m³; at 800°C, the steam flow rate increases from 0.3kg/h to 0.6kg/h, and the low calorific value have an increase of 2111.36KJ/m³.

3. The trend of the gas exergy efficiency with temperature is the same with the low gas calorific value at different steam flow rates as the temperature increases first and then decreases. At the highest exergy efficiency, the steam flow rate increased from 0.3kg/h to 0.6kg/h and the gas efficiency increased by 6.65\%.

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