Investigation of biomass (pine wood) gasification: Experiments and Aspen Plus simulation

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Abstract
Biomass gasification is currently a hot research topic. To achieve a high hydrogen content in the product gas, the gasification feedstock used in this study is air-dried pine woodchips. Experiments are performed in a downdraft gasifier by varying the operation parameters of the particle size (60 mesh, 80 mesh, 100 mesh), temperature point (700, 750, 800, 850, 900°C), and steam-to-biomass mass (S/B) ratio (0, 0.7, 1.4, 2.1, 2.8). The main effects of particle size, temperature, and S/B ratio on the composition of the product gas are analyzed to predict the optimal operation parameters of biomass feedstock. For pine woodchip gasification, the optimal particle size is 80 mesh or 0.17 mm, the preferred temperature is 850°C, and the optimal S/B ratio is 1.4. Although there is an error between the experiment and the simulation, the difference is not significant. The Aspen Plus model can provide guidance for the gasification of pine woodchips and can be extended to the gasification of other kinds of biomass.

KEYWORDS
aspen plus simulation, biomass gasification, operation parameters, product gas

1 | INTRODUCTION

The competition for traditional energy sources exists at the international level, and the trend of the use of renewable sources to replace petroleum products has attracted worldwide attention.1-3 Biomass is defined as a green energy source due to its renewability. Biomass resources are widely distributed in nature, and they can be processed directly or indirectly through conversion into gas, liquid fuel, and solid fuel.4,5 All types of products have a variety of uses, depending on their properties and the technical means.6,7

There are many types of biomass feedstocks that show a variety of characteristics, and the current standard for selecting a feedstock varies according to product needs.8 Biomass resources can be converted into multiple forms of energy through two types of process: (a) biochemical and (b) thermochemical.9,10 A biochemical process decomposes the biomass into flammable gas rich in CH₄ and H₂ by the action of microorganisms under specific conditions. Nevertheless, the inefficiency of the biochemical process does not meet industrial requirements.10

In the thermochemical conversion process, the biomass products include syngas, which is similar to natural gas; biodiesel, which is a replacement for petrochemical diesel; and a carbon product that is used for fuel and adsorption processes.5 In general, gasification and pyrolysis are the main ways to produce the product gas. Gasification is a promising way to obtain hydrogen-rich gas. In gasification, different feedstocks and different operation conditions and reactions are interrelated owing to the complexity of gasification.11-14 To optimize the operating conditions to produce high-quality product gas, some published literature has already described the impacts of the operating parameters of biomass gasification.10,15
For a selected biomass feedstock, different operation parameters can lead to various gasification results.\textsuperscript{14,16-18} The product gas mainly is made up of CO and H\textsubscript{2}, which can be used directly as a fuel for generating electricity and conveyance and as a raw material for chemical production.\textsuperscript{19} Many studies have suggested that future biorefineries will incorporate hydrothermal gasification and use the internally produced hydrogen.\textsuperscript{20} Gasification using steam is an appropriate route for a polygeneration mode conducted to produce hydrogen and electrical energy.\textsuperscript{21} A previous study showed that the hydrogen yield can be upgraded by introducing steam directly in the reduction reaction.\textsuperscript{10} According to the work of G. Mirmoshtaghi et al,\textsuperscript{17} a steam-to-biomass (S/B) ratio of 0.7, a particle size of 3 mm, and a moisture capacity of 9 wt\% resulted in the optimal product gas. Aydin et al\textsuperscript{22} suggested that an operating temperature range of 800-820°C and a S/B ratio of 1.3 were the optimal operating conditions. Xiang et al showed that the calorific value of product gas per hour was the greatest under the conditions of $T_1 = 800^\circ\text{C}$, steam/coal = 2, and coal/biomass = 0.25. The product gas that is considered a chemical material mostly demands high H$_2$ content; the parameters are listed as follows: coal/biomass = 0.25, steam/coal = 2, and $T_1 = 980^\circ\text{C}$.\textsuperscript{23} The calorific value of the product gas when using O$_2$ and saturated steam as the gasification agent is higher than that using air and saturated steam as the gasification agent.\textsuperscript{24} Shayan et al\textsuperscript{15} reported that a rise in the gasification temperature led to a reduction in the hydrogen yield. However, Refs. 23,25-29 indicated that an increase in the gasification temperature led to an increase in the hydrogen yield. Introducing steam into gasification is more favorable for the hydrogen yield than pure air.\textsuperscript{22,25,26}

To accurately predict the gasification results, many scholars have developed models to obtain predictions. The CFD-DEM model has been used in the simulation of glucose gasification, showing that a higher wall temperature and a lower flow rate are favorable for gasification.\textsuperscript{30} The Aspen Plus model has been used in gasification, adopting steam as the gasifying agent and showing the effects of temperature, S/B ratio, and temperature shift on the gas ingredients.\textsuperscript{27,31} A mathematical model adopting the COMMENT code has been used to analyze the effects of multifarious operating parameters.\textsuperscript{28} In the event that the existing models and formulas can be further modified by adding additional experimental data, the improved models will predict the product composition more accurately.\textsuperscript{32,33}

The advantages and disadvantages of certain types of gasifiers are listed in the study by Samiran.\textsuperscript{19} The self-moisture gasification of fresh biomass is an innovative method of biomass application that is different from conventional gasification.\textsuperscript{34} Steam gasification has drawn a great deal of attention to realize a higher H$_2$/CO ratio and hydrogen yield. A substantial amount of experimental work has been performed on a downdraft gasifier with steam.\textsuperscript{21,24,25,30,32} Numerous simulation studies have been compared with experimental results.\textsuperscript{23,27,30,31} However, there is no unified conclusion. In the present study, experimental work is performed on pine woodchip gasification in downdraft gasifiers, and an Aspen Plus model is used to simulate the gasification process. This paper seeks the optimal gasification operating conditions of pine woodchips by changing the operating parameters. Comparing the experimental data with the data of the Aspen Plus model can reflect the reliability of the experiment and verify the adaptability of the Aspen Plus model to the gasification process. The conclusions in the present paper are complementary to those of previous studies.

### METHODS

#### 2.1 Experiment

##### 2.1.1 Experimental setup

The entire experimental setup is displayed in Figure 1, which contains five pieces of equipment: an inert atmosphere
device, a steam generator, a downdraft biomass gasifier, a gas filtering system, and a gas collection and analysis system. The inert atmosphere device is composed of a nitrogen bottle and a switching valve. The steam generator includes a steam generator, a switching valve, and an electric heater. The downdraft biomass gasifier is composed of a screw feeder, a quartz tube gasifier (inner diameter: 0.5 m; height: 1.3 m), and a PID temperature control system. A filter cartridge, a scrubbing bottle, and a gas drying bottle constitute the gas filtering system. The gas collection and analysis system contains a sucking pump, an infrared gas analyzer, and a gasbag. Many resistance wires are used to heat the quartz tube gasifier and keep the wall temperature at a specific constant temperature, providing an external heat source as required.

2.1.2 | Experimental procedure

The experimental flowchart is shown in Figure 2. The main experimental steps are as follows:

1. Do not connect the infrared gas analyzer. All switching valves are closed. Turn on the power switch and heat the quartz tube gasifier to a specified temperature by operating the PID temperature control cabinet.
2. To form an inert atmosphere, open valve 2, and sweep the entire system with N₂. Then, put the biomass into the gasifier. If steam is introduced as a gasification agent, close valve 2, and open valve 4. The mass flow rate of the steam introduced into the gasifier is determined according to the S/B ratio. Switch on the sucking pump and connect the infrared gas analyzer. When collecting the product gas, the gasbag will be connected to the outlet of the infrared gas analyzer.
3. During the gasification process, the product gas from the gasifier goes through the scrubbing bottle and the gas drying bottle. Then, it enters the infrared gas analyzer under negative pressure from the sucking pump and is collected in the gasbag.

2.1.3 | Test methods for important parameters

Pine woodchips as the gasification feedstock are processed into micro-sized pieces of biomass using a small blade mill and then sieved through 60 mesh, 80 mesh, and 100 mesh filters.

The biomass properties are the key factors affecting the gasification results. A proximate analysis and an ultimate analysis are performed using a MAC-3000A automatic analyzer and a Vario Micro cube ultimate analyzer. The product gas is analyzed using an infrared gas analyzer (Gasboard-3100) that can calculate the volume fraction quickly and effectively.

2.1.4 | Description of all parameters in the experiments

The results of the proximate analysis and the ultimate analysis of the pine woodchips are listed in Table 1. The other parameters used in the experiment are listed in Table 2.

2.1.5 | Index parameters

The product gas mainly consists of CO, H₂, CH₄, CO₂, N₂, and H₂O. The gas production and the calorific value of the product gas are mutual restraint parameters. CO₂ has no contribution to the gas calorific value, CH₄ has little contribution to the gas production, N₂ is an inactive gas, and H₂O is absorbed during the filtering phase. Thus, the main measurable indicators are the contents of H₂ and CO. Compared to CO, H₂ is an eco-friendly gas fuel with a high calorific value, which makes it more desirable. The ratio of H₂/CO is thus the most appropriate evaluation indicator¹⁰,²⁵,³¹ and reflects volume changes as well as changes in the quality of the product gas.

2.2 | Aspen Plus simulation

The Aspen Plus flowchart for the gasification of pine woodchips is shown in Figure 3. Creating an Aspen Plus model involves the following steps: appointing the setup; appointing all system components and classifying nonconventional
and conventional components; selecting the method for describing the properties, especially the nonconventional properties, and specifying the stream class; establishing the main flowchart (using unit operation blocks and material streams); appointing the feed streams that contain flow rates (mass or mole), compositions, and thermodynamic conditions; and specifying the unit operation blocks that contain thermodynamic conditions, calculation options, and chemical reactions. Then, the model is debugged and run.

2.2.1 | Fundamental assumptions

The assumptions of the model are listed below:

1. The mass flow rate of the biomass is 3 g/min at 1 bar and 25°C, and steam is supplied at 200°C.
2. The gasification process is steady-state and isothermal.15,25
3. The internal pressure of the gasifier is kept at approximately 1.1 bar.31
4. The formation of tar is ignored, and all sulfur (S) is formed by H₂S.31
5. Char is the product of the preliminary drying and deashing step. Char is mostly made of carbon, and it is assumed to be pure carbon.25,27
6. All carbon is transformed.27
7. All gases are in an ideal state.15,31
8. The product gas contains only CO, CO₂, H₂, CH₄, N₂, H₂O, and H₂S.31
9. The gases involved are in compliance with the Peng-Robinson (Peng-Rob) equation of state with the Boston-Mathias (PR-BM) modification property.31

In the RYIELD block, the product component and basis yield are given according to the total mass balance. Due to the limitation of the residence time in the gasifier, the actual gasification process is extremely complicated and has difficulty achieving chemical equilibrium. Using the Gibbs equilibrium model results in considerable differences in the product gas composition between the simulation and the experiment.34 Using the restricted equilibrium method in the model can achieve better agreement between the simulation and the experiment.31 In this model, the RGIBBS block makes a choice of the calculation option “Restrict Chemical Equilibrium-Specify Temperature Method or Reactions,”33 and the zero temperature approach specification is used in individual reactions. Table 3 lists chemical reactions R1-R8 that are considered in the gasification process. However, in the present model, aspects of hydrodynamics, the restricted heat transfer in the reactor, the reactor size, the tar formation reaction, the catalyst deactivation side reaction, and other reactions are not considered. The Peng-Robinson (Peng-Rob) equation of state with the Boston-Mathias (BM) modification is used to calculate the thermodynamic properties of the conventional components in this model. PR-BM is chosen for the chemical industry.

| TABLE 1 | Proximate analysis and ultimate analysis of pine woodchips |
| Proximate analysis (wt%, ad) | Ultimate analysis (wt%, ad) |
| FC | A | V | M | C | H | O | N | S |
| 11.79 | 12.09 | 74.52 | 11.70 | 43.45 | 4.24 | 39.1 | 0.72 | 0.4 |

The values given in Table 1 are input into the Aspen Plus model; “ad” denotes air-dried.

| TABLE 2 | Parameters used in the gasification process |
| Ambient temperature | 25°C |
| Ambient pressure | 1.0 bar |
| Inner diameter of gasifier | 0.5 m |
| Height of gasifier | 1.3 m |
| Gasifier operating temperature (°C) | 700; 750; 800; 850; 900 |
| Gasifier operating pressure | 1.1 bar |
| Steam temperature | 200°C |
| Biomass mass flow rate | 3 g/min |
| Particle size | 60 mesh; 80 mesh; 100 mesh |
| S/B ratio | 0.7; 1.4; 2.1; 2.8 |

FIGURE 3 Flowchart for biomass gasification
Chemical reactions

Biomass gasification is an extremely complicated process involving many chemical reactions. R1-R9, listed in Table 3, are considered for the gasification process in this study. However, in this study, the reactions containing nitrogen and sulfur are not the main reactions.

R1, R2, R3, and R5 are endothermic reactions, meaning that a high temperature is favorable for the positive reaction. R4 and R6 are exothermic reactions, meaning that a high temperature is favorable for the reverse reaction. Although the process is isolated from air, the biomass itself contains oxygen. In the simulation, R1-R8 are considered.

2.2.3 Description of the Aspen Plus flowsheet

The flowchart for biomass gasification is displayed in Figure 3. The BIOMASS stream is designated as a nonconventional stream, and the mass flow rate of the feedstock is 3 g/min. In light of the ultimate and proximate analyses of the biomass feedstock, the component attributes of the BIOMASS stream can be defined. The BIOMASS stream goes to the yield reactor RYIELD block, generating conventional components such as carbon (C), H₂, O₂, N₂, S, steam (H₂O), and ash. The ultimate analysis of the feedstock determines the yield distribution to the RYIELD reactor block. The yields of each component are determined by the yield distribution, which determines the mass flow of each component in the RYIELD block export stream ELEM1. Then, as the only nonconventional component, the ash yield is specified as 100% by the ultimate and proximate analyses. The export stream ELEM1 out of the RYIELD block passes to the separation unit ASHSEP. The separation unit ASHSEP isolates ash as a stream ASH from the other components, such as C, H₂, O₂, N₂, and H₂O, as the stream ELEM2. Based on the component distribution, the mixer flow mass and the ASH flow mass are set. The gasifying agent steam is added to the MIXER reactor as stream STEAM. The stream ELEM3, containing C, H₂, O₂, S, H₂O, and N₂ from the MIXER reactor, enters the gasification reactor RGIBBS, where the gasification process takes place, and all sulfur present in the feedstock is converted to H₂S. The stream PRODGAS consists of H₂, CO, CH₄, CO₂, H₂O, H₂S, and N₂.

### Table 3

| No | Reaction, k | Name                           | Heat of reaction (kJ/mol) |
|----|-------------|--------------------------------|---------------------------|
| R1 | C + H₂O → CO + H₂ | Water-gas reaction | +131.0                     |
|    | k₁ = [CO][H₂] / [H₂O] | |                           |
|    | lg k₁ = 541.3 / T + 1.5561gT − 0.081092T / T² + 2.554 | |                           |
| R2 | CO + H₂O → CO₂ + H₂ | Water-gas shift reaction | +41.0                     |
|    | k₂ = [CO₂][H₂] / [H₂O][CO] | |                           |
|    | lg k₂ = 291.2 / T + 0.9115 lgT − 0.09738T / T² + 0.098 | |                           |
| R3 | C + CO₂ → 2CO | Boudouard reaction | +172                     |
|    | k₃ = [CO]² / [CO₂] | |                           |
|    | lg k₃ = 8947.7 / T + 2.4675 lgT − 0.0010824T / T² + 2.772 | |                           |
| R4 | C + 2H₂ → CH₄ | Methanation of carbon | −242                     |
|    | k₄ = [CH₄] / [H₂]² | |                           |
|    | lg k₄ = 5416.7 / T − 5.957lgT + 0.001867T² / T² + 11.79 | |                           |
| R5 | CH₄ + H₂O → CO + 3H₂ | Steam reforming of methane | +206.0          |
| R6 | H₂ + S → H₂S | H₂S formation | −20.2                    |
| R7 | C + O₂ → CO₂ | Carbon combustion | −393.0                   |
| R8 | C + 0.5O₂ → 2CO | Partial oxidation of carbon | −112.0          |
| R9 | H₂ + 0.5O₂ → H₂O | Hydrogen partial combustion | −242.0          |

k is the equilibrium constant, which is mainly affected by temperature, and [] indicates concentration.
TABLE 4 Reactor block description used in the simulation

| Block ID | Reactor name | Description |
|----------|--------------|-------------|
| RYIELD   | RYield       | Decomposes biomass into conventional elements according to yield distribution data |
| ASHSEP   | Sep          | Separates ash from the other products |
| MIXER    | Mixer        | Mixes H₂O with C, H₂, O₂, N₂, S, and H₂O |
| RGIBBS   | RGibbs       | Equilibrium reactor; estimates the phase equilibrium and chemical equilibrium of the system by minimizing the Gibbs free energy. Useful when the temperature and pressure are given and the reaction stoichiometry is unknown |

In the RGIBBS block, the gasification temperature varies between 700 and 900°C, and the stream STEAM mass flow rate varies depending on the steam-to-biomass (S/B) ratio (0, 0.7, 1.4, 2.1, and 2.8). The gasification reactions R1-R8 are specific to the RGIBBS block.

Descriptions of the blocks used in the flowsheet are given in Table 4.

3 | RESULTS AND DISCUSSION

3.1 | Effect of particle size on the product gas

The gasifier is maintained at 900°C and 1.1 bar. The mass flow rate of pine woodchips is 3 g/min, and 60 mesh, 80 mesh, and 100 mesh filtered pine woodchips are the gasification feedstock. The experimental results are shown in Table 5 and Figure 4A,B.

Table 5 and Figure 4A display the volume fraction profile of the main product gases (H₂, CO, CO₂, and CH₄). As the particle size changes from 60 mesh to 100 mesh, the proportions of CO and CO₂ decrease by 2.25% and 4.84%, respectively, and the proportions of H₂ and CH₄ increase by 6.85% and 0.49%, respectively. The volume ratio of each component gas does not change substantially. Similar trends were reported in Refs. 17,25.

The increase in H₂ is greater than the increase in CO, leading to growth in the H₂/CO ratio.

When the pine woodchips are crushed, the cellulose structure is effectively destroyed at the microcosmic level. As crystallinity decreases, the porosity of the particles increases, and the reduction in the particle size increases the specific surface area of the biomass particles that can react with the surrounding atmosphere, which benefits heat exchange between the pine woodchips and the surrounding atmosphere. R1 and R5 are shifted toward the positive direction, and the yield of H₂ increases. However, the yield of CO decreases.

CO is mainly generated by R1 and R3. R1 and R3 benefit from the high temperature, but the reactions are only slightly shifted in the positive direction. In R1, the fluctuation in the equilibrium constant k₁, which is mainly affected by

Table 5 Gasification results for different particle sizes (the data are normalized)

| Parameter category | Particle size and results |
|--------------------|--------------------------|
|                    | 100 mesh | 80 mesh | 60 mesh |
| CO (%)             | 52.24    | 52.83   | 54.49   |
| H₂ (%)             | 32.74    | 30.53   | 25.89   |
| CH₄ (%)            | 2.28     | 1.95    | 1.79    |
| CO₂ (%)            | 12.12    | 14.69   | 16.96   |

FIGURE 4 (A) Volume fraction of the gas composition with various particle sizes. (B) H₂/CO ratios with various particle sizes
temperature, is not obvious, and H₂O is derived from the internal water contained in the biomass itself. The concentration of H₂O does not greatly change, and the concentration of CO decreases.

CO₂ is mainly generated by R2. In R2, k₂ experiences little or no change and the change in the concentration of CO₂ has the same trend as that of CO. CH₄ is mainly generated by R4, and the proportion of CH₄ increases with that of H₂.

In Figure 4B, the H₂/CO ratio increases almost linearly as the particle size decreases, and an inflection point is observed when the particle size is 80 mesh. As the particle size increases from 60 mesh to 80 mesh, the H₂/CO ratio increases by 11.41% compared to a 3.75% increase when the particle size changes from 80 mesh to 100 mesh. Considering the cost of broken pine woodchips, 80 mesh may be the optimal particle size for the gasification of pine woodchips.

### 3.2 Effect of temperature on the product gas

The pine woodchips are maintained at a mass flow of 3 g/min at 25°C and 1.1 bar. The gasification temperature varies between 700 and 900°C, and the particle size of the pine woodchips is 80 mesh. Figure 5A,B shows the changes in the gas composition and the H₂/CO ratio with the temperature.

Figure 5A suggests that the content of CO decreases by 4.17% from 700 to 900°C, and the content of H₂ increases by 5.43%. Similar conclusions were reported in Refs. 23,25-27,29. The fraction of CH₄ decreases by 6.95% as the fraction of CO₂ increases by 5.69%. Similar trends were reported in Ref. 23.

As the temperature increases, R1, R2, R4, and R5 move toward H₂ production, R1 and R3 move toward CO production, R4 and R5 move toward a decrease in CH₄, and R2...
moves toward an increase in CO2 and a decrease in CO. The equilibrium constant k in the reactions is mainly affected by the temperature, and k₂ is significantly more sensitive to temperature than k₁ or k₃. Moreover, when the temperature is lower than 850°C, the rate of the reverse reaction in R3 is higher than that of the positive reaction, in contrast to the case at temperatures above 850°C. Based on the above analysis, the observed experimental phenomena have a theoretical basis. According to R1-R5, as the concentration of H₂ grows, in a similar way, the proportion of CO₂ increases, and the fractions of CO and CH₄ decrease.

As shown in Figure 5B, the ratio of H₂/CO increases from 700 to 850°C and decreases from 850 to 900°C, and thus, 850°C is the optimal temperature for the gasification of pine woodchips.

Figure 5C reveals that the differences in the H₂/CO ratio at different temperatures between the experiment and the simulation are −14.1%, −9.6%, −0.24%, and −0.35%, and the lowest value is −0.24% at 850°C. The experimental conclusion agrees well with the simulation data. 850°C is thus the optimal temperature for the gasification of the pine woodchips in this study.

3.3 Effect of gasifying agent dosage

In this experiment, steam is chosen as the gasifying agent. Pine woodchips with a particle size of 80 mesh are the gasification feedstock. The gasifier temperature is maintained at 850°C, the mass flow rate of pine woodchips is 3 g/min, and the S/B ratio is 0.7, 1.4, 2.1, or 2.8. The experimental results are shown in Figure 6A,B.

Figure 6A clearly shows that the content of H₂ increases by 6.78% as the S/B ratio increases from 0.7 to 2.8. In Refs. 25,27,31, similar conclusions were obtained. The content of CO decreases by 19.52%, the content of CH₄ decreases by 1.9%, and the content of CO₂ increases by 13.74%. Pala et al31 and Kaushal and Tyagi27 made similar arguments. After introducing steam as a gasification agent, the composition of the product gas varies greatly, especially the concentrations of CO and CO₂.

The introduction of steam is conducive to the formation of H₂. An increase in the H₂O concentration promotes the forward reactions of R1, R2, and R5, resulting in more conversion of CO into CO₂. The fractions of CO and CH₄ decrease. However, the steam temperature is lower than the ambient temperature, leading to heat loss, which impacts heat and mass transfer. As the S/B ratio increases from 1.4 to 2.8, the fraction of H₂ does not greatly increase, and thus, excess steam may inhibit the generation of H₂.

The introduction of steam during the gasification process promotes the further pyrolysis and gasification of byproducts such as tar and coke to enhance the gasification reaction and improve the quality of the product gas. As shown in Figure 6B, the H₂/CO ratio is the highest when the S/B ratio is 2.8 in the simulation. However, the degree of increase of the H₂/CO ratio in the experiment is 1.073 when the S/B ratio increases from 0.7 to 1.4. The greatest growth rate with the different S/B ratios is 1.073. The amplitude of the CO/CO₂ ratio distinctly decreases as the S/B ratio increases from 0.7 to 1.4. The CO/CO₂ ratio is less than one when the S/B ratio is >1.4, and the calorific value of the product gas declines.

The difference in the H₂/CO ratio between the simulation and experiment first decreases, an inflection point is observed when the S/B ratio is 1.4, and then, the difference gradually increases, although the difference is not obvious. The simulation results are obtained under ideal conditions, making the results much better than they truly are.

Steam gasification is a good option for hydrogen production. However, the use of additional high-temperature steam requires additional external heat sources. This study finds that the S/B ratio of 1.4 is optimal, which is in agreement with the results in Ref. 25.
4 CONCLUSIONS

The present work displays the effects of particle size, temperature, and S/B ratio on the composition of the product gas in the gasification of pine woodchips. Based on the experimental study and Aspen Plus simulation, the following conclusions can be drawn:

1. The optimal particle size of pine woodchips for gasification is 80 mesh or 0.17 mm.
2. The preferred temperature for pine woodchip gasification is 850 °C.
3. The optimal S/B ratio of pine woodchips for gasification is 1.4.
4. Although the H₂/CO ratio in the simulation slightly deviates from the experimental data, the trend of the two ratios is consistent. The Aspen Plus model can be extended to the gasification of other biomass feedstocks.
5. Follow-up studies can analyze other operating parameters of gasification, such as the catalyst and the residence time.

ACKNOWLEDGMENTS

This work was supported by the National Science and Technology Support Program (No: 2015BAD21B00).

CONFLICT OF INTEREST

None declared

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**How to cite this article:** Huang F, Jin S. Investigation of biomass (pine wood) gasification: Experiments and Aspen Plus simulation. *Energy Sci Eng*. 2019;7:1178–1187. [https://doi.org/10.1002/ese3.338](https://doi.org/10.1002/ese3.338)