MODELING & SIMULATION OF BIOMASS GASIFIER: EFFECT OF OXYGEN ENRICHMENT AND STEAM TO AIR RATIO

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ABSTRACT

Gasification is one of the efficient ways to convert the energy embedded in biomass. Understanding of the effect of a few key parameters such as oxygen enrichment and preheating of air on major design parameters is crucial in designing of a biomass gasifier. In the present study, equilibrium modeling is used to predict the performance of a downdraft gasifier. The composition of producer gas and, hence, the calorific values are determined. The effects of oxygen enrichment of air, preheating of air, and steam to air ratio on gas composition, reaction temperature and calorific values are investigated. The calorific values of the producer gas increase as the oxygen fraction increases and also as the steam to air ratio increases.

Keywords: Biomass; Gasification; Equilibrium Modeling; Downdraft Gasifier; Simulation; Renewable Energy

1. INTRODUCTION

Biomass and waste are widely recognized to be the major potential for energy production. Wood and other forms of biomass including energy crops and agricultural and forestry wastes are some of the main renewable energy resources available. Biomass fuels and residues can be converted to energy via thermal, biological and physical processes. In principle, the gasification units employed for coal can also be applied for biomass and waste, but significant differences exist between the two fuel categories. Coal pyrolysis yields 60 to 80% char while the balance coming from gases and tars. When biomass is pyrolyzed, gases and tars represent 70 to 90% of the total mass fed, whereas only 30 to 10% is a highly reactive char [1]. In the thermo-chemical conversion technologies, biomass gasification has attended the highest interest as it offers higher efficiencies compared to combustion and pyrolysis [2]. Gasification is the conversion of solid carbonaceous fuel into combustible gas by partial combustion. The mixture of combustible gases thus produced is called producer gas [3]. In view of the considerable interest in the gasification process worldwide, it is necessary to model and predict the performance of the gasifier *in priori*. Babu and Chaurasia in their studies [4,5,6,7,8,9] reported extensive results on pyrolysis, which is one of the zones of a biomass gasifier.

The residence time for the biomass in a gasifier is long enough. It will allow pyrolysis products to burn and subsequently to achieve an equilibrium state in the reduction zone before leaving the gasifier [10,11]. An equilibrium model has been developed and the variation with moisture content for fixed temperature was found out. An equilibrium model based on minimization of Gibbs free energy for wood waste (saw dust), has been simulated by Altafini et al. [11]. The effects of oxygen factor and moisture content of wood on gas composition, reaction temperature and calorific values are investigated. The calorific values of the producer gas decreases as the oxygen factor increases and also as the moisture content increases [12]. The effect of one of the important parameters such as oxygen enrichment of air is not reported in the literature.

Hence the present study focuses on developing equilibrium model and studying the effects of oxygen enrichment of air on composition, reaction temperature and calorific values of the gases. Model predictions are also compared with the experimental data reported by Jayah et al. [13]. For fixed oxygen factor the effects of preheating of air on

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the reaction temperature is also studied. The effect of saturated steam gasification along with dry air is included in the equilibrium modeling and the variation with steam to air ratio is found out.

2. MODEL

The equilibrium model assumes that all the reactions are in thermodynamic equilibrium. It is expected that the pyrolysis product burns and achieves equilibrium in the reduction zone before leaving gasifier; hence an equilibrium model can be used in the downdraft gasifier [10]. The reactions are as follows:

$CO + H_2O \longleftrightarrow CO_2 + H_2$ (+41,200 J/mol)

$C + 2H_2 \longleftrightarrow CH_4$ (+75,000 J/mol)

The equilibrium constant for methane generation (K_1) is

$$K_1 = \frac{P_{CH_4}}{\left(P_{H_2}\right)^2} \qquad (1)$$

And equilibrium constant for shift reaction (K_2) is

$$K_2 = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}} \qquad (2)$$

The typical chemical formula of woody material, based on a single atom of carbon, is $CH_{1.44}O_{0.66}$.

The global gasification reaction can be written as follows:

$$CH_{1.44}O_{0.66} + wH_2O + mO_2 + 3.76mN_2 = x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76mN_2 \qquad (3)$$

Where w is the amount of water per kmol of wood, m is the amount of oxygen per kmol of wood, x_1 to x_5 are the coefficients of constituents of the products. For the known moisture content, the value of w becomes a constant and m can be found out from the airflow rate per kmol of wood. From the global reactions, there are six unknowns x_1 to x_5, and T, representing the five unknown species of the product and the temperature of the reaction. Therefore six equations are required, which can be obtained from the following material and energy balances.

Carbon Balance:
$$1 = x_2 + x_3 + x_5 \qquad (4)$$

Hydrogen Balance:
$$2w + 1.44 = 2x_1 + 2x_4 + 4x_5 \qquad (5)$$

Oxygen Balance:
$$w + 0.66 + 2m = x_2 + 2x_3 + x_4 \qquad (6)$$

The heat balance for gasification process (assumed to be adiabatic) is:

$$\begin{bmatrix} H^0_{fwood} + w\left(H^0_{fH_2O(l)} + H_{(vap)}\right) + mH^0_{fO_2} \\ + 3.76mH^0_{fN_2} + \Delta T'\left(mC_{pO_2} + 3.76mC_{pN_2}\right) \end{bmatrix} = \begin{bmatrix} x_1H^0_{fH_2} + x_2H^0_{fCO} + x_3H^0_{fCO_2} \\ + x_4H^0_{fH_2O(vap)} + x_5H^0_{fCH_4} + \Delta T(x_1C_{pH_2} + \\ x_2C_{pCO} + x_3C_{pCO_2} + x_4C_{pH_2O(vap)} + x_5C_{pCH_4} \\ + 3.76\, mC_{pN_2})] \end{bmatrix} \qquad (7)$$

Where $\Delta T = T_2 - T_1$, & $\Delta T' = T_2' - T_1$

T_1 = temperature of the inlet,
T_2 = temperature of the reduction zone
T_2' = air inlet temperature

If steam were also fed to the gasifier then energy balance would be modified as follows.

$$\begin{bmatrix} H^0_{fwood} + w\left(H^0_{fH_2O(l)} + H_{(vap)}\right) + mH^0_{fO_2} \\ +3.76mH^0_{fN_2} + s\left(H^0_{fH_2O(g)} + \Delta T'' C_{pH_2O(vap)}\right) \\ +\Delta T'\left(mC_{pO_2} + 3.76mC_{pN_2}\right) \end{bmatrix} = \begin{bmatrix} x_1H^0_{fH_2} + x_2H^0_{fCO} + x_3H^0_{fCO_2} \\ + x_4H^0_{fH_2O(vap)} + x_5H^0_{fCH_4} + \Delta T(x_1C_{pH_2} + \\ x_2C_{pCO} + x_3C_{pCO_2} + x_4C_{pH_2O(vap)} + x_5C_{pCH_4} \\ +3.76\,mC_{pN_2})] \end{bmatrix} \quad (8)$$

And in the material balance equations w would be replaced by $w + s$.

Where $\Delta T'' = T_2'' - T_1''$
s = kmol of steam per kmol of wood
T_2'' = the steam temperature
T_1'' = the ambient temperature

From Eq. (4)
$x_5 = 1 - x_2 - x_3$ (9)

From Eq. (5)
$x_4 = w + 0.72 - x_1 - 2x_5$ (10)

Substituting the value of x_5 from the Eq. (4) into Eq. (5)
$x_4 = - x_1 + 2x_2 + 2x_3 + w - 1.28$ (11)

From Eq. (1)
$x_1^2 K_1 = 1 - x_2 - x_3$ (12)

Substituting the value of x_4 from the Eq. (11) into Eq. (6)
$- x_1 + 3x_2 + 4x_3 = 2m + 1.94$ (13)

Substituting the value of x_4 from the Eq. (11) into Eq. (2)
$x_1x_3 = K_2 x_2 [\ - x_1 + 2x_2 + 2x_3 + w - 1.28\ ]$ (14)

From Eq. (7),

$$T_2 = T_1 + \frac{\begin{bmatrix} H^0_{fwood} + w\left(H^0_{fH_2O(l)} + H_{(vap)}\right) + H^0_{fO_2} + 3.76mH^0_{fN_2} + \Delta T'\left(mC_{pO_2} + 3.76mC_{pN_2}\right) \\ - x_1H^0_{fH_2} + x_2H^0_{fCO} + x_3H^0_{fCO_2} + x_4H^0_{fH_2O(vap)} + x_5H^0_{fCH_4} \end{bmatrix}}{\left[\left(x_1C_{pH_2} + x_2C_{pCO} + x_3C_{pCO_2} + x_4C_{pH_2O(vap)} + x_5C_{pCH_4} + 3.76mC_{pN_2}\right)\right]} \quad (15)$$

The general equation for $\ln K_1$ [10] is given by

$$\ln K_1 = \left[\frac{7082.848}{T} + (-6.567)\ln T + \frac{7.466\times10^{-3}}{2}T + \frac{-2.164\times10^{-6}}{6}T^2 + \frac{0.701\times10^{-5}}{2(T)^2} + 32.541\right] \quad (16)$$

The general equation for $\ln K_2$ [10] is given by

$$\ln K_2 = \left[\frac{5870.53}{T} + 1.86\ln T - 2.7\times10^{-4}T - \frac{58200}{(T)^2} - 18.007\right] \quad (17)$$

The set of equations (12) to (17) can be solved using the following algorithm:

1. Specify the value of *m* and *w*.
2. Assume temperature T_2, find K_1 & K_2 using Eq. (16) and Eq. (17).
3. Find x_1, x_2, & x_3 using Eq. (12), Eq. (13), & Eq. (14) respectively.
4. Find x_4 & x_5 using Eq. (9) & Eq. (11) respectively.
5. Calculate the new value of T_2 using Eq. (15).
6. Repeat the above steps until successive value of T_2 becomes constant.

3. RESULTS AND DISCUSSION

Model predictions are compared with the experimental data reported by Jayah et al. [13]. Composition of the producer gas is compared and shown in the Fig.1. Experimentally reported compositions are for air flow rate of 55.6 kg/hr, wood rate of 18.6 kg/hr, and wood moisture rate of 3.4 kg/hr [13]. Using these values, oxygen factor and initial moisture content are found to be of 0.5 and 15.5% respectively. These values are used to predict the gas compositions and compared with the experimental data. Fig.1 shows that compositions of all components are in good agreement with experimentally reported data. A sensitivity analysis of the model results is carried out, by varying the oxygen content of air, preheated temperature of air, and the steam to air ratio.

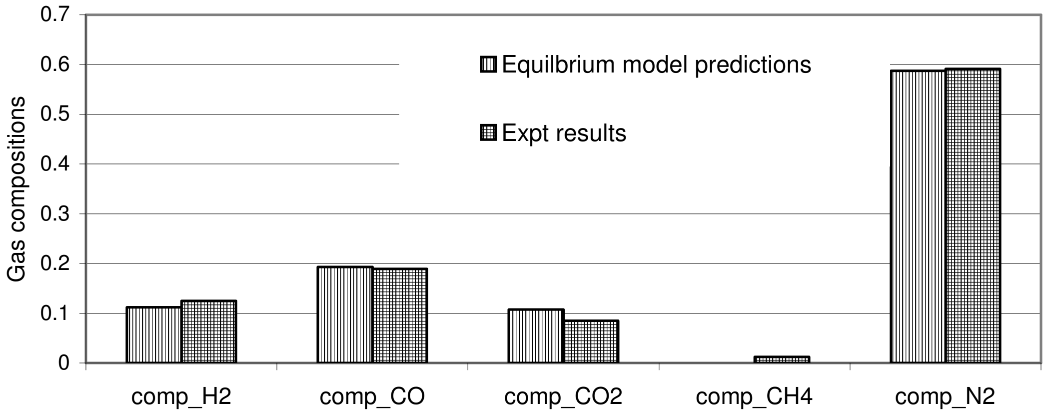

Fig.1 Model comparison with expt. data of Jayah et al.

3.1 Oxygen Enrichment of Air

$CH_xO_y + mO_2 \longleftrightarrow CO_2 + 0.5\,x\,H_2O$ with $m = 1 + 0.25\,x - 0.5\,y$

Oxygen factor (*F*) is the O_2 fraction of stoichiometric O_2 amount used in a neutral and theoretical combustion process. For wood the values are $x = 1.44$ and $y = 0.66$, which gives $m = 1.03$ (stoichiometric value). The gasification process takes place when there is a lack of O_2, let us take an O_2 amount equal to the ¼ of the stoichiometric in a theoretical amount in a theoretical combustion, that is $F = 25.75\%$ [14]. Along with *m* moles of O_2, (0.79/0.21)*m* moles of N_2 would be entering in the gasifier. For air with an oxygen content of 30% by volume, along with *m* moles of O_2, (0.7/0.3)*m* moles of N_2 would be entering into the gasifier. There would be a decrease of N_2 moles entering the gasifier for oxygen-enriched air.

3.2 The influence of the Oxygen Enrichment

Fig. 2 shows how the composition of gas changes with oxygen fraction in the air for an oxygen factor of 0.3 and initial moisture content of 10% with no preheating of air. Mostly all variations of the molar fractions versus oxygen fractions are more or less linear. The mole fraction of N_2 decreases with increasing oxygen fraction as expected. The composition of methane produced is very low. The percentage of hydrogen in the fuel gas increases continuously with oxygen fraction from about 22% to 28% for an increase of oxygen fraction from 25% to 50%. A similar trend is also observed for carbon monoxide. It is interesting to know that carbon dioxide and water vapor percentages are also increasing as nitrogen percentage are decreasing. In producer gas, nitrogen, which is an inert, reduces and other component fractions would increase as is evident from Fig. 2.

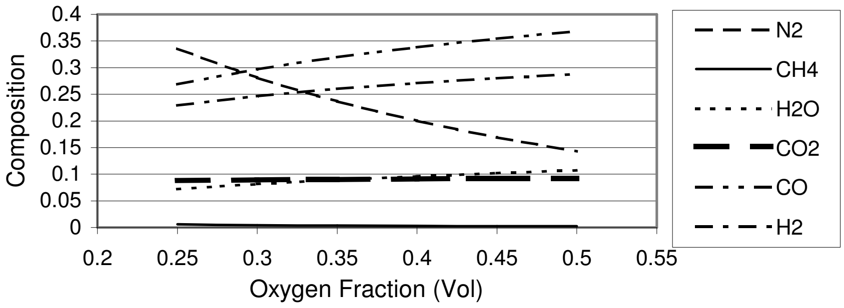

Fig. 2 Effect of oxygen enrichment on the composition

Fig. 3 shows that the reaction temperature goes up from 1090 K to 1240 K when oxygen fraction increases from 25% up to 50%. This is due to the increased oxygen and thereby decreased amount of N_2, which generally acts as a heat carrier.

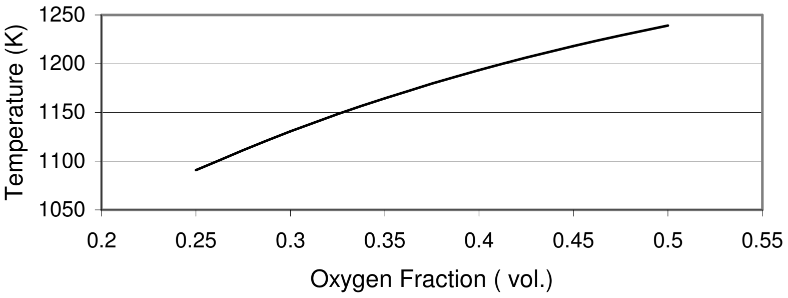

Fig. 3 Effect of oxygen enrichment on reaction temperature

Fig. 4 shows a significant increase in the calorific values of fuel gas by increasing the oxygen fraction. Calorific value increases nonlinearly from 1665 kJ/m^3 to 2140 kJ/m^3 for an increment of oxygen fraction 0.25 to 0.5. Calorific value increment is due to increase in the amount of CO and of H_2.

Amount of oxygen required to enhance particular amount of calorific value is calculated. To increase the calorific value by 255 kJ/m^3, oxygen fraction of 0.35 is needed, which can be inferred from Fig. 4. Based on the cost estimation, it was found that the added extra energy per unit cost of investment for oxygen to enrich air is 350 kJ/Rs.

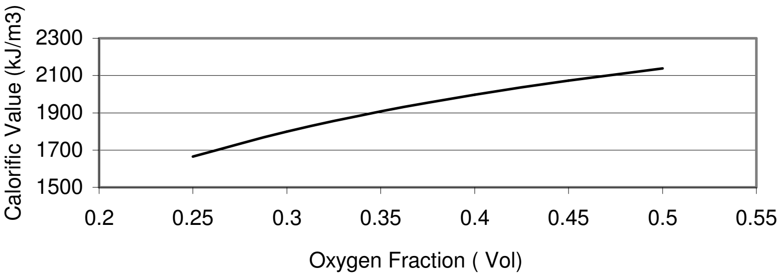

Fig. 4 Effect of Oxygen Enrichment on Calorific Values

3.3 The Effect of preheating of air

Fig. 5 shows the effect of preheating temperature on reaction temperature. Reaction temperature increases from 1090 K to 1255 K for preheating from ambient temperature to 800 K. The variation is linear and calorific values and gas composition changes very slightly with preheating of air. Preheating of air is useful to increase reaction temperature and may be employed in biomass gasifier when reaction temperature falls down due to high moisture content of biomass.

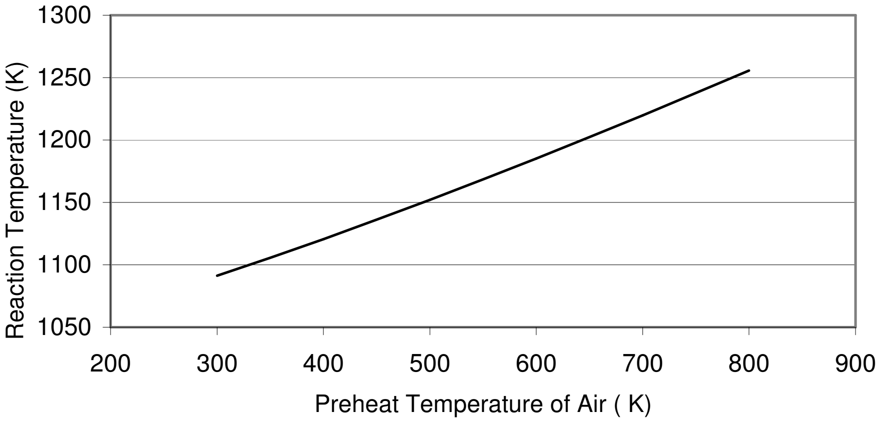

Fig. 5 Effect of Preheating of air on reaction temperature

3.4 Steam to air ratio variation and its effect on the composition

In some gasifiers, the injection of steam in the bed allows controlling reaction temperature and favors the Hydrogen production by water gas shift reaction. At the same time carbon monoxide amount decreases.

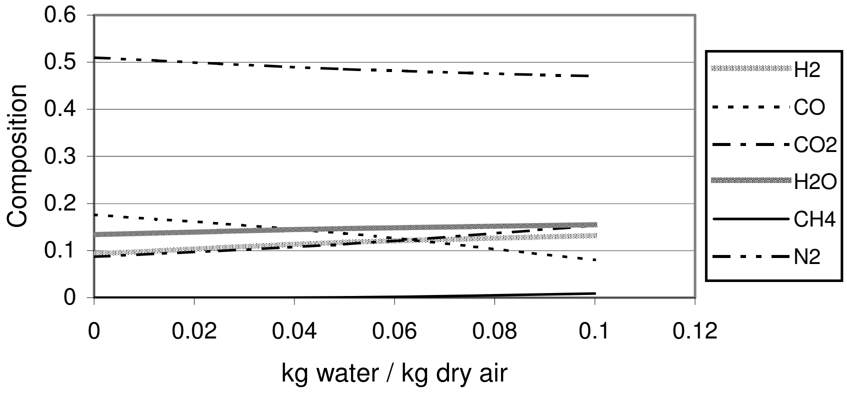

Fig. 6 Influence of steam to air ratio on gas compositions

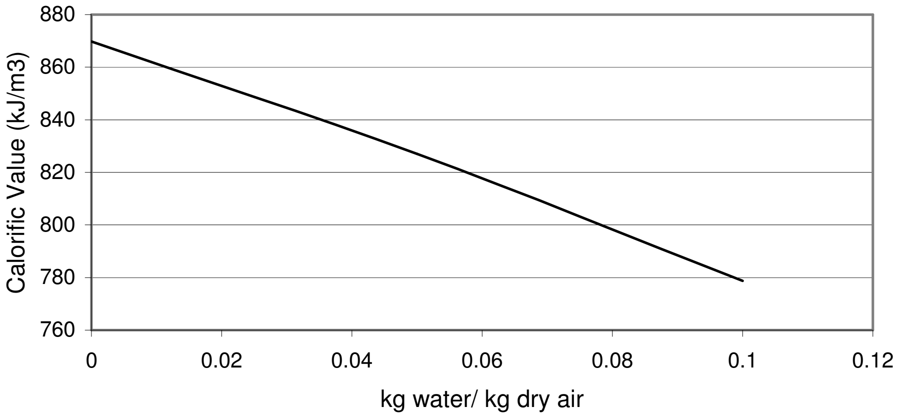

Fig. 7 Effect of steam on calorific value

Fig. 6 shows the change of composition as steam to air ratio increases for oxygen factor of 0.5 and without oxygen enrichment and preheating of air. Fig. 6 clearly indicates the increment of hydrogen from 9% to 13% for a steam to air ratio of 0 to 0.1. It also shows a decrement of CO from 17 % to 8% for the same change of steam to air ratio. Due to this calorific values decreases and it is shown in Fig. 7. Methane increases very little for a steam to air ratio decrement. Fig. 8 indicates the nonlinear temperature variation with steam to air ratio. Temperature decreases from 1600 K to 1000 K for a steam supply of 0 to 0.1 kg water/ kg dry air. Steam gasification can be used to decrease the reaction temperature.

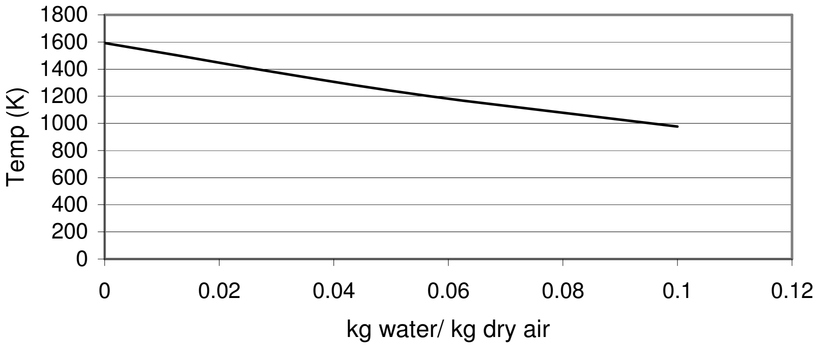

Fig. 8 Effect of steam on the reaction temperature

4. CONCLUSIONS

The modeling of gasification process in a downdraft gasifier is performed using an equilibrium model. The calculations of the composition and the calorific value of the producer gas with wood as a raw material are illustrated. From the sensitivity analysis for the oxygen enrichment in the air, preheating of air, and the steam to air ratio, following conclusions are drawn:

1. The content of hydrogen in producer gas increases with oxygen fraction and also with increment in steam to air ratio.
2. The carbon monoxide content in producer gas increases with oxygen fraction and decreases nonlinearly with steam to air ratio.
3. The methane content in producer gas increases with steam to air ratio and also with oxygen fraction. The amount of methane is insignificantly low in value to increase the calorific value.
4. The reaction temperature increases with oxygen fraction and decreases with steam to air ratio, almost in a linear fashion. The reaction temperature also increases for preheated air intake.
5. The calorific value increases with increasing oxygen fraction and decreases with steam to air ratio.

These conclusions suggest that by using air with enriched oxygen gives higher calorific values of producer gas. There is very less effect on gas composition of preheating the air. Steam gasification may be desirable for H_2 production but not useful for producer gas generation as it degrades it. The results of this study are very useful in choosing the appropriate controlling parameters, while operating a downdraft biomass gasifier.

Nomenclature

$C_{p,i}$	Specific heat of component i (kJ/mol)
F	Oxygen factor
$H^0_{f,i}$	Heat of formation of component i (kJ/mol)
K	Equilibrium constant
m	Moles of oxygen per mole of wood
P_i	Partial pressure of component i (kPa)
T	Temperature (K)
w	Moles of water per mole of wood
s	Moles of steam per mole of wood

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