Mathematical modelling of gasification processes of the biofuel in the conditions of chemical equilibrium

Anatoliy Pavlenko and Anna Maria Slowak

Kielce University of Technology, aleja Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Wydział Inżynierii Środowiska Geomatyki i Energetyki

Email: annmarii@windowslive.com

Abstract. The article presents the results of experimental studies of the process of biomass heat treatment. The method of mathematical modeling of the biomass gasification process is improved on the basis of the thermodynamic model of Gibbs free energy minimization. In most countries, their energy strategies involve an increase in the share of renewable energy sources, including using a sufficiently large biomass potential. The solution of the Lagrangian function made it possible to determine the composition of the generator gas and the efficiency of the process. The accuracy of the proposed mathematical is estimated. The obtained results of the work can be used to determine the optimal conditions for gasification in the development of biomass gasification technologies.

1. Introduction

One of the most effective technologies for using biomass is its thermochemical processing and the production of combustible gas (generator gas). The use of biomass by gasification has several advantages over direct combustion, such as:

- the possibility of using a wide range of biomass and combustible waste types, including those with a high moisture content;
- a significant reduction in atmospheric pollution when using biofuels;
- the possibility of increasing the efficiency of combustion equipment.

At present, installations and technological systems for generator gas production by biomass gasification need to be improved. There are the methods for predicting the composition of generator gas and then its performance depending on parameters of the equipment.

The synthesis of biogas is carried out by various methods, for example, by the method of biochemical oxidation of raw materials, as shown in work [1]. Such an approach makes it possible to obtain related products [2,3], but these methods are not suitable for all types of raw materials. In addition, it is difficult to predict the composition of the synthesized gas, it determines the efficiency of the boiler equipment [4,5].

The problems of processes are reflected in the works of many authors, for example, [6,7] and others. In that papers, the results of experimental studies of the gasification of solid fuels are presented, but the development of methods for predicting the composition of generator gas and determining the optimal parameters of the gasification of biomass has been neglected. Nevertheless, the use of these methods would increase the efficiency of designing appropriate gasification technologies.

Thus, the prediction of the composition of the gas is an important task in synthesis technologies, since it increases the reliability and efficiency of equipment operation. To develop a method for
predicting the composition of the gas, we took as a basis the works of the authors [8,9], where the energy characteristics of the resulting gases were evaluated. Nevertheless, in our opinion, it is very important to know also the composition of the gas and the influence of each component on the energy characteristics of this gas. This would allow to optimize the composition and predict the basic thermal characteristics. That was the task of our research.

In this paper, we present the results of experimental studies of biomass gasification processes under multifactor experiment and results of mathematical modeling of gasification processes.

2. The development of a mathematical model and its solution

The purpose of the work is to develop a mathematical model of the biomass gasification process for predicting the composition of the generator gas and the technological parameters of the operation using a complex parameter - maximum thermodynamic efficiency. To achieve this goal, it is necessary to solve the following tasks:

- to carry out research of the processes occurring during the gasification of biomass in installations with fluidized bed;
- perform a physico-chemical analysis of gasification processes;
- perform an experimental check of the mathematical model.

The real process of gasification depends on many factors. Existing mathematical models of this process usually take into account only some of them, so the accuracy of modelling remains rather low. A significant number of models are based on experimental data or hypotheses and are correct only for certain process conditions.

Among all the existing approaches to mathematical modelling of the gasification process, attention should be paid to the method of minimizing the Gibbs free energy. It does not require the specification and selection of certain gasification reactions [10] and considers only the initial and final products of the process. Therefore, this method is more suitable for considering complex systems in which a large number of reactions take place. The method is based on the study of the equilibrium state between all participants in the reactions of the gasification process.

The essence of the method is the use of the thermodynamic potential of the system, the change of which tends to the minimum value under the condition of its equilibrium [10]. Let us write the general equation for determining the isobaric and isothermal potential (Gibbs energy) of a system of ideal gases:

\[ G_{\text{tot}} = \sum x_i \cdot \mu_i \]  

where \( G_{\text{tot}} \) – the Gibbs energy of the system, kJ/kmol;
\( \mu_i \) – the chemical potential of the component of the system, kJ/kmol;
\( x_i \) – the amount of substances in the component of the system, kmol.

\[ \mu_i = G \cdot RT \cdot P_{0i} + \ln P_i \]  

where \( P_i \) – the partial pressure of the ith component of the system, Pa; \( R \) – the universal gas constant, kJ/(kmol • ° C);
\( T \) – the temperature of the system, K;
\( G_{0i} \) – the standard free Gibbs energy of the formation of the component, kJ/kmol.

Assuming that the pressure in the gasification chamber is 1 ata, the properties of the gases are close to those of an ideal gas, we write equation (2) in expanded form:

\[ G_{\text{tot}} = \sum x_i \cdot (H_{0i} - TS_i^0) + RT \sum x_i \ln \frac{x_i}{\sum x_i} \]  

where \( H_{0i} \) – enthalpy of formation of the i-th component of the system, kJ/kmol; \( S_i^0 \) – entropy of the i-th component of the system, kJ/(kmol • K).

The problem of determining the composition of a synthetic gas at an equilibrium state of the system reduces to the search for a composition that corresponds to the minimum value of the function expressed by equation (3) \( (G_{\text{tot}} \to \text{min}) \), under certain limiting conditions. The limiting conditions for
this method of modelling the gasification process will be the equations of the mass balances of the elements of the system and energy.

3. Mathematical model

3.1. Basic simplifications
Using the thermodynamic equilibrium method involves a number of simplifications, the main ones of which are presented below:
- the time of passage of all gasification reactions is sufficient to establish an equilibrium state between all the gasification products;
- all gases taking part in the gasification process have the properties of an ideal gas;
- components of biomass, the proportion of which does not exceed 1%, and ash is not taken into account;
- the components of the generated synthesis gas are CO₂, CO, H₂, H₂O, CH₄, C₂H₄, C₆H₆, N₂.

1) Accounting for air moisture. In most studies of the gasification process, the authors do not take into account the moisture of the air supplied to the gasifier, citing the fact that its share will not be significant. However, the amount of moisture coming in with the blast air can reach 7% relative to 1 kg of fuel. This amount of moisture will have a significant effect on the efficiency of the gasification process and should be taken into account in the mathematical model of the gasification process.

The air moisture is determined by the dependence (total water mass per kg of dry fuel):

\[ w_{\text{air}} = \frac{d_{\text{air}} \alpha_{\text{bio}} m_{\text{bio}} (M_{\text{O}_2} + 3.76M_{\text{N}_2})}{M_{\text{H}_2}\cdot 1000} \]  

\( d_{\text{air}} \) – moisture content of air, g/kg; \( \alpha_{\text{bio}} \) – coefficient of excess air in the process of gasification; \( m_{\text{bio}} \) – the amount of oxygen for stoichiometric combustion of 1 km of biomass, kmol; \( M_i \) – molecular mass of the i-th component, kg/kmol.

2) The presence of an unconverted carbon residue. In [11] it was experimentally proved that with increasing temperature in the gasification process, while maintaining the remaining process parameters, the concentration of CO₂ decreases in favour of CO. To form 1 kmol of CO, you need twice as much oxygen as for the formation of 1 kmol of CO₂, with the same amount of carbon. Therefore, oxygen will enter the composition of other gas components (H₂O) or remain in the free form (O₂). But gasification products practically do not contain free oxygen in their composition under different gasification conditions [11], and the H₂O concentration decreases with increasing temperature in favour of H₂. Therefore, it is advisable to talk about an increase in the conversion of carbon with increasing temperature. Also, an increase in the conversion rate of carbon occurs with an increase in the amount of moisture entering the reactor [12-14].

In the proposed model, the amount of non-gasified carbon residue is proposed to be determined by empirical relationships obtained on the basis of the results of the conducted experimental studies.

The obtained dependence has the following form

\[ \gamma = 1 - \{0.63(0.589\alpha_{\text{bio}} + 0.641)(0.001T + 0.51)(0.0003W' + 0.963)\} \]  

Where \( W' \) - the total mass of H₂O is given by 1 kg of dry gasified fuel, kg (H₂O)/kg (dry biomass); \( \gamma \) - amount of carbon that remained in the ash residue, kmol.

This regression equation is obtained after statistical processing of experimental data. We assumed that the total carbon balance contains its main components: CO, CO₂, CH₄, C₂H₄, C₆H₆ and unreacted carbon (C). It is obvious that the quantities of these components will depend on the factors mentioned above, the values of which changed in the experiments within: \( \alpha_{\text{bio}} = 0.05-0.5; T = 800-1000 \degree C; W' = 5-50\% \).

3) Empirical determination of the yield of hydrocarbons. The output of such components as methane and other hydrocarbons (C₄H₈) cannot be accurately predicted using a stoichiometric model. Unless neglecting even the relatively low yield of hydrocarbon compounds has a significant effect on predicting the yield of other components of the synthetic gas. Since part of the hydrogen (H) and carbon (C) does not lead to the formation of molecules of the (C₄H₈) type, but to the formation of
other gas components, this leads to an overestimation of the concentration of the combustible components of the synthesis gas in the stoichiometric model. Therefore, it is proposed to determine the yield of some hydrocarbons using empirical relationships, compiled from the results of experimental studies. The resulting dependence for the molar yield of CH₄ in the above experimental conditions is:

$$
CH_4 = 0.0678(0.0722 - 0.0314\alpha_{\text{CO}})(23.34 - 0.00977)(0.0003W' + 0.9626)
$$  \hspace{1cm} (6)

4) There are non-adiabatic process conditions. Most papers consider the gasification process under adiabatic conditions (without loss of heat or additional heat input). Unless under real operating conditions, heat losses are unavoidable, and with a small power of the gas generator, heat losses can significantly affect its efficiency.

In the developed mathematical model, such components as heat losses in the gas generator are introduced into the energy balance equation, which gives the possibility of a more accurate and broader assessment of the gasification process.

3.2. Equations of mass balances

As noted above, the process of gasification can be considered without dividing it into stages and taking into consideration only the initial and final products of the process. To do this, let's make a general equation of the gasification process:

$$
\text{CH}_3\text{O}_4\text{N}_4 + \alpha \text{H}_2 \text{O} + (3.76 \text{N}_2) + \text{w} \text{H}_2 \text{O} + q \text{V}_\text{SG} + f \text{V}_\text{FG} + (\alpha_{\text{mg}} - 1) \text{m}_{\text{mg}}(3.76 \text{N}_2) = \gamma \text{C} + x_1 \text{H}_2 + x_2 \text{CO} + x_3 \text{CO}_2 + x_4 \text{H}_2 \text{O} + x_5 \text{CH}_4 + x_6 \text{C}_2 \text{H}_4 + x_7 \text{C}_6 \text{H}_6 + z \text{N}_2
$$  \hspace{1cm} (7)

where $x_1, x_2, x_3, x_4, x_5, x_6, x_7, z$ - predicted yield H₂, CO, CO₂, H₂O, CH₄, C₂H₄, C₆H₆, N₂, relatively, kmol;

$V_{SG}$ - total yield of volatile components in the gasification process, kmol;

$q$ - Synthesis gas recycling ratio in gas generator, units.;

$m_{mg}$ - amount of oxygen for stoichiometric combustion of 1 kmole of generator gas, kmol;

$V_{FG}$ - amount of combustion products during stoichiometric combustion of 1 kmole of synthesis gas, kmol;

$w$ - total H₂O entering the gas generator, kmol.

In general, the mass balance equation for each $j$-th element in the system containing $M$ elements will look like:

$$
\sum_{i=1}^{N} h_{ji} n_i^{\text{out}} + A_j^{\text{out}} = \sum_{i=1}^{N} h_{ji} n_i^{\text{in}} + A_j^{\text{in}}
$$  \hspace{1cm} (8)

where $h_{ji}$ - the number of atoms of the $j$-th element in the $i$-th gas or liquid component of the system;

$n_i^{\text{in}}, n_i^{\text{out}}$ - the amount of substance of the $i$-th gas or liquid component at the entrance to the system and at the output from the system, kmol; $A_j^{\text{in}}, A_j^{\text{out}}$ - the number of atoms of the $j$-th element in the solid form, per 1 kmol of biomass at the entrance to the system at the output of the system, respectively.

3.3. Equation of energy balance

The generalized equation of the energy balance of the gasification process is as follows:

$$
\sum_{i=1}^{n} Q_i^{\text{in}} = \sum_{i=1}^{n} Q_i^{\text{out}}
$$  \hspace{1cm} (9)

where $Q_i^{\text{in}}$ - energy flow at the entrance to the gasification plant, W;

$Q_i^{\text{out}}$ - energy flow at the outlet from the gasification unit, W.

In expanded form, equation (9) can be written as follows:

$$
H_{\text{bio}}^{\text{in}} = w_{\text{bio}}H_{\text{bio}}^{\text{in}} + w_{\text{air}}H_{\text{air}}^{\text{in}} + w_{\text{steam}}H_{\text{steam}}^{\text{in}} + a_{\text{bio}}\Delta h_{\text{bio}}(3.76H_{\text{N}_2}^{\text{in}}) + qH_{\text{SG}}^{\text{in}} + fH_{\text{FG}}^{\text{in}} + Q_{\text{ex}} = \gamma H_{\text{C}}^{\text{out}} + x_1 H_{\text{H}_2}^{\text{out}} + x_2 H_{\text{CO}}^{\text{out}} + x_3 H_{\text{CO}_2}^{\text{out}} + x_4 H_{\text{H}_2 \text{O}}^{\text{out}} + x_5 H_{\text{CH}_4}^{\text{out}} + x_6 H_{\text{C}_2 \text{H}_4}^{\text{out}} + x_7 H_{\text{C}_6 \text{H}_6}^{\text{out}} + zH_{\text{N}_2}^{\text{out}} + Q'_{\text{acc}} + Q_{\text{loss}}
$$  \hspace{1cm} (10)

$H_{\text{bio}}^{\text{in}}$ - total energy of the dry part of the biomass, kJ;

$H_{\text{bio}}^{\text{in}}$ - total energy of moisture of biomass, kJ;

$H_{\text{air}}^{\text{in}}$ - the total energy of the water of the blown air supplied to the gas generator kJ;

$H_{\text{steam}}^{\text{in}}$ - total energy of water vapor for gasification, kJ;
\(H^\text{in}_{O_2}, H^\text{in}_{N_2}\) - total energy \(O_2\) and \(N_2\) of air, kJ;
\(H^\text{in}_{SG}\) - total energy of the recycled generator gas, kJ;
\(H^\text{in}_{FG}\) - the total energy of the combustion products entering the gas generator, kJ;
\(Q^\text{ex}\) - additional energy entering the gas generator from external sources, kJ;
\(H^\text{out}_{H_2}, H^\text{out}_{CO}, H^\text{out}_{H_2O}, H^\text{out}_{CH_4}, H^\text{out}_{C_2H_4}, H^\text{out}_{C_6H_6}\) - total energy \(H_2, CO, CO_2, H_2O, CH_4, C_2H_4, C_6H_6\) as gasification products, kJ;
\(Q'_{ach}\) - loss of heat with ash, kJ;
\(Q_{loss}\) - loss of heat to the environment (from the body of the gas generator), kJ

The total energy of the element of the system consists of its energy of formation and physical heat:
\[H_i = \Delta H^0_i + Q'_i,\]  
(11)

where \(\Delta H^0_i\) - standard enthalpy of formation of 1 kmol of the \(i\)-th component, kJ/kmol. Standard enthalpy of substance formation;
\(Q'_i\) - physical heat of 1 kmol of the \(i\)-th component of the system, kJ/kmol.

We write in general form the Lagrange function, which is a Gibbs function and bounds the conditions in a general form:
\[L = G_{tot} - \sum_{j=1}^{M} \lambda_j \left( \sum_{i=1}^{N} h_{ji} x_i^{out} + A_j^{out} - \sum_{i=1}^{N} h_{ji} x_i^{in} - A_j^{in} \right)\]  
(12)

where \(L\) - the Lagrange function of the system;
\(\lambda_j\) - the Lagrange multiplier at the \(j\)-th element.

The partial derivatives for each component of the generator gas equal to zero form a system of equations (12) that solution makes it possible to determine the composition of the generator gas under certain conditions of gasification. Since the mole yield of \(CH_4, C_2H_4,\) and \(C_6H_6\) is determined by empirical relationships, they will enter the system (13) as constant values for the chosen conditions of running the gasification process.

In the system of equations (13), in addition to the variables \(x_1, x_2, x_3, x_4\), the value of the free Gibbs energy \(G^0_f\), the value of which depends on the temperature, is also taken into account. In this case, the temperature of the system can be determined from the general equation of the energy balance (10) and is a function of the final composition of the generator gas.

The solution to this task is performed by an iterative method.

\[
\begin{align*}
\frac{\partial L}{\partial x_1} &= RT \cdot \ln \left( \frac{x_1}{\Sigma x_i^{+}} \right) + G^0_{fH_2} + \lambda_{H}(2q - 2) = 0; \\
\frac{\partial L}{\partial x_2} &= RT \cdot \ln \left( \frac{x_2}{\Sigma x_i^{+}} \right) + G^0_{fCO} + \lambda_{c}(q - 1) + \lambda_{O}(q - 1) = 0; \\
\frac{\partial L}{\partial x_3} &= RT \cdot \ln \left( \frac{x_3}{\Sigma x_i^{+}} \right) + G^0_{fH_2O} + \lambda_{c}(q - 1) + \lambda_{O}(2q - 1) = 0; \\
\frac{\partial L}{\partial x_4} &= RT \cdot \ln \left( \frac{x_4}{\Sigma x_i^{+}} \right) + G^0_{fH_2O} + \lambda_{H}(2q - 1) + \lambda_{O}(q - 1) = 0; \\
\frac{\partial L}{\partial x_i} &= RT \cdot \ln \left( \frac{x_i}{\Sigma x_i^{+}} \right) + G^0_{fH_2O} + \lambda_{H}(2q - 1) + \lambda_{O}(q - 1) = 0; \\
1 - \gamma + q(1 - \gamma) + f(1 - \gamma) &= x_2 + x_3 + x_5 + 2x_6 + 6x_7; \\
(b + 2w)(1 + q + f) &= 2x_1 + 2x_4 + 4x_6 + 4x_6 + 6x_2; \\
c + 2\alpha_{bio} m_{bio} + w + q(c + 2\alpha_{bio} m_{bio}) + f(c + 2\alpha_{bio} m_{bio}) + w + 2\alpha_{sg} m_{sg} &= \\
&= x_2 + 2x_3 + x_4.
\end{align*}
\]  
(13)

Experimental studies of the gasification process were carried out in a gasification plant with a fluidized bed generator that is shown in Figure 1. Based on the results of experimental studies, the material and energy balances of the process for various gasification conditions were compiled, which allowed to fully assess the efficiency of the gas generator and the quality of thermochemical treatment of biomass.

After the mathematical processing of the research results, the graphs were shown in Figures 2-5. The lines marked with the letter "S" characterize the humidity of the biomass 14%, "S+" - humidity 35%.
3.4. **Experimental studies with the scheme of experimental gasification plant**

**Figure 1.** Scheme of experimental gasification plant (1 - biomass gasification reactor, 2 - solid fuel chamber, 3 - gate valve, 4 - screw transporter for fuel transport, 5 - reactor thermal insulation, 6 - installation places for pressure and temperature measuring instruments, electricity consumed, 7 - blowing distribution system, 8 - generator gas flow meter, 9 - graphite gas filter, 10 - cooling and condensing unit, 11 - control and data collection assembly, 12 - screw drive of the fuel transfer system); 13, 14, 15 - electric heaters of different reactor zones (lower, middle with the upper respectively); 16 - electric heater of the pre-heating system; 17 - steam water jet flow meter; 18 - oxygen and nitrogen flow meter; 19 - tap for sampling gas to the filter; 20 - filter assembly heater; 21 - reactor cover; 22 - filter chamber cover; 23 - blowing control unit; 24 - steam superheater.

**Figure 2.** Graphs for the CO₂ output at the warehouse generating gas.
**Figure 3.** Graphs for the CO output at the warehouse generating gas.

**Figure 4.** Graphs for the H\(_2\) output at the warehouse generating gas.

**Figure 5.** Graphs for the H\(_2\)O output at the warehouse generating gas.
The data obtained are shown in Figures 2-5. The lines represent calculated data, points are experimental.

3.5. Checking the accuracy of the simulation

Checking the accuracy of the mathematical model of the gasification process is performed using the experimental data. For this, the correlation coefficients between the experimental and simulation results under the same gasification conditions and the relative error of the obtained data were determined.

The output data accepted for modelling are identical to the conditions for carrying out experimental studies of biomass gasification. The results of the comparison are shown in Figures 6-9.

![Figure 6. Component output graphs generator gas with variable α, W=5%.

Analysis of the results shows that correlation coefficients between experimental data sets and arrays of simulation results for the absolute majority of studies are 0.99 and higher, and only for some 0.85 ... 0.95. It is worth noting the high accuracy of modelling for low gas generation temperatures, the relative error in modelling the output of the components of the generator gas is 5 ... 10%. And a
somewhat higher error at high temperatures is 15...20%. Characteristic is a certain underestimation of the yield of the combustible components of the generator gas at high temperatures from the simulation results.

Figure 8. Component output graphs generator gas with variable humidity, \( \alpha = 0.3 \).

Figure 9. Component output graphs generator gas at variable temperature, \( \alpha = 0.3 \).

This accuracy is quite high and allows us to objectively assess the effect of the parameters of the gasification process on its result.

Thus, a new mathematical model of the process of gasification of biomass has been developed with the possibility of analyzing the thermodynamic efficiency of various factors and their influence (both separated and complex) on the energy characteristics and composition of the synthesized gas. Another important result of this work is the optimization of the biomass gasification process by determining the operating modes of the gas generator.

4. Conclusions
A wide range of single and multifactor experimental studies of biomass gasification under various conditions have been carried out. Experimental setup with compensation of energy losses of gas generator took into account the dynamics of exothermic reactions of biomass oxidation. This made it
possible to investigate the effect of separate regime factors of the gas generator on the composition of the generator gas.

A mathematical model of the biomass gasification process was developed on the basis of minimizing the isobaric-isothermal potential (Gibbs energy) function. It predicted the composition of the generator gas and the technological parameters of the gas generator. The obtained model gives high reliability of the predicted composition of the generator gas, the process temperature and the excess air factor in the reaction zone of the gas generator.

The obtained results can be used in the development of industrial installations for gasification of biomass.

**Literature**

[1] Kaosol T and N Sohgrathok 2013 Enhancement of biogas production potential for anaerobic codigestion of wastewater using decanter cake *Am. J. Agric. Biol. Sci.* 7 494-502

[2] Malakahmad A, S B Nasrudin and S M Zain 2013 Anaerobic transformation of biodegradable waste; simultaneous production of energy and fertilizer *Am. J. Environ. Sci.* 9 113-119

[3] Puah CW, YM Choo and SH Ong 2013 Production of palm oil with methane avoidance at palm oil mill: A case study of cradle-to-gate life cycle assessment *Am. J. Applied Sci.* 10 1351-1355

[4] B Kantorovich 1958 Fundamentals of the theory of combustion and gasification of solid fuel M.: Publishing House of the Academy of Sciences of the USSR 593

[5] Lavrov N V 1957 Physicochemical principles of combustion and gasification of fuel M.: Metallurgizdat 288

[6] Christus Jeya Singh, Joseph Sekhar V S, Thyagarajan K 2014 Performance studies on downdraft gasifier with biomass energy sources available in remote villages *American Journal of Applied Sciences* 11(4) 611-622

[7] Koroneos C, Lykidou S 2011 Equilibrium modeling for a downdraft biomass gasifier for cotton stalks biomass in comparison with experimental data *Journal of Chemical Engineering and Materials Science* 2(4) 61-68

[8] Z A Zainal , R Ali, C H Lean, K N Seetharamu 2001 Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials *Energy Conversion and Management* 42 1499-1515

[9] W Yang, A Ponzio, C Lucas, W Blasiak 2006 Performance analysis of a fixed-bed biomass gasifier using high-temper ature air *Fuel Processing Technology* 87 235-245

[10] S Jarunghanamchote, A Dutta 2008 Equilibrium modeling of gasification: Gibbs free energy minimization approach and its application to spouted bed and spout-fluid bed gasifiers *Energy Conversion and Management* 49 1345-1356

[11] X Li, J R Grace, A P Watkinson, C J Lim, A Ergudenler 2001 Equilibrium modeling of gasification: a free energy minimization approach and its application to a circulating fluidized bed coal gasifier *Fuel* 80(2) 195-207

[12] V Skoulou, A Zabaniotou, G Stavropoulos, G Sakelaropoulos 2008 Syngas production from olive tree cuttings and olive kernels in a downdraft fixed-bed gasifier *International Journal of Hydrogen Energy* 33 1185-1194

[13] Q Miao, J Zhu, Sh Barghi, Ch Wu, X Yin, Zh Zhou 2013 Modeling biomass gasification in circulating fluidized beds: Model sensitivity analysis *International Journal of Energy and Power* 2(3) 57-63

[14] Pavlenko A 2018 Dispersed phase breakup in boiling of emulsion *Heat Transfer Research* 49 (7) 633-641