The Influence of Fuel and Steam Consumption on Characteristics of Fixed Bed Process of Woody Biomass Steam Gasification with Intensive Heat Supply

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Abstract — **Plant biomass is one of the most widespread renewable energy sources. Energy utilization of biomass allows solving some problems associated with the development of off-grid energy systems and the processing of combustible waste (primarily agricultural and forestry waste). This paper is devoted to the study of an allothermal gasification process of plant biomass materials using a kinetic-thermodynamic model developed by the author. The gasification process is considered stationary, and steam is used as a gasification agent. The power of the supplied heat is considered constant (10 kW). One of the significant tasks related to allothermal gasification is to choose flowrate parameters so that the heat supplied is efficiently used in chemical reactions without the threat of reactor overheating. The determination of the boundaries of the safe gasifier operation involved variant calculations with a view to optimizing the gasification conditions. The calculation results show that the allothermal gasification process can proceed with a thermochemical efficiency of about 70%. For each fixed fuel consumption level, there is an optimal fuel-steam ratio. The complete conversion of biomass requires sufficiently high temperatures. The produced gas contains a significant steam fraction (>50 vol%) even under optimal conditions. The calculated fraction of hydrogen in dry gas is up to 60vol%. The data obtained can be used to assess the efficiency of energy units with biomass gasification using high-temperature sources, for example, in systems that use and store solar thermal energy.**

Index Terms: **bioenergy, allothermal gasification, mathematical modeling, hydrogen, solar energy.**

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I. Introduction

Thermochemical biomass conversion technologies have prospects for being used in distributed generation systems, not only in agricultural regions, where a large quantity of cheap reserves of combustible waste is available [1, 2] but also in developed countries, where renewable energy sources are attractive due to their environmental characteristics [3, 4]. The significant energy potential of biomass (primarily forestry and agriculture waste) is currently used to an extremely small extent, although it can be technically and economically beneficial for a wide range of energy systems [5, 6]. Biomass is used both as an addition to fossil fuels to reduce hazardous emissions produced [7, 8] and as the primary fuel [9]. The involvement of biomass in energy production requires new methods and modification of the known methods of its thermochemical processing. The reliable technologies based on these methods can only be created through an in-depth scientific study of all stages of the process, from the selection of suitable raw materials to the control of processes in the reactor and design of cleaning systems [10, 11].

Biomass is characterized by a high moisture content, high reactivity (compared to fossil fuel), the variability of mechanical properties (biomass particles may agglomerate [12], or, vice versa, disintegrate during thermal conversion [13]), production of significant amounts of tarry products during heating and oxidation [14], and a low content of ash (which, however, often has increased corrosive properties and a tendency to form fine particulate matter [10, 15]). Combustion (including co-combustion) is the most widely

used biomass conversion technology [16]. Many processes of low-temperature thermochemical processing of biomass with the production of high-calorific gas through pyrolysis and gasification have been proposed [17, 18], but their efficiency is very sensitive to the conditions of their implementation. There are more specific conversion processes, for example, plasma processing [19], and the use of supercritical fluids [20]. However, they are technologically more complicated and have high energy demands.

Pyrolysis and gasification of biomass have the potential to be applied in the areas with low energy consumption, in decentralized power supply systems. Researchers tend to consider low-capacity power units [21, 22], working with internal combustion engines [23, 24], microturbines [25], fuel cells [26], or gas burners [27]. Analysis of the life cycle of bioenergy units, even for small capacities, shows their high environmental efficiency compared to the units using fossil fuels [28, 29]. Gasification efficiency in typical small-scale processes (fixed bed and fluidized bed) is about 50-70%. Given the thermal efficiency of the gas engine at the level of 20-30%, one can obtain fuel utilization efficiency of 10-20%. One of the ways to improve the efficiency of gasification-based energy units is to use external heat sources to enhance conditions in the reactor.

Solar radiation is usually concentrated using collectors [30–32], which allow reaching a peak thermal power of up to 100 MW with a radiation collection efficiency of the order of several tens of W/m². The use of biomass makes it possible to smooth stochastic generation as part of hybrid power plants [33, 34]. The processes of thermochemical conversion of biomass can be used to store the energy of solar radiation (along with electric batteries [35, 36], carbonate and oxide cycles [37, 38], and others). To this end, fixed or fluidized bed reactors and vortex devices were developed [39-41]. The gasification agent is usually steam or vapor-air mixtures [42, 43]. The produced combustible gas with high hydrogen content can be used for direct oxidation or stored in a gasholder [44, 45]. Concentrated solar radiation can also be used at thermal power plants with solid fuel processing, for example, for heating of working fluid [46] or air when burning low-calorific fuels [47].

Experimentally, biomass and coal gasification and combustion under the intense radiation were investigated in [48-50]. The conversion factor of radiant energy in the biomass gasification process is usually low (10-20%). Kinetics of gasification of carbonaceous materials at high temperatures was studied in [51, 52]. Mathematical models of gasification processes under the influence of solar radiation are proposed in [53-58]. Allothermal processes of biomass pyrolysis and gasification were investigated in [59–67], including those in a staged gasification unit [68, 69]. Schemes with the heat recirculation of the produced gas were proposed in [70]. Mathematical models of allothermal reactors were proposed in [71–75]. This study considers a

version of the model [74] with fuel and steam heating by a constant heat flow. The gasification process is optimized by direct calculation of an output parameters on a grid of input parameters and selection of the best parameters according to efficiency criteria (completeness of fuel conversion, hydrogen yield) under some constraints (for example, on the maximum temperature). The computational efficiency of the mathematical model allows making such calculations in a reasonable time.

II. MATHEMATICAL MODEL DESCRIPTION AND INITIAL DATA

The equations describing stationary heat transfer in the fuel bed can be written as follows:

$$\lambda^g \frac{d^2 T^g}{dz^2} - C_p^g J^g \frac{dT^g}{dz} - \alpha_1 S_1 \left(T^g - T^f \right) -$$
$$- \alpha_2 S_2 \left(T^g - T^w \right) + q^g(z) = 0,$$
$$\lambda^f \frac{d^2 T^f}{dz^2} - C_p^f J^f \frac{dT^f}{dz} + \alpha_1 S_1 \left(T^g - T^f \right) -$$
$$- \alpha_3 S_2 \left(T^f - T^w \right) + q^f(z) = 0,$$
$$\frac{d^2 T^2}{dz^2} + \alpha_2 S_2 \left(T^g - T^w \right) + \alpha_3 S_2 \left(T^f - T^w \right) + q^w(z) = 0.$$

Here T is temperature, K; C_p is heat capacity, J/kg/K, λ is effective thermal conductivity, W/m/K; α is heat transfer coefficient, W/m²/K; J is flowrate, kg/m²/s; S_1 is gas-fuel heat transfer surface, m²/m³; S_2 is gas-wall heat transfer surface, m²/m³; q is a heat source, W/m³; z is spatial coordinate (reaction zone length), m; indexes f, g, and w correspond to fuel, gas and wall.

When solving the problem numerically, the reactor is divided along the axis into some small-volume elements. Knowing the residence time of the gas in each of these elements, one can write the function of the heat source for the selected i-th element in the form:

$$q = Q_{dry} r_{dry} + Q_{pyr} r_{pyr} + Q_{gas} r_{gas}$$

Here Q is a thermal effect, J/kg; r is process rate, kg/m³/s; indexes dry, pyr, and gas correspond to drying, pyrolysis, and char gasification processes, respectively. Values of q could be calculated using enthalpies of individual components and mass balance for every spatial element of length Δz:

$$q_i = \frac{J_{i-1}}{\Delta z} \sum_j h_{i-1}^j \left(T_{i-1} \right) y_{i-1}^j - \frac{J_i}{\Delta z} \sum_j h_i^j \left(T_i \right) y_i^j.$$

Here index i corresponds to spatial element number; h^j is specific enthalpy of j-th component, J/kg; y^j is the mass fraction of j-th component.

The change in the chemical composition is calculated in two steps. The first step suggests considering heterogeneous processes: drying, pyrolysis, and the charcoal reactions with CO_2 and H_2O (oxidation by O_2 is not taken into account):

$$\frac{dy_{H_2O}}{dz} = \frac{\rho^g}{J^g} \beta S_1 \left(\frac{C^{eq}_{H_2O}}{\rho^g} - y_{H_2O} \right),$$

$$\frac{dm_V}{dz} = -\frac{\rho^f}{J^f} k_{pyr} m_V,$$

$$\frac{dm_C}{dz} = \frac{1-V_{daf}}{V_{daf}} \frac{dm_V}{dz} + \frac{\rho^f}{J^f} \left(-k^{eff}_{CO_2} S_1 \rho_g y_{CO_2} - k^{eff}_{H_2O} S_1 \rho_g y_{H_2O} \right).$$

Here ρ is the density, kg/m³; β is coefficient of mass transfer, m/s; C^{eq} is the equilibrium concentration of water vapors, kg/m³; k_{pyr} is pyrolysis rate constant, s⁻¹; m_V is the quantity of volatiles in the fuel, kg; m_C is the amount of carbon in the fuel, kg; y_{CO_2}, y_{H_2O} are mass fractions of gasification agents in the porous volume; k^{eff} is the effective rate constant of a heterogeneous reaction, m/s. The effective rate constant of the heterogeneous reaction k^{eff} is determined in the quasi-stationary approximation [76]:

$$k^{eff} = \frac{1}{\dfrac{1}{\beta} + \dfrac{1}{k_0 e^{-\frac{E}{RT}}}}.$$

Here k_0 is the pre-exponential factor, m/s; E is the activation energy, J/mol; R is the universal gas constant. Chemical kinetics of reactions in the gas phase is not considered: it is assumed that the gas phase quickly reaches a state of equilibrium. Thus, at the second step of the calculation, chemical transformations are described using a thermodynamic model with macrokinetic constraints on the rate of heterogeneous transformations. This approach is applicable to high-temperature processes, in which the rate of gas-phase processes is quite high, compared to that of heterophase processes. In the iterations, the local temperature can be considered a constant parameter, and the heat balance is taken into account when solving the heat transfer equations [77]. Kinetic coefficients are presented in Table 1.

Table 1. Kinetic coefficients

Reaction	k_0, s⁻¹	E_a, kJ/mol
Pyrolysis	5×10^4	96
$C + CO_2$	1.32×10^7	250
$C + H_2O$	9.3×10^5	175

The presented model of a fixed bed conversion was used earlier in the study on low-grade fuels gasification processes in [78, 79]. This research assumes that the reaction zone of the reactor is uniformly heated through the wall with a constant heat flux of 10 kW. The reaction zone dimensions taken for calculations are - length is 0.25 m and diameter is 0.2 m. The fuel is woody biomass with the following composition: $W^r = 12\%$, $A^d = 0.67\%$, $V^{daf} = 80\%$ $C^{daf} = 46.96\%$, $H^{daf} = 5.92\%$; $O^{daf} = 45.23\%$; $N^{daf} = 1.08\%$; $S^{daf} = 0.08\%$; average particle size is 2.5 cm. Variable parameters are fuel flowrate (4-10 kg/h) and steam flowrate (2-10 kg/h). The fuel inlet temperature is 300 K, the steam inlet temperature is 600 K. The characteristics of interest are the outlet gas composition, the degree of fuel conversion, and the thermochemical efficiency of the process (η). Efficiency is defined as the ratio of the output flow of chemical energy (calorific value of the generator gas $Q^g J^g$) to the input flow of energy (calorific value of the fuel $Q^f J^f$ and supplied heat q^{ex}):

$$\eta = \frac{Q^g J^g_{out}}{Q^f J^f_{in} + q^{ex}}.$$

The calorific value of the generator gas is calculated as the weighted sum of the calorific values of its constituent components. With a higher calorific value of the feedstock of about 15 MJ/kg, the supplied heat is equivalent to 25-60% of the calorific value of the biomass entering the reactor.

III. Results and discussion

At low biomass and steam flowrates, most of the supplied heat goes to temperature increase: as seen in
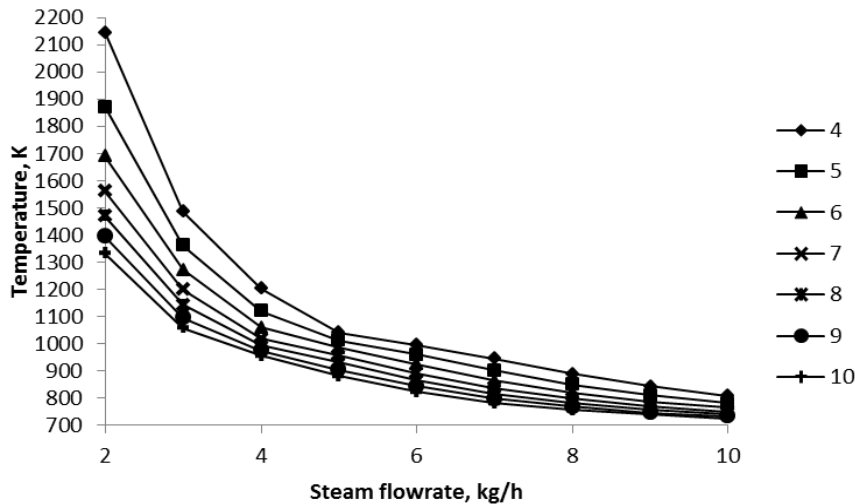

Fig. 1. Relationship between maximum temperature in gasifier and steam and fuel flow rates (numbers in the legend are fuel flowrates, kg/h).
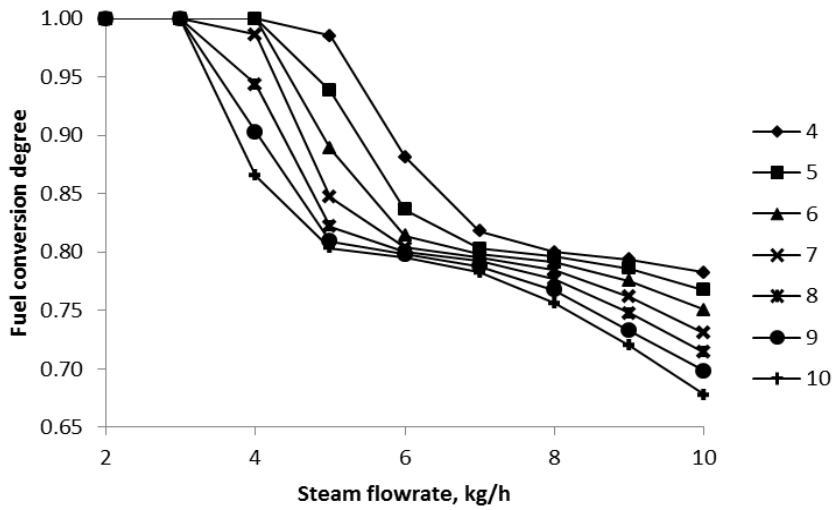
Fig. 2. Relationship between fuel conversion degree and steam and fuel flowrates (numbers in the legend are fuel flowrates, kg/h).
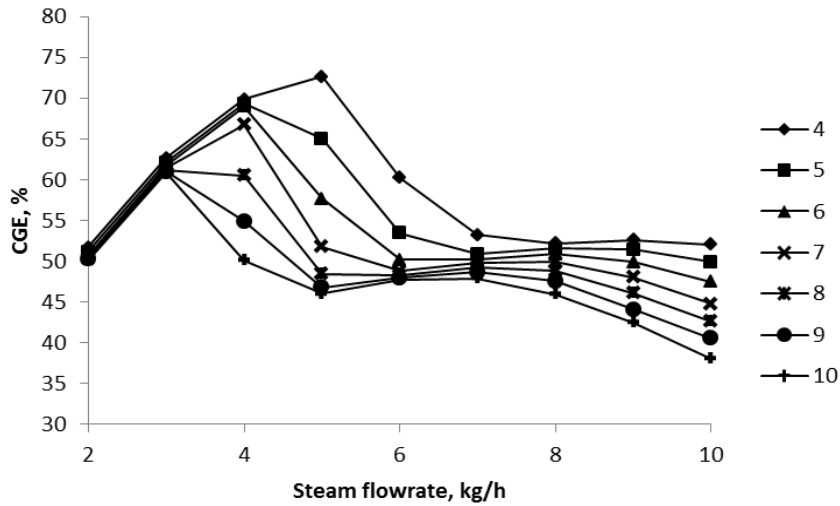

Fig. 3. Relationship between thermochemical efficiency of gasification process and steam and fuel flowrates (numbers in the legend are fuel flowrates, kg/h).
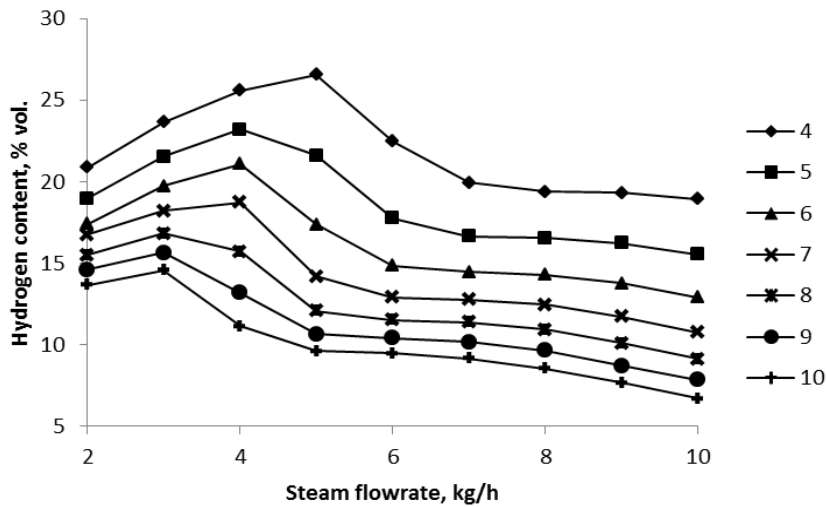

Fig. 4. Relationship between hydrogen concentration in raw produced gas and steam and fuel flowrates (numbers in the legend are fuel flowrates, kg/h).
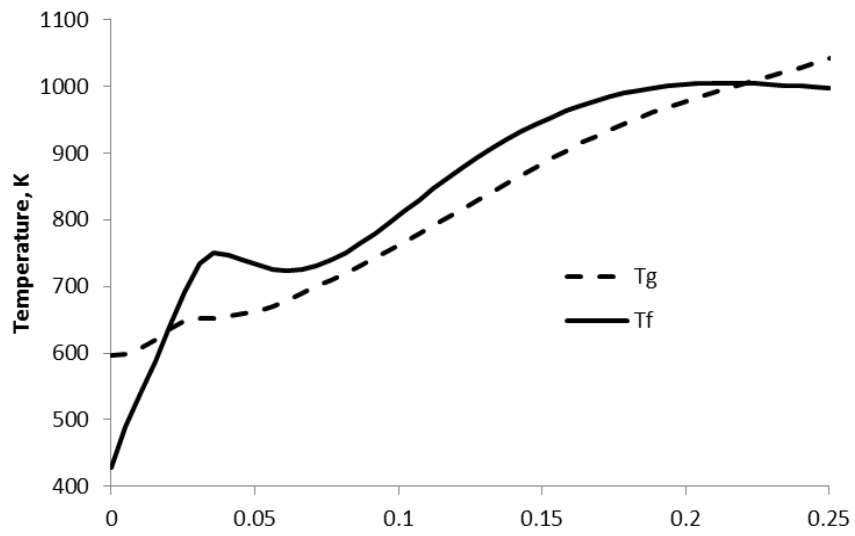
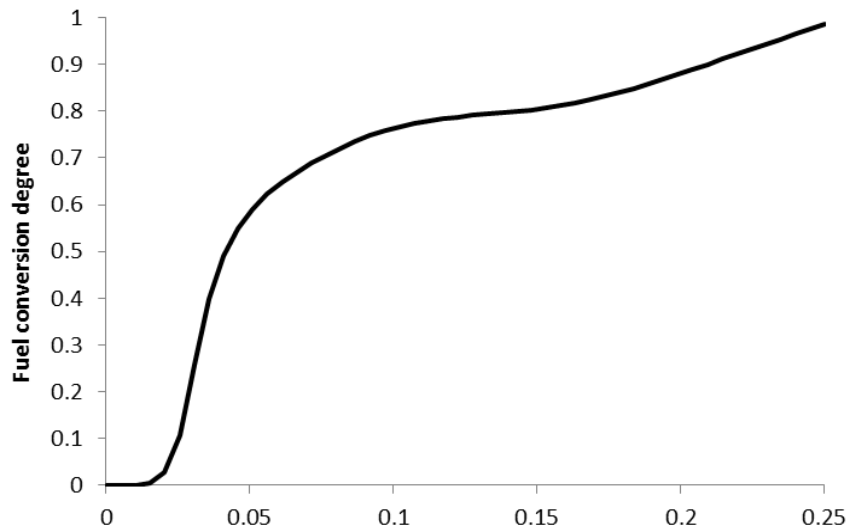*Fig. 5. Distribution of gas and fuel temperature along the reaction zone.*

Fig. 6. Distribution of fuel conversion degree along the reaction zone.
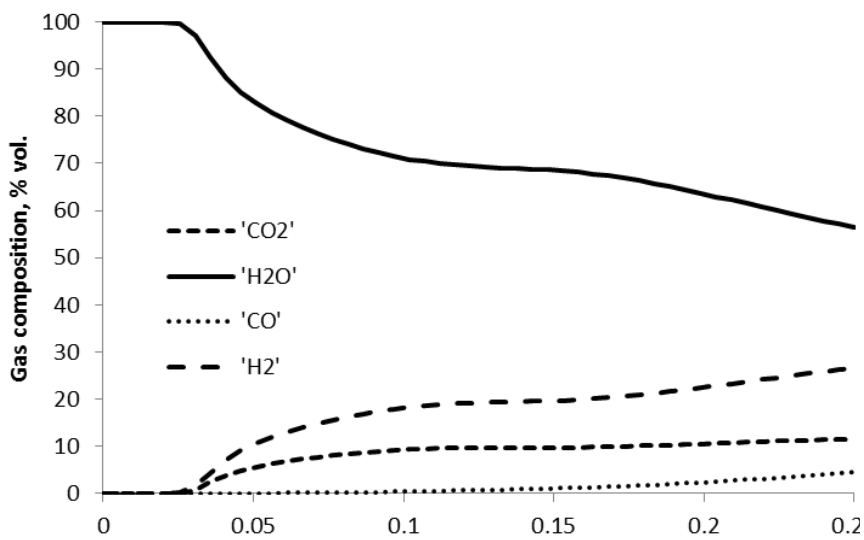

Fig. 7. Distribution of gas composition along the reaction zone.

Table 2. Comparison of modeling results with published data on dry gas composition (vol%.)

Source		H$_2$	CO	CO$_2$	CH$_4$
[82]		44.7	25.2	5.8	1.8
[83]	Pyrolysis	44.2	51.8	18.3	23.8
	Gasification	48.8	32.8	16.7	1.7
[49]		52.4	38.9	3.2	1.5
[67]		44.6	19.7	22.3	13.4
[40]		37.2	40.0	11.1	8.8
Present work	High steam-fuel ratio	54.5	26.7	15.5	2.5
	Optimal	61.0	10.3	26.4	1.5

Fig. 1, temperatures can reach very high values (up to 2000 K). These conditions are not suitable for real units due to constraints on material properties. Additionally, the kinetics of chemical reactions and transport processes at high temperatures may differ from that assumed in the model. Already in this stage of consideration, it is possible to exclude a range of inappropriate parameters.

With an increase in the fuel and steam flowrate, however, the conversion of fuel decreases (Fig. 2). The lower the temperature, the lower the gasification rate, which is why, at a steam flowrate of more than 3-4 kg/h, charcoal yield increases sharply. At a high fuel flowrate, the reactor can operate as a pyrolyzer (for example, for the production of activated carbon [80]). For complete gasification of biomass, it is necessary to select conditions with low fuel flowrates and high steam flowrates, most of which serves as ballast to prevent overheating. Fig. 3 shows the relationship between the efficiency and the process parameters: with a change in the steam flowrate and fixed fuel flowrate, the gasification process efficiency has an extremum corresponding to the complete conversion of fuel carbon. The maximum concentration of hydrogen in the produced gas is also observed (about 26 vol%).

Thus, with a fixed external heat supply, the optimal parameters of the allothermal gasification process are determined by the fuel-steam ratio and the total flowrate of reagents (at low flowrates, the temperature in the reactor becomes unacceptably high). The range of suitable temperatures, in which the gasification reactions proceed quite intensively, can be limited, but the reactor overheating is not observed in a range of 1000-1100 K. Then, according to Fig. 1, one can cut off the area of unsuitable conditions. The temperature distribution over the reactor length for one set of parameters (fuel flowrate 4 kg/h and steam flowrate 5 kg/h) is shown in Fig. 5. The fuel is heated at an almost constant rate until intense devolatilization begins.

As seen in Fig. 6, with an increase in the degree of conversion, the devolatilization slows down. The gasification stage begins approximately in the middle of the bed but has enough time to complete. The gas composition is shown in Fig. 7: an excess of water vapor leads to a shift in the equilibrium in the water-gas reaction towards the formation of hydrogen and carbon dioxide, CO is formed only at the gasification region, and its fraction

in gas is very low (4.5 vol%). If the produced gas is dried by cooling and complete condensation of water vapors, then hydrogen content in it can reach 60%. Some of the hydrogens, however, will be converted into a water shift reaction ($CO_2 + H_2 = H_2O + CO_2$).

Fuel gasification using concentrated solar radiation, in reality, occurs with significant fluctuations of heat flow even at short times, which is associated with the natural variability of atmospheric conditions. Therefore, for a more accurate assessment of the efficiency of such processes, it is necessary to take into account the variable nature of heat supply. Another disadvantage of the model is the absence of tar in the gasification products: according to experimental data on allothermal gasification, the tar yield can be up to 45% per organic mass [81]. These problems are to be solved in further works. A comparison of the obtained results with experimental data is presented in Table 2.

It is worth noting that the experimental data are very heterogeneous: some relate to continuous reactors (mainly, fluidized bed), while others are obtained by averaging unsteady conditions. Nevertheless, the experimental data can be ranked according to their proximity to pyrolytic conditions. During biomass pyrolysis, methane content is quite high (up to 10-20 vol%). During gasification, methane content is up to 2 vol%. Thus, the presented simulation results are in good qualitative agreement with data on solar-driven steam gasification of biomass. The pyrolysis region is described with lower accuracy: the equilibrium model predicts an increase in the hydrogen yield with a decrease in the specific steam flowrate (due to high temperature and water vapor concentration), but experiments show an increase in the methane yield.

IV. Conclusion

The present study considers a mathematical model of the biomass gasification process with steam under intensive external heat supply. It focuses on the influence of fuel and steam mass flowrates on the efficiency of the gasification process. The findings suggest that to maintain the process at a suitable temperature (i.e., to prevent overheating and provide sufficient fuel conversion), it is necessary to accurately estimate mass flowrates and a

fuel-stream ratio. The results show that under 10 kW of external heat supply, suitable parameters are fuel flowrate is of 4-10 kg/h and the steam flowrate is of 3-6 kg/h. The maximum thermochemical efficiency of the allothermal gasification process (given the heat consumption for heating the reactor) is about 70%; the maximum hydrogen content in the dry produced gas is about 60%. The suitable parameters for biomass gasification are in the area where the complete conversion of fuel carbon is not achieved.

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