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A semi-empirical approach to the thermodynamic analysis of downdraft gasification

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HIGHLIGHTS

- We suggest an approach to the analysis and optimization of process parameters.
- The approach was tested by the experiments on downdraft gasifier.
- For the charcoal and biomass cases the mass and energy balances were made up.
- The results are generalized as cold gas efficiency constraints.
- A hypothesis about the wood gasification mechanism is put forward.

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ABSTRACT

For most commercial biomass gasifiers the cold gas efficiency makes up 50–70%. However, thermodynamic modeling demonstrates the possibility of its increase to 80–85%. Thermodynamic models predict an optimal composition of flows coming to the gasifier, and a temperature. These parameters are hard to reproduce at gasifier since they often depend on the operating parameters. This paper proposes a semi-empirical approach which makes it possible to carry out a thermodynamic analysis of operating parameters and optimization of gasifier operation.

To test the approach we did experiments on charcoal and biomass gasification in a downdraft gasifier. Modeling was done on a non-stoichiometric model maximizing the reaction system entropy.

The semi-empirical approach reveals three limitations of the cold gas efficiency of the experimentally observed process. The first limitation is related to the attainment of a carbon boundary line (which is estimated thermodynamically) by the reaction system. This line corresponds to the maximum cold gas efficiency of the process. The second limitation deals with a shift along the carbon boundary line. The third limitation is a stoichiometric limitation on the formation of combustible gas components.

The process of wood gasification is characterized by a number of phenomena which are untypical of the downdraft process. These phenomena underlie the hypothesis about the wood gasification mechanism. According to this hypothesis the process of gasification runs in the layers of individual particles. At the same time there is either no fuel bed stratification or it does not manifest itself.

1. Introduction

1.1. Background

Biomass is a promising renewable energy source. Its advantages compared to the traditional types of fuel are as follows: biomass is considered to be a carbon neutral fuel, which makes it possible to reduce carbon dioxide emissions; its use may contribute to an increase in the energy security of the countries importing energy resources, decrease their dependence on fossil and nuclear fuel supplies; an increase in the energy use of biomass is an additional factor of economic support to the agricultural regions [1]. A specific feature of biomass is low density of its distribution across the territory, which limits the cost effective radius of its collection and arouses interest in the energy plants of small unit capacity [2].

One of the efficient biomass processing methods is gasification. This is the process of thermochemical fuel conversion under the effect of gaseous oxidizers or supercritical water [3]. Unlike other

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processes of thermochemical conversion such as burning, pyrolysis, liquefaction, carbonization and torrefaction, the target product of gasification is gas intended for energy and production purposes.

Gasification of solid fuel is not a new technology and over the last century and a half several periods of its development have changed one another [3]. Since early 2000s again there has been an increase in the interest in this technology, which was caused by the following factors: the aims to reduce carbon dioxide emissions and improve the environmental friendliness of the energy industry; a considerable increase in the cost of hydrocarbon feedstock; an intensive development of the economy and growing energy consumption in China and India [4].

Despite the existing potential, the gasification technologies have not been widely commercialized [5], so far and the major share of energy produced from biomass falls on the process of direct combustion [6]. This situation can be explained by a number of technological problems characteristic of gasifiers [7,8]. Research into the production process line of biomass processing has shown that the main difficulties are related to the stages of gasification and gas cleaning [8].

One of the technological barriers to the gasification commercialization is insufficiently high cold gas efficiency of the existing plants. This characteristic reflects the share of chemical energy of the fuel which is transferred to the chemical energy of gas. Sensible heat of gas in this case is not considered. The overwhelming majority of commercial plants are characterized by comparatively low cold gas efficiency, about 50–70% (Table 1). Interestingly, this level is typical of the plants of different capacity, which have different design and conditions of process organization, and process fuel of different origin and composition. At the same time there are experimental studies demonstrating the possibility of increasing the cold gas efficiency. In the autothermal process that occurs without external heat supply the cold gas efficiency of 77% was reached [9]. With heat supplied, in the allothermal process it is possible to achieve higher efficiency values, reaching 124% [10]. This value is indicative of the fact that the energy of gas exceeds the energy of fuel used to produce this gas. Additional energy comes to the process in the form of heat and is converted to the chemical energy of gas.

Comparatively low efficiency of demonstration and pilot plants is related to the non-optimal conditions for the operation of reactors, and in some cases – to the non-optimal choice of gasification method of one or another fuel type. This research aims to enhance the cold gas efficiency of gasification process.

1.2. Thermodynamic modeling of gasification

A widely spread approach to the research into the gasification process and assessment of the degree to which it is perfect is a thermodynamic approach [19,20]. The approach is based on the equilibrium approximation. This is why the assumptions made in the models were as follows:

1. Consideration is given to a steady-state process which occurs in a continuous stirred-tank reactor. Thermodynamic models are zero-dimensional. They do not take into account possible gasifier configurations, such as fixed bed, fluidized bed and pneumatic transport [21].
2. Chemical system is supposed to attain equilibrium. There is a systematic deviation between equilibrium and experimental yield of substances. The measured yield of tar, C_2-hydrocarbons, methane and char often exceeds the equilibrium values [22,23]. The calculated equilibrium ratio H_2/CO exceeds the experimental one.
3. Mineral part of the fuel is represented by a mechanical mixture of metal oxides and silicon oxide [24]. Chemical transformations of these components are either not considered [24] or are limited by pure condensed substances – carbonates, silicates, aluminum silicates, etc. [25,26]. Such an approximation is related to the insufficient accuracy and stability of thermodynamic data for phases and components of ash, and the presence of liquid and glass phase, etc. [27].

In order to take into account the non-equilibrium composition of reaction products, which is experimentally observed, researchers introduce mass constraints on the formation or consumption of one substance or another. The constraints are caused by insufficient residence time of the substances in the reaction zone, and are of a kinetic nature. They are formed on the basis of experimental data obtained at gasifiers. The constraints can be taken into account in the model by applying quasi-equilibrium temperature, which is lower than the temperature of the process and better simulates the yield of char residue and methane [28,29]. In stoichiometric models, constraints are introduced by adjusting the equilibrium constants of water–gas shift reaction and methane formation. The equilibrium constants are multiplied by coefficients depending on the process temperature, oxygen content or equivalence ratio [30,31]. Non-equilibrium content of substances can be taken into account directly in the mass balance. In this case the required mass of the substance is stoichiometrically excluded from the initial matter of the system, is sent through bypass and mixed with equilibrium products of the reaction [32,33]. Additional models can be used to describe the conversions of substances that pass through the bypass [34].

Thermodynamic models make it possible to find optimal operating conditions of a certain reactor or an entire plant. The optimized parameters include energy and exergy efficiency, hydrogen and carbon dioxide yield, gas heating value and its output with a certain ratio of H_2 to CO [35–39]. The result of modeling represents an optimal set of input parameters that mirrors the

Table 1
Performance characteristics of commercial biomass gasifiers.

Size, MW(th)	Scale	Gasifier type	Agent type	Feedstock	Moisture wb, %	Ash db, %	CGE[a], %	Carbon conv., %	Refs.
26.5	Commercial	Shaft-furnace	Oxygen-rich air	Municipal solid waste	44.0	16.3	49.2	95.3	[11]
18.9	Commercial	Shaft-furnace	Oxygen-rich air	Municipal solid waste	42.8	32.3	54.6	91.7	[11]
2.0	Pilot	Bubbling fluidized bed	Air/steam	Sewage sludge	3–8	39.5	70	n/a	[12]
1.2	Pilot	Two-stage downdraft	Air	Wood chips	12.3	0.6	53	74	[13]
1.1	Demonstration	Updraft	Air, Air/steam	Municipal solid waste	30.0	11.7	32–58[b]	n/a	[14]
0.5	Demonstration	Bubbling fluidized bed	Air	Sewage sludge	3–8	57	66	n/a	[12]
0.4	Pilot	Entrained-flow (cyclone)	Air	Peat, rice husk, bark, wood	<15	0.6–19.3	43–52	70–95	[15]
0.3	Pilot	Entrained-flow	O_2/N_2	Wood powder	3.0	0.9	58	89	[16]
0.25	Pilot	Downdraft	Air	Wood sawdust, pellets	9.5	2.1	68	n/a	[17]
0.06–0.08	Pilot	Bubbling fluidized bed	Air	Wood pellets	6.3	0.7	55–60	89–95	[18]
0.04–0.07	Pilot	Bubbling fluidized bed	Air	Olive oil waste (orujillo)	8.7	14.2	53–60	70–94	[18]

[a] Cold gas efficiency.
[b] The calculations considered heat supplied to the process.