Plasma gasification of waste as a method of energy saving

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Abstract. Several versions of the organizations of the process of plasma-chemical gasification with the use of air, carbon dioxide, steam and their mixtures as the plasma-forming gas are considered in the presentation. The results of the calculation-theoretical evaluations of the quality of synthesis gas and efficiency of gasification, and also the results of experiments on plasma gasification of wood waste carried out on the experimental IEE RAS test-bench are given. The results of calculations are compared with experimental data.

1. Introduction

In the second half of the 20-th centuries the rate of waste formation and energy consumption per capita steadily grew together with increase of a life standard. In 2008 capacity of global consumption of primary energy made approximately $4.73 \times 10^{11}$ GJ [1] at total population size of $6.68 \times 10^9$ person [2]. That is, on average one person consumes ~2.24 kW of primary energy. In the developed countries 400-760 kg of municipal waste are formed annually per capita [3] and it is consumed 60-390 GJ per capita [1]. If to assume, that combustion heat of municipal solid waste (MSW) makes 15-20 MJ/kg, then the use of waste will allow saving about 3-15 % of primary energy. These wastes on 15-68 % consist of paper and cardboard which composition is similar to wood. Besides, wood materials in their self are the important source of renewed energy [4].

The process of direct burning of biomass and waste for energy generation is ineffective [5] and ecologically hazardous. Now gaseous fuel combustion has higher efficiency. Therefore, it is expedient to subject solid fuel to the gasification process as a result of which primary energy of solid fuel will be transformed to chemical energy (energy of combustion) of synthesis gas (mixture of hydrogen and carbon monoxide). Besides, the produced synthesis gas can be a raw material for production of liquid fuel [6] and hydrogen.

Due to plasma application it is possible to increase power efficiency of gasification and to decrease the content of incombustible components of synthesis gas (nitrogen, carbon dioxide). Thus energy content of the plasma gasification products can exceed the combustion heat of initial raw material. Besides, it allows decreasing of the specific emission of greenhouse gases both on power stations, and at incineration plants.

Synthesis gas can be used as a raw material for production of hydrogen, liquid fuel and other substances of chemical-technological purpose. Synthesis gas can be produced from hydrocarbonic waste of various morphological compositions [7].

2. Ways of organization of plasma gasification and their features
There are several ways of solid fuel gasification, namely: updraft, downdraft, twin-fire, crossdraft, entrained flow, fluidized bed. These schemes can be transferred without change on plasma gasification methods. Figure 1 shows inlet and outlet points of mass flows for various schemes, and also characteristic zones of the gasification processes.

Two basic zones: oxidizing and reduction can be marked out in all schemes. The oxidizing zone is located at a point of plasma inlet, therefore the highest temperatures are observed in it and the most part of chemical reactions proceeds. The reduction zone is next to the oxidizing zone (in the direction of gas movement). There the oxidation of semicoking products by carbon dioxide and steam takes place. If fuel is supplied into the low temperature zone, so it is possible to separate a zone of pyrolysis in the reactor volume. Temperatures in this zone are high enough for evaporation of moisture and primary decomposition of fuel with release of simple gases and tars, but insufficient for reduction reactions. There is no oxygen in this zone; therefore the composition of products of pyrolysis of raw material is determined only by the rate of heating and pressure.

Updraft plasma gasification is well adapted for high humidity biomass gasification due to availability of thermal energy of syngas for raw material drying. The hot gases, ascending from the zone of oxidizer inlet, heating up cold biomass, intensifying pyrolysis and evaporation of an excess moisture. The evaporated moisture does not get into zones of oxidation and reduction, therefore less energy is required for its heating. However, products of low-temperature pyrolysis do not pass through high-temperature zones and as a result the synthesis gas is polluted by tars. There are solid products of pyrolysis having high combustion heat in a zone of plasma inlet. Therefore, high temperatures are achieved in this zone even at use of air blasting without energy input. For example, at gasification of graphite by air in the adiabatic mode the temperature of products (in which CO$_2$ practically is absent) is ~1200 °C. Use of air plasma in this case will lead to increase in temperature in the oxidizing zone, to increase the reduction zone and insignificant reduction in the amount of incombustible admixtures in synthesis gas. Use of CO$_2$ or H$_2$O as a plasma forming gas will lead to increase in a specific energy
output from a mass unit of raw material and to increase in power inputs. The important advantage of the method is the opportunity of liquid slag discharge.

In the downdraft gasification process all products of pyrolysis pass through the high temperature zone in which the tars are subjected to cracking. That is why the syngas at the gasifier outlet contains insignificant amount of tar (comparing with the previous method). Then, steam and carbon dioxide take part in the oxidation process of solid products of the pyrolysis in the reduction zone. Reactions of CO\textsubscript{2} and H\textsubscript{2}O with carbon are exothermal that is why high temperature should be maintained in the reduction zone. Thus, input of energy with plasma will lead to intensification of reduction reactions and to deeper tar cracking. It will result in increase in power efficiency of gasification and decrease in the content of incombustible admixtures in syngas.

Twin-fire gasification is an improved version of the previous one. At the expense of the additional point of plasma inlet the temperature in the reduction zone increases and its length can be increased. Solid products of pyrolysis are in the lower oxidizing zone with the increased ash content, as a part of their carbon has been gasified in the reduction zone by the products of plasma conversion of volatile substances. That is, the basic purpose of this zone is increase of a temperature level in the reduction zone due to burning out of residual carbon. By analogy with the updraft process, it is possible to organize liquid slag discharge.

In crossdraft gasification the point of plasma inlet is at the same level with the point of gas outlet. The oxidizing and reduction zones divide the reactor shaft in horizontal plane. That is why part of the oxidizing products gets into the oxidizing zone and is subjected to deep cracking, while other part gets in the reduction zone. As a rule, these zones are high-temperature therefore the content of tar in synthesis gas will be less than in the updraft process. However, because of small length of the reduction zone the content of H\textsubscript{2}O and CO\textsubscript{2} in raw synthesis gas will be higher than in the downdraft process. This method differs in the increased temperatures of synthesis gas at the reactor outlet.

In entrained flow gasification the speeds and trajectories of movement of solid and gas phases coincide. The release of volatile agents and water evaporation happens directly in the oxidation zone. Residence time of the solid phase in the reduction zone is short in comparison with other ways. Shredding of raw material provides the increase in level conversion of raw material, and supply of the excess oxidizer amount provides high temperatures. The energy efficiency of this method in comparison with the downdraft process will be lower due to higher energy consumption for achieving of higher temperatures. Besides, synthesis gas will be highly polluted with solid particles. Application of plasma allows achievement of the same temperatures at the decreased oxidizer consumption. The mixing (initial) temperature will be considerably higher than the average temperature in the reactor. Recirculation of solid particles is one more way of increase in conversion level of raw material. In the case of low reactivity of fuel the recirculation use results in increase of power inputs.

The general flow diagram of the process of fluidized bed gasification, except for position of a point of raw material inlet, corresponds to gasification in the entrained flow (figure 1 e). The reaction volume of gasifiers working under this scheme as a rule has a shape expanding to the top. In the top layers of fluidized bed there are the smallest pieces of raw material, and in the bottom layers are the biggest ones. Constant mixing of pieces of fuel promotes more uniform distribution of temperatures in cross-section section of the reactor. Depending on the location of the point of raw material inlet this method will have similar characteristics either with the updraft or with the downdraft process. If the raw material is supplied from the top, so during falling and migrations of a piece in a high-temperature bottom layer it will have time to lose a part of the moisture and volatile agents that results in synthesis gas pollution with tar. If the raw material is entered from the bottom, an output of volatile agents and evaporation of water is carried out in the oxidizing zone where tars are subjected to deep cracking. As well as at gasification in the entrained flow the synthesis gas will be highly polluted by solid particles. Their size will be determined by the least speed of gas flow at the top part of the gasifier.

Thus, energy of plasma will be most effectively used in the downdraft and twin-fire processes (under condition of supply of the basic plasma stream in the top inlet point). It is caused by mixture of plasma with pyrolysis products directly in the inlet plasma point and long residence time of solid
components in a high-temperature zone. Use of steam or CO₂ plasma can also be justified in the updraft process. For example, if it is necessary to produce high-calorific synthesis gas from fuels with high humidity.

3. The description of a design procedure
The developers of technologies of synthesis gas use are greatly interested in its composition, power inputs and specific yield of chemical energy of gas.

The following assumptions have been made for modeling of the plasma gasification process and calculation of potential parameters of processes of electric power generation and synthesis of liquid fuels:
- the mixture of plasma and ash-free mass of wood waste reaches the thermodynamic equilibrium state at temperature of 1500 K and pressure of 101.3 kPa;
- the inorganic component of wood waste does not participate in chemical reactions, and power inputs on its heating is from 298 K up to 1500 K that is ~1.367 MJ/kg;
- there are no changes in composition of gasification products at their cooling to 298 K;
- mass composition of wood waste: C – 50.25, H – 6.09, O – 43.35, N – 0.2, S – 0.1 % (dry, ash-free mass), ash content– 1 % (dry mass), humidity – 20 % (as received); LHV – 13.90 MJ/kg (as received) [8];
- mass composition of air: N₂ – 74.43, O₂ – 22.81, Ar – 1.27, CO₂ – 0.04, H₂O – 1.45 %;
- dependence between efficiency of combined cycle and temperature in range of 1400-2000 K, as it is described in [9], was approximated by polynomial to estimate specific yield of electric energy:
\[ \eta = 0.133 + 4.3 \times 10^{-5} \cdot T + 2.6 \times 10^{-7} \cdot T^2 - 7.9 \times 10^{-11} \cdot T^3 \] (1)
where \( \eta \) – efficiency of combined cycle (part of an unit), \( T \) – temperature (K);
- efficiency of combined cycle at temperatures higher then 2000K was considered as constant and equal to efficiency at 2000K;
- if volumetric ratio H₂/CO ≥ 2 then it is potentially possible (in conformity with stoichiometry of Fischer-Tropsch process), that the specific yield of liquid fuel is defined by the formula:
\[ G_{SF} = G_{SG,d} \chi_{CO} \rho_{CH₂} \] (2)
where \( G_{SF} \) – liquid fuel yield (kg/kg), \( G_{SG,d} \) – dry syngas yield (Nm³/kg), \( \chi_{CO} \) – volume fraction of CO in syngas (part of an unit), \( \rho_{CH₂} \) – density (at 25 °C, 101.3 kPa) of the conceptual gas with chemical formula CH₂ (kg/m³);
- if volumetric ratio H₂/CO < 2 then it is potentially possible (in conformity with stoichiometry of Fisher-Tropsh process), that the specific yield of liquid fuel is defined by the formula:
\[ G_{SF} = G_{SG,d} (\chi_{H₂} + \chi_{CO}) \rho_{CH₂}/3 \] (3)
where \( \chi_{H₂} \) – volume fraction of H₂ in syngas (part of an unit).

4. Results of calculations of synthesis gas composition and efficiency of plasma gasification of wood waste
Figure 2 represents the dependence of composition of dry syngas versus specific power inputs (per mass unit of wood waste) at use of air, carbon dioxide and steam as a plasma forming environments.

It is obvious from (figure 2) that at wood waste gasification by air plasma the increase in the specific power inputs (on 1 kg of raw material) leads to the increase in concentration of combustible components (H₂ and CO) and decrease in concentration of incombustible gases (CO₂ and N₂). The reverse tendency is observed at use of carbon dioxide or steam. It is caused by the energy of plasma of "passive" oxidizers (H₂O or CO₂) goes not only on a covering of endothermic effect of gasification,
but also for decomposition of molecules of an oxidizer, and its flowrate increases with growth of power inputs for passive oxidizers (see figure 3).

![Figure 2](image1.png)

**Figure 2.** Influence of energy consumption on volumetric composition of dry gas at plasma gasification of wood waste.

Relation \(\text{H}_2/\text{CO}\) over the calculation range changes from 0.64 to 1.07 at use of air plasma, 0.18-1.07 for \(\text{CO}_2\) plasma, 1.07-3.65 for steam plasma. Presence of the relation 1.07 common for all is explained by existence of the common mode of plasma gasification for all oxidizers – a mode of pyrolysis (if the oxidizer flowrate vanish, parameters of the process aspire to the pyrolysis parameters).

Differences in tendencies of component concentration variations are caused by the character of changes introduced by the oxidizer in the element balance of a mixture of fuel with an oxidizer. At increase in the air flowrate the percentage of nitrogen and oxygen in the mixture increase, and relation of carbon and hydrogen weakly varies. At increase in \(\text{CO}_2\) flowrate the percentage of oxygen and carbon increase. At increase in the steam flowrate the percentage of oxygen and hydrogen increase. At plasma gasification it is possible to vary the relation \(\text{H}_2/\text{CO}\) over a wide range, changing the plasma forming gas composition and compensating the energy consumption changes for the process due to energy input from the outside.

At air-plasma gasification the yield of chemical energy linearly increases with increase in energy consumption (figure 4): on 1 MJ of the input energy the chemical energy yield of synthesis gas increases on ~1.55 MJ. Energy consumption for pyrolysis of wood make ~6.57 MJ/kg. The maximum of specific chemical energy yield is reached near to the point of pyrolysis.
At use of CO$_2$ plasma the specific chemical energy yield grows with increase in power inputs, and for steam plasma – it decreases. It is caused by displacement of equilibrium state (at 1500 K) aside to hydrogen oxidations and carbon dioxide reduction.

Figure 5 shows the estimation of influence of the specific energy consumption on the specific yield of electric power from the system using plasma gasification and the combined cycle for the electric power generation from wood waste. It is visible that use of air plasma allows increasing on ~20 % of the electric power yield from a mass unit of raw material, and use of steam and carbon dioxide plasma is not expedient.

Figure 6 represents the estimation of influence of specific energy consumption on the specific yield of synthetic liquid fuel from the system using plasma gasification and Fischer-Tropsch process for liquid fuel production from wood waste. It is visible that use of air plasma allows increasing the yield of liquid fuel from a mass unit of raw material more than in 2 times, and use of steam and carbon dioxide plasma leads to rise in price of the end-product.

5. Experiment results on air-plasma gasification of wood

The pilot installation for plasma gasification of carbonaceous materials was created in IEE RAS [10]. On this installation a series of experiments on plasma gasification of wood by air has been performed
In the beginning of each experiment the installation was warmed up within 6-8 hours due to gasification of charcoal. Charcoal was loaded periodically during the warming up phase. After that the wood was loaded periodically instead of charcoal and the reactor switched over its mode to plasma gasification of wood process within 1-2 hours.

The wood with moisture of ~20\% (measured by the continuous drying method) and LHV of ~13.9 MJ/kg was used in the tests. It was assumed that dry wood mass consists of C - 49.75, H - 6.03, O - 42.92, N - 0.20, S - 0.10, ash – 1 \%, mass composition of blowing in air is N\textsubscript{2} – 74.4, O\textsubscript{2} – 22.8, Ar – 1.27, CO\textsubscript{2} – 0.04, H\textsubscript{2}O – 1.45 \%.

In table 1 the parameters of two characteristic experimental modes of air-plasma gasification of wood are compared with calculated values.

| Source | E\textsubscript{in} \(^a\) (MJ/kg) | G\textsubscript{in} \(^b\) (kg/kg) | G\textsubscript{SG,d} (Nm\textsuperscript{3}/kg) | Composition of dry syngas (%vol.) | Q\textsubscript{out} \(^c\) (MJ/kg) |
|--------|------------------|-----------------|-----------------|-----------------|------------------|
|        |                  |                 |                 | H\textsubscript{2} | CO | N\textsubscript{2} | O\textsubscript{2} | Ar | CO\textsubscript{2} |
| exp.   | 3.10             | 1.22            | 2.38            | 32.2            | 26.1 | 33.4 | 0.27 | 0.40 | 7.64 | 14.7 |
| calc.  | 3.10             | 1.22            | 2.22            | 27.2            | 29.3 | 35.8 | 0.43 | 7.22 | 13.5 |
| exp.   | 2.16             | 1.44            | 2.45            | 28.0            | 23.6 | 38.2 | 0.28 | 0.46 | 9.30 | 13.5 |
| calc.  | 2.16             | 1.44            | 2.34            | 24.7            | 25.6 | 40.1 | 0.48 | 9.01 | 12.7 |

\(^a\) Specific energy consumption.
\(^b\) Specific air consumption.
\(^c\) Specific yield of the syngas chemical energy.

The same deviations of concentration of hydrogen and carbon monoxide in experimental and calculated data are explained by effect of water-gas shift reaction at cooling of synthesis gas. It leads to reduction in CO concentration and increase in H\textsubscript{2} and CO\textsubscript{2} concentration in dry synthesis gas. This effect is not considered in calculation. The increase in experimental (in comparison with calculated) values of a specific yield of chemical energy of synthesis gas happens due to the temperature field influence. Stationary temperature of products of plasma gasification of charcoal is higher than the similar parameter for wood. Therefore reactor lining is warmed up to higher temperatures, than at plasma gasification of wood. At transition from charcoal to wood the lining starts to give a part of the saved energy to the gasification products. As a whole the results of experiments are well agreed with calculated data.

**6. Conclusion**

The downdraft and twin-fire schemes of gasification allow most effectively use of plasma energy due to mixture of pyrolysis products with plasma in a point of its inlet and long residence time of solid pyrolysis products in a high-temperature zone. The most suitable oxidizer for plasma gasification of wood waste is air as on 1 MJ of the input energy the chemical energy yield of synthesis gas increases on ~1.55 MJ. Application of plasma during gasification allows increasing the efficiency of the electric power generation and liquid fuel production from wood waste.

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