Energy-technological complex with reactor for torrefaction

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Abstract. To eliminate shortcomings of raw plant materials pelletizing process with thermal treatment (low-temperature pyrolysis or torrefaction) can be applied. This paper presents a mathematical model of energy-technological complex (ETC) for combined production of heat, electricity and solid biofuels torrefied pellets. According to the structure the mathematical model consists of mathematical models of main units of ETC and the relationships between them and equations of energy and material balances. The equations describe exhaust gas straining action through a porous medium formed by pellets. Decomposition rate of biomass was calculated by using the gross-reaction diagram, which is responsible for the disintegration of raw material. A mathematical model has been tested according to bench experiments on one reactor module. From nomographs, designed for a particular configuration of ETC it is possible to determine the basic characteristics of torrefied pellets (rate of weight loss, heating value and heat content) specifying only two parameters (temperature and torrefaction time). It is shown that the addition of reactor for torrefaction to gas piston engine can improve the energy efficiency of power plant.

1. Introduction
Raw plant materials are widely used as an alternative renewable fuel especially in a small power [1]. Although raw biomass is spread everywhere it has several disadvantages: low energy density, high humidity and heterogeneity geometric shape. The latter leads to the difficulty of mechanization of the combustion process. Some disadvantages are eliminated by granulation of biomass, resulting in solid pellets, which are widely used in energy, especially in Europe [2].

The world’s leading companies are actively carrying out research in support of the technologies of biomass thermochemical treatment, to improve consumer properties of solid biofuels. The biomass is heated in oxygen-free environment at temperatures 200–300 °C (torrefaction). As a result, biomass becomes hydrophobic and at little loss of heat content due to devolatilization increased its heating value (up to 21–23 MJ/kg) [3]. Torrefied biomass can be used for partial or total replacement of coal in coal-fired boilers [4].

Despite the increasing interest in process and the creation of torrefaction plants nowadays, most of the projects are just pilot samples [5]. Absence of significant progress in this direction is due primarily to the low energy process efficiency and, consequently, low economic performance of technology.

The energy efficiency of the process depends largely on efficiency of heat generating unit and process of heat application to the torrefied product. All known technologies can be divided into
two groups: the technology with indirect heating of raw biomass and technology with direct biomass heating. Direct heating technology is more effective in terms of organizing the process of heat transfer, but heat-transfer agent has direct contact with the raw material. Therefore, the exchange gas must be chemically neutral. In systems with direct heating as heat-transfer agent combustion products are used [4].

It is well known that the combined technology is usually economically more advantageous than separate production [6]. A classic example in the energy sector is the usage of co-generation and trigeneration schemes [7]. One of the possible ways of direct heating the biomass in reactor for torrefaction is using the exhaust gases from gas engine.

The paper presents a scheme of energy-technological complex (ETC) developed at JIHT RAS. Complex produces electricity, heat and torrefied biomass (pellets). Due to the seasonality of raw materials supply and heat demand such trigeneration schemes, in addition to the production of a new commercial product, will promote the efficient use of energy resources. Mathematical model and the results of numerical calculations of the energy and mass flows and the efficiency of energy-technological complex are present in the paper.

2. Experimental energy-technological complex
Block diagram of the experimental energy-technological complex is shown in figure 1. The complex includes gas piston engine (GPE), two gas–water heat exchangers (HE1 and HE2) and
modular reactor for torrefaction. Wood pellets are preheated by blow heater to a temperature of 100 °C. This temperature corresponds to the conditions at the outlet of the granulator. Further pellets enter the hopper and subsequently pass through three reactor modules: preheating section 1, torrefaction section 2 of heating and cooling section 3 for pellets (see figure 1). Construction of all modules is identical and residence time of biomass in each module is equal.

After the end of cyclic operation cooling pellets are unloaded from cooling section, then this section are loaded by pellets from torrefaction section, which further enter pellets from preheating section. Untreated pellets are loaded at preheating section and the cycle repeated. This provides quasi-continuous operation of process.

Part of the exhaust gases from gas engine passes through the gas-water HE1. At the outlet of the heat exchanger temperature is maintained at a desired level for cooling the pellets in the cooling section. From the cooling section “cold” exhaust gases enter the mixer where they are mixed with the hot gas. The ratio of the flow of hot and cold gases is regulated so that the temperature of the exhaust gases at the entrance to the torrefaction unit maintained at setpoint. The mixture of exhaust gases, pyrolysis gases and vapors released during destruction of biomass, sequentially passes through a torrefaction zone and a preheating zone and than enter the gas-water HE2. The gaseous phase is diverted to the industrial chimney and condensation products of pyrolysis are collected in recycling unit.

3. Mathematical model

Selection of the optimal scheme and plant contents, characteristics of its constituent units and determining the optimal modes of operation require large amount variant calculations. For this purpose is necessary to develop a mathematical model and the relevant calculation computer codes. In order to estimate the effectiveness of the ETC it is necessary to determine the energy and material flows and calculate required cycle time of reactor for the torrefied pellets having a given condition. Due to immature market of torrefied pellets, the standard requirements to their performance have not yet been developed. Therefore necessary to determine a quality for pellets that can be used in the calculations.

The experimental results [3] showed that consumer properties of torrefied pellets (specific heating value, hydrophoby), the higher the greater the weight loss during torrefaction. Thus it is logical to take as a criterion for the quality of pellets relative value of the loss of mass 1 – m(t)/m0, where m(t)—current weight of pellets, m0—in initial mass of pellets.

Mathematical model consists of the models of main units of ETC and communication between them. During the modeling of GPE processes in the internal combustion engine is not considered in detail. The model input parameters are rate, temperature and composition of natural gas, air rate (excess air coefficient) and temperature. Output characteristics are rate, composition, enthalpy, temperature and density of the combustion products, the active electric power and efficiency of the power plant. Characteristics of GPE were based on empirical relations—test bench data. Thermodynamic characteristics of the exhaust gases are calculated in the approximation of thermodynamic equilibrium [8]. Mathematical model of torrefaction reactor is based on the conservation equations. The equations describe exhaust gas’s straining action through a porous medium formed by pellets. Pellet layer was simulated by solid spheres of the same diameter with a regular packing [9].

The mathematical model consists of four blocks: preheating section, torrefaction section, cooling section and block of exchange gas mixing. A formal description of the first three blocks is the same. The difference between preheating and torrefaction blocks from cooling section is necessity of accounting processes of thermal degradation of the feedstock.

For the middle section of the reactor parameters of heat and mass transfer are described by non-stationary one-dimensional differential equations in partial derivatives. As the heat transfer in the gas due to heat conduction is significantly less than convection, conduction term in the
energy equation for gas is negligible. The diameter of the spheres, simulating layer of pellets, during heating process is not changed. Also, we assume that the thermal conductivity and heat capacity of the material of pellets varies slightly. Then the conservation equations for gas and a layer of pellets can be written as follows: for gas

\[ f \frac{\partial \rho_g}{\partial t} = -\frac{\partial \rho_g u}{\partial x} + V, \]  

\[ f \frac{\partial (\rho_g c_g T_g)}{\partial t} + \frac{\partial}{\partial x}(\rho_g u c_g T_g) = \alpha(T_s - T_g); \]  

for pellets

\[ (1 - f) \frac{\partial \rho_s}{\partial t} = -V, \]  

\[ (1 - f) c_s \rho_s \frac{\partial T_s}{\partial t} = \lambda_s \frac{\partial^2 T_s}{\partial x^2} - \alpha(T_g - T_s). \]

Here \( \rho_g, c_g \) and \( T_g \) are density, heat capacity and temperature of combustion products; \( \rho_s, c_s, T_s \) and \( \lambda_s \) are density, heat capacity, temperature and thermal conductivity of pellets; \( u \) —velocity of combustion gases; \( \alpha \) —heat-transfer coefficient; \( f \) —pore volume of pellet layer; \( t \) —time; \( x \) —coordinate; \( V \) —source term.

Source term in equations (1) and (3) is defined as the mass loss rate of the pellets in the heating process. The mathematical model used a simple diagram of a gross-reaction responsible for the breakdown of the initial biomass [10]. Changes in the relative weight of the pellets during heating caused by devolatilization, can be written as:

\[ \frac{dX}{dt} = -k_0 \exp\left(-\frac{E}{T(t)}\right)X^g, \]

where \( X = (m(t) - m_0)/(m_0 - m_c); m(t) \) —current weight of pellets; \( m_0 \) —initial mass of dry pellets; \( m_c \) —mass of carbon residue; \( E \) —energy of activation; \( k_0 \) —preexponential factor; \( g \) —order of reaction.

In view of (5) the source terms in the equations (1) and (3) can be written as:

\[ V = -\rho_0^0(1 - \frac{m_c}{m_0})k_0 \exp\left(-\frac{E}{T(t)}\right)X^g. \]

The system of equations (1)–(6) is supplemented by the equation of state for a mixture of ideal gases, relations for the thermo-physical properties of the gas and pellets, boundary and initial conditions.

For the heat transfer coefficient \( \alpha \) was used empirical relation of the form [11]

\[ \alpha = 2.74\lambda_s \left(\frac{1 - f}{f}\right)^{1.36} \frac{\text{Re}^{0.64} \text{Pr}^{1/3}}{4\rho^2}, \]

where \( r \) —radius of a sphere of equivalent volume; \( \text{Re} \) —Reynolds number; \( \text{Pr} \) —Prandtl number.

Pore volume of pellet layer \( f \) is given as a function of the selected model structure of the porous medium.

As the mass flow of exchange gas is constant and much greater than the mass flow of gaseous pyrolysis products, the source term in equation (1) can be neglected. Therefore, the equation of state is sufficient to determine the density of gas. For the numerical solution of equations (1)–(6) used its discrete analogue, obtained by integrating the differential equations over control volume [12]. For the calculation process in the preheating and torrefaction sections to system
of equations added the equation describing the mass loss kinetics of the pellet. As the mass exchange between the calculated cells is absent and the mass flow of pyrolysis gases is negligible compared with the mass flow of exchange gas, discrete analog of the kinetic equation can be written as

$$\frac{\partial X_i}{\partial t} = -k_0 \exp \left( \frac{E}{RT} \right) X_i^g, \quad (8)$$

$$X_i = \frac{m_i(t) - m_c}{m_0 - m_c}. \quad (9)$$

The density of the pellets in the cell at time $t$ is calculated from the ratio

$$\rho_{s_i}(t) = X_i(t) \rho_{s_0} \left( 1 - \frac{m_c}{m_0} \right) + \rho_{s_0} \frac{m_c}{m_0}, \quad (10)$$

where $\rho_{s_0}$—initial density of pellets.

To calculate the relative specific heat of combustion of torrefied pellets used the data in [13, 14], which are approximated by linear dependence.

The relative heat content of torrefied pellets was calculated from the ratio

$$\frac{Q_t}{Q_0} = \frac{m_t q_t}{m_0 q_0}, \quad (11)$$

where $Q_t$, $Q_0$—the heat content of torrefied and initial (dry) pellets; $q_t$, $q_0$—heating value of torrefied and initial (dry) pellets.

The system of equations is solved by Adam’s numerically multistep methods with automatic selection of the time step [15]. Mathematical models are implemented in the software package ETCC v.01 (Energy Technological Cogeneration Complex).

4. Results of calculations

To test the program blocks for calculating torrefaction reactor used the test data of individual sections of the modular reactor, which is part of a pilot energy-technological complex (figure 1). Comparisons were made between the calculated and experimental temperature–time relationship during heating and cooling. It has been shown that the coincidence of the main characteristics of the process—heating (cooling) time to a predetermined temperature is quite satisfactory.

The torrefaction process is characterized by three main parameters: rate of weight loss, the relative heating value of torrefied pellets and their relative heat content [14]. The results of calculations for torrefied pellets are shown in figures 2–4, which present chart of relative weight loss, relative heating value and heat content for torrefied pellets heating at temperature 250–270 °C. Time on the charts corresponds to the residence time of the pellets in one section.
Figure 2. Dependence rate of weight loss of torrefied pellets from temperature and time of torrefaction process.

Figure 3. Dependence of relative heating value of torrefied pellets from temperature and time of torrefaction process.
Figure 4. Dependence of the relative heat content of torrefied pellets from temperature and time of torrefaction process.

Figure 5. The calculated values of the mass and energy flows.

The graphs allow evaluating the main characteristics of torrefaction process without additional calculations. This is possible by setting the two major parameters: temperature and time of torrefaction process.

Diagram on figure 5 shown calculated values of mass and energy flows with operating conditions: torrefaction temperature 250 °C and operating time is 1 hour. The data allow estimating the effectiveness of using reactor of torrefaction as a wasteheat exchanger for power plant. Year divided into two equal duration of the season “winter” and “summer”. If the unit operates as co-geneqeration plant, we assume that the demand for heat is only available in the
Figure 6. Comparative effectiveness of different schemes of energy-technological complex.

winter period (six months). Determine the coefficient of fuel utilization \((k_t)\) as the ratio of sum of ETC produced electricity and heat, and the heat energy of the combustion products used in torrefaction process, to heat content of using natural gas.

Analytic models are presented in table 1. In the table the following notation: “+”—product is produced throughout the year, “−”—product is not made, “±” or “∓”—product is produced throughout six months.

The results of calculations for the coefficient of fuel utilization of various models are shown in figure 6.

5. Conclusion

Technological scheme and mathematical model of energy-technological complex with GPE and reactor for torrefaction of fuel pellets are presented. A mathematical model allows to determinate parameters of ETC, which will provide the necessary characteristics of pellets. The dependences of productivity of reactor and the main characteristics of torrefied pellets (rate of weight loss, heating value and heat content) from the process temperature and the heating time are presented. On the basis of the calculations show that using reactor of torrefaction as a wasteheat exchanger for power plant (cogeneration or trigeneration schemes) increases the energy efficiency of power plant.

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