Verification of the stage scheme of low-grade solid fuel gasification

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Abstract. This paper considers development of the model of wood pyrolysis in a screw reactor as the first stage of the multistage gasification process. To prevent clinkering of particles and thermal inhomogeneities, screw-type transportation is used to transport fuel. In order to describe kinetics of pyrolysis and transport of volatiles within the wood particles and their transition to the gas phase, we carried out the studies using a complex of synchronous thermal analysis. A detailed numerical modeling of pyrolyzer was performed with the use of Comsol Multiphysics Software, which enables optimizing the design and operating parameters of the pyrolysis process in a screw reactor.

1. Introduction
At present, the screw reactor pyrolysis is a promising and rapidly developing technology, because it helps obtain the end product, which is charcoal, resin, and synthesis gas. Additionally, pyrolysis can be considered as a preliminary stage for making the charcoal of the preset conversion for its further gasification when obtaining coal-derived gas. Brassard et al. made an overview of 19 various screw pyrolysis reactors, where the pyrolysis was carried out in different conditions: the temperature was varied from 330 to 990°C, the fuel residence time was changed from 8 to 120 min, the yield of resin varied in the range 19.2÷73.6 and the yield of charcoal – in the range 6÷45.1%. On the basis of the overview, Brassard arrived to a conclusion that it was impossible to derive any analytic generalizations. This fact is explained by a wide range of possible geometric dimensions of the screw and the yield of the end product. Besides, Funke [2] showed that the screw pyrolysis scaling is a very time-consuming and difficult problem. Therefore, this research aims at establishing relationships between the operational parameters of pyrolysis and obtaining the charcoal of preset conversion by means of mathematical modeling, full-scale experiment, and instrumental studies. Such comprehensive research ensures the accurate initial data, verification of the model, and optimal parameters for obtaining the product with preset properties as well as for further scaling of the reactor.

In terms of design, the pyrolyzer represents a recuperative heat exchanger where a mix of stack and recirculation gases is considered as a heat carrier. To prevent sintering of particles, the screw transportation of fuel is used. To describe kinetics of pyrolysis and transportation of volatile products inside wood particles and their transfer to gas phase, the research is conducted using the simultaneous thermal analysis system: the weighting system of Netzsch STA 449 F1, quadruple mass-spectrometer QMS 409 C Aeolos and the system of pulse gas supply PulseTA (a unique high-temperature research plant). For the indicated plant we have developed original techniques for interpreting measurements, including methods for technical analysis of fuels and determination of the kinetic coefficients and...
The pyrolysis mechanism. The Comsol Multiphysics Software is used as a simulation environment. Heat exchange in the process of pyrolysis is simulated considering physical properties (porosity, permeability, etc.) of the medium. The constructed calculated mesh consists of 604 thousand elements of three types (tetrahedrons, prisms and pyramids) and has the minimum size of 0.2 mm. For the range of considered operating conditions we show the possibility of applying stationary experimental relationships to determine the rate of change in the density of solid fuel, volatile yield, etc. [3].

2. The stage scheme of low-grade gasification

![Technological scheme of the laboratory stand of a screw pyrolyzer](image)

**Figure 1.** Technological scheme of the laboratory stand of a screw pyrolyzer: 1 – fuel bunker, 2 – fuel storage tank, 3 – screw drive, 4 – screw, 5 – reactor, 6 – thermal isolation, 7 – sampler, 8 – charcoal storage tank, 9 – cyclon, 10 – heat exchanger, 11 – filter, 12 – gas chromatograph, T1-T6 – thermocouples, HS1-HS4 – heater sections.

The experimental study was carried out at the laboratory stand of a screw pyrolyzer, the technological scheme of which is given at Fig. 1. The test material was wood pellets with the following characteristics: 6-8 mm in diameter; 2-5 cm long; ultimate and proximate analysis: C – 48 %, H – 4.6 %, O – 47.5 %; devolatilization 81.7 %, ash content 2.2 %, and moisture 8.2 %.

The pellets in the reactor shaft (5) were moved by means of a screw (4) rotated by a variable speed drive (3). In the experiment, three rates of pellet transfer along the length of the reactor were used: 0.19, 0.37, and 0.6 mm/s. The wood pellets were heated by four sections of the electric heater HS1-HS4 located on the outer surface of the reaction chamber. Figure 2 shows the heating of the pyrolysis reactor at different fuel velocities.

It can be seen from Fig. 2 that the initial warm-up stage lasts for two hours, and then we observe a decrease in the temperatures of the sections. It takes the screw pyrolyzer an hour to reach the stationary state.

To estimate the yield of producer gas, we used a balance for the inert gas-marker (argon), a certain amount of which was continuously supplied to the unit. The hopper was purged with argon to remove air in the fuel mass. Then the fuel entered the storage tank (2) through an airproof gateway. To calculate the pellet consumption, the time of arrival of each portion of fuel into the storage tank was fixed.

The bulk of the reacted wood pellets enters the cooled charcoal storage tank (8). Sampling of charcoal to determine its technical characteristics (moisture, ash content, volatilization, elemental composition, heat of combustion) is carried out through the sampler (7). The producer gas enters the cyclone (9), in which solid particles and high boiling tar (Tar 1) are separated. The producer gas is cooled in the heat exchanger (10), where a low-boiling tar (Tar 2) is separated, and then passes through the filter (11). The yield of liquid products of the wood pyrolysis is estimated by the weight of the tar samples taken from the cyclone (9) and the heat exchanger (10). The thermocouples T1-T6 are used to
measure the temperature of the pyroliser wall. The thermocouples that measured the layer temperature are immersed into the layer through special ports in the chamber wall. As a result of the experiment, we have obtained the charcoal with a maximum conversion rate of 97% at the fuel velocity of 0.19 mm/s.

Verification of the mathematical model described in [3] was carried out at the first stage (5) of the gasification setup. One of the tasks was to determine the heat losses from the setup surface. This was achieved by measuring the temperature of water heated in the ash tower, as well as by thermal imaging of the setup surface. The values of heat fluxes in the output section of the reactor (5), calculated on the basis of these observations, as well as losses to the environment were added to the mathematical model:

\[ \rho C_p u \cdot \nabla T + \nabla \cdot (-k_{eff} \nabla T) = -Q_1 - Q_2. \]

The measured values of the heat fluxes were: \( Q_1 = G_c \Delta T_{water} = 0.97 \text{ kW}; \)
\( Q_2 = Q_{rad} + Q_{conv} = 0.45 \text{ kW}. \) To remove the chemical reaction effect on thermal processes during the heat exchange verification experiments, we used claydite. Compensation of heat losses to the environment \( Q_2 \) will be taken into account in further studies on optimization of the multistage gasification scheme.

3. Chemical block verification
To perform verification of the fuel conversion parameters, we chose the following boundary conditions:

- An inlet temperature of fuel is 20°C;
- An inlet temperature of heating gases is 600°C;
- A velocity of fuel flow in pyrolyzer is 0.19 mm/s;
- An inlet velocity of modelling heating gases is 0.1 m/s.

![Figure 2. Wood pyrolysis mechanism at the first stage](image)

The detailed description of the model for aerodynamics and heat exchange in a screw reactor can be found in [3]. It was confirmed that under the considered thermal conditions the process of fuel conversion proceeds to completion. The current research employed kinetic relations for determining the volatile yield and resin formation: (Fig. 2):

- **gases formation**: \( k_G = 0.63 \cdot 10^{11} e^{-177/rT} \).
- **charcoal formation**: \( k_C = 3.45 \cdot 10^{11} e^{-125/rT} \).
- **tar formation**: \( k_L = 7.25 \cdot 10^{11} e^{-149/rT} \).

The exit and inlet conditions for the concentration flux can be represented in the following form:

\[ c_0 = 0, \quad -n \cdot D_t \nabla c_L = 0. \]

Table 1 presents the experimental results obtained at the setup with different solid fuel feed rates. The calculated values of the yield of charcoal, gases and tar are based on the dependences used for the
kinetic reactions. They show good agreement with the results of the experiment. At the same time, it is worth noting that the closing relations (2)–(4) obtained in the present work essentially differ from those given in [4].

Table 1. Comparison between Numerical and Experimental Results

| Fuel flow Velocity (mm/sec) | Charcoal (g/sec) | Tar (g/sec) | Gases M (g/sec) |
|---------------------------|-----------------|-------------|-----------------|
|                           | Num             | Exp         | Num             | Exp         |
| 0.19                      | 0.227           | 0.23        | 0.505           | 0.5         | 0.41 | 0.405 |
| 0.36                      | 0.47            | 0.47        | 0.95            | 0.94        | 0.78 | 0.66  |
| 0.62                      | 0.97            | 0.98        | 1.45            | 1.47        | 0.55 | 0.542 |

Conclusions
The model of heat transfer and aerodynamics of the pyrolyzer was developed for express optimization calculations. Inclusion of the kinetic block in the model of heat transfer allowed determining the concentration fields of the formed substances (charcoal, tar and gases). We verified the model using the experimental data obtained when using the designed multistage setup for low-grade solid fuel gasification.

References
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