The Transition to Energy Efficient Biomass Torrefaction Technology

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Abstract. Torrefaction or low-temperature pyrolysis makes it possible to obtain high-quality solid biofuel from various types of biomass (peat, wood and agricultural waste, various types of biowaste) for the needs of distributed energy. The creation of energy supply systems based on local fuel and energy resources is a priority task for Russian Federation. The article presents the results of research on the development of a new method for energy utilization of biomass by torrefaction.

1. Introduction
The head direction of energy development is currently the transition to distributed generation. The main economical preference of distributed power supply is the possibility of cogeneration of heat and electricity. Cogeneration production provides a higher degree of fuel utilization in relation to schemes with separate production of electric and thermal energy. In addition, the transition to distributed power generation is also due to the fact that in the Russian Federation 70% of the territory, where more than 20% of the population lives, is outside the zone of distribution of central power supply. Distributed power supply is the predominant use of local fuel and energy resources, which mainly include peat, wood and agricultural waste, as well as various types of biowaste.

As it is known, pyrolysis of biomass is accompanied by endothermic and exothermic reactions. In the temperature range 250–300 °C, typical for the torrefaction process, the main score is made by exothermic reactions associated with the decomposition of hemicellulose.

In traditional torrefaction schemes, it’s usually tried to prevent the occurrence of spontaneous, poorly controlled heating of the biomass, because this leads to the ignition of the processed raw materials, the destruction of the reactor.
Earlier, in the 18th-19th centuries, for the production of biochar, including for metallurgical production, a charring method was widely used in which biochar was produced due to exothermic heat release during the wood thermal processing [3]. The charring temperature is 800–900 °C [4]. It is enough to heat the wood from an external source to ~ 300 °C, after which the charring process continues due to the internal heat release, while the organic part of the wood is completely destroyed. The energy of the exothermic effect in this case ($T = 400–900$ °C) reaches a value of 1 MJ/kg [4].

The torrefaction process is characterized by a much narrower temperature range than the charring process, and only partial destruction of the organic part of the biomass. Therefore, when using exothermic effects for torrefaction, it is important to stop the avalanche-like exoreaction in time, preventing the transition of low-temperature pyrolysis to the stage of classical pyrolysis.

Research on the creation of torrefaction technologies is carried out in many scientific centers around the world [5-10], but so far no industrial torrefaction technologies have been created. As far as can be judged from the analysis of literature data, the main reason for this is the fact that existing developments in the field of torrefaction do not pay off in their industrial application. Those. the cost of producing torrefied fuel is not offset by the benefits derived from the use of torrefied fuel.

At the Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), research is being carried out on thermal effects during torrefaction of biomass, aimed at reducing energy costs and optimizing the torrefaction technology. The obtained scientific results in the future can make it possible to carry out a transition to an industrial economically justified use of this process for the needs of local and distributed energy.

The scheme of the torrefaction reactor is shown in figure 1.
1 - feeding hopper, 2 - loading and heating section, 3 - torrefication reactor, 4 - mixing section, 5 - cooling section, 6 - rotary flap unit, 7 - unloading hopper, 8 - sealed flap, 9 - level sensor, 10 - rotary flap, 11 - relief valves

Figure 1. Principal scheme of torrefication reactor.
2. JIHT RAS energotechnological unit with torrefaction reactor

In JIHT RAS a torrefaction unit [11] was designed and manufactured. This unit implements the concept of a controlled exothermic effect to significantly increase the productivity and energy efficiency of the process. As a heat carrier in torrefaction reactor exhaust gases from a gas piston unit (GPU) are used, in which natural gas is burned and electrical energy is produced. The GPU exhaust gases are supplied to the torrefaction reactor as an oxygen-free coolant. The GPU operation on natural gas is economically justified even if the combustion products are emitted into the atmosphere. Thus, in the JIHT RAS scheme, the cogeneration principle is used.

The article presents the results of characteristic launches, representative of the features of exothermic torrefaction, which makes it possible to significantly increase the energy efficiency of this process, which is characterized by specific energy consumption for obtaining one kilogram of torrefied product [12]:

\[
\eta = \frac{G_g \Delta H_g}{G_s},
\]

for \( G_s \) – reactor capacity; \( G_g \) – heating gas mass flow; \( \Delta H_g \) – actuation of the enthalpy of the coolant in the reactor.

In all modes, the GPU electric power was maintained at the level of 25 kW, which corresponded to the consumption of combustion products of 0.044 kg/s. Wood pellets were used as the processed raw material. Before the start of the experiment, the reactor filled with pellets was heated with hot air using a heat gun to a temperature of 90 °C. Further heating was carried out by the combustion products of the GPU in two stages. At the first stage, the temperature of the heat carrier gas (thermocouple T4) was about 220 °C and heating was carried out until the temperature of the lower layer of pellets (thermocouple T5) reached 200 °C. After that, the temperature of the heat carrier gas (thermocouple T4) increased to a value of 275 °C. The indicated value was chosen based on the results of preliminary experiments, from which it follows that this temperature corresponds to a change in the sign of the effective heat capacity of a wood sample, indicating a significant exothermic effect.

The time dependences of temperature in different sections of the reactor for two modes A and B are shown in Fig. 2 and 3. Mode A - torrefaction with uncontrolled exotherm. Mode B - torrefaction with controlled exotherm. The numbers of the curves in Fig. 2-3 correspond to the thermocouple numbers shown in fig. 1.

From fig. 2 it can be seen that after 4000 seconds from the start the temperature of the lower layer of pellets (thermocouple T5) equaled the temperature of the heat carrier gas (thermocouple T4) and continued to grow, indicating the presence of an internal heat source caused by exothermic reactions accompanying the thermal decomposition of wood. When the temperature at T5 reached 300 °C, the lower layer of pellets (about 3 kg) was unloaded into the cooling section (mark "1" on curve 5), which caused a "dip" on curves 5 - 9 (time mark 4250 s). This "dip" is due to a decrease in temperature in a particular section due to the entry of colder pellets into it from the overlying layers. At the same time, the observed increase in temperature in the zone of thermocouple T4 is associated with the ingress of hot pellets from the torrefaction reactor into the cooling zone. The further observed temperature drop in the zone of thermocouple T4 (mark "3" on curve 4) is associated with the earlier unloading of pellets from the cooling section into the unloading hopper and, accordingly, a decrease in temperature in the cooling section. At the same time, the automatic mixing regulator worked only partially.
Repeated unloading of part of the pellets into the cooling section (mark "2" on curve 5), carried out 190 s after the first, led to changes in temperature profiles in various sections of the torrefaction reactor, qualitatively similar to those observed during the first unloading. It should be noted that at the moment of repeated unloading, the temperature of the heat carrier gas exceeded not only the temperature in the section where the T5 thermocouple is located, but also in the zone of the T6 thermocouple, i.e. overheating due to the exothermic effect spread up the torrefaction reactor. Subsequently, the unloading of pellets from the cooling section to the unloading hopper was not carried out, and the mixing controller was unable to provide the temperature of the coolant gas at 275 °C at the reactor inlet. As a result, a sharp increase in the temperature of both the coolant gas (due to its heating in the cooling section) and the pellets along the entire height of the reactor began. After the time mark of 4500 s, the temperature in all sections along the height of the reactor exceeded the temperature of the coolant gas and continued to grow, reaching a value of 350 °C. At this point, the entire reactor was unloaded and the experiment was completed. The weight loss of pellets in mode A was ~ 45%. Thus, it was shown that it is impossible to carry out torrefaction in the temperature range corresponding to the manifestation of the exothermic effect without taking special measures, since this will lead to an uncontrolled increase in the temperature in the reactor.

It should also be noted that at a temperature in the reactor at the level of 320-350 °C, the release of volatiles was significantly intensified. As a result, the gas mixture at the outlet of the reactor was enriched with heavy hydrocarbons. A number of reactor working units were covered with a mixture of condensed volatile pyrolysis products and wood dust, which led to an increase in back pressure to 3.8 mbar and negatively affected the operation of the GPU.

In mode B, a specially selected algorithm for torrefied pellets unloading from the reactor into the cooling section was applied. The time dependence of the pellet temperature in different sections of the torrefaction reactor in mode B is shown in Fig. 3.
When the temperature recorded by the T5 thermocouple reached a value exceeding the responses of the T4 thermocouple by more than 5 °C (time interval 4000-7500 s in Fig. 3), a portion of torrefied pellets was unloaded into the cooling section. The unloading was carried out once every 80 seconds in portions of ~4 liters (in terms of the feedstock). At the same time, a corresponding portion of pellets was loaded into the upper part of the reactor from the loading and heating section. Periodically, at the signal of the corresponding level sensor, a portion of the pellets from the cooling section was transferred to the unloading hopper. The constancy of the temperature of the coolant gas at the inlet to the torrefaction reactor was maintained using a mixing regulator operating in an automatic mode. Temperature maxima on curve 4 correspond to the moments of unloading. The reason for the fluctuations observed in the temperature dependences in sections 5 - 9, as in mode A, is the movement of pellets into this layer from the upper layer with a lower temperature. From those presented in Fig. 3 dependences it can be seen that due to the cyclic unloading of pellets, it is possible to stabilize their temperature in the lower part of the reactor (thermocouple T5) at 280 °C and prevent uncontrolled heating of the processed raw materials. Pellet weight loss in mode B was 30%. At the same time, based on the frequency of unloading and the volume of the discharged portion of pellets, the productivity of the torrefaction reactor with a constant operating mode of the heat generating device (in this case, GPU), which provides the technological process with a coolant gas, actually means an equivalent increase in the energy efficiency of the torrefaction reactor.

3. Numerical simulation

Numerical experiments on modeling transient processes in a torrefaction reactor of granular biomass with a moving bed were carried out on the assumption of a two-stage model of biomass destruction [13], in which the primary reactions of the initial biomass decomposition are endothermic, and the secondary ones are exothermic.

It is assumed that the reaction rates are described by the Arrhenius formula [14]:

\[ k_i = A_i \exp \left(-\frac{E_i}{RT}\right), \]

for \( k_i \) – rate constant of the corresponding reaction \((1/s)\), \( A_i \) – pre-exponential factor \((1/c)\); \( E_i \) – activation energy \((J/mol)\); \( R=8,314 \text{ J/(mol×K)} \) – universal gas constant.

The processes of thermochemical conversion of biomass in a cylindrical torrefaction reactor with direct heating of feedstock by heating gas are described by a system of differential equations for the conservation of mass and energy for each of the considered components in the solid and gas phases in the approximation of a nonstationary one-dimensional model, assuming that the change in the studied...
parameters along the reactor radius is insignificant compared to with changes in height. The calculations were performed using the program [15].

Figure 4 shows the calculated curves of the biomass temperature change over time during heating and the reactor reaches a quasi-stationary mode in various sections along the height (in the lower section - thermocouple T5, T6, T7 and in the upper layers of the reactor - T9 - Fig. 1).

![Temperature Curves](image)

**Figure 4.** Change of biomass temperature in the process of entry to stationary mode in different sections along the height of the reactor.

At the first stage of heating, a smooth increase in the biomass temperature is observed over the entire height of the reactor. When the control temperature (300 °C) is reached in the lower layers of the torrefaction section, after about 800 seconds, the first unloading is performed - a portion of torrefied pellets is unloaded into the intensive cooling zone. The entire column of the remaining biomass goes down, colder layers are displaced into the hot coolant supply zone, a portion of the same volume of feedstock with a temperature of 120 °C is moved from above, a decrease in temperature is observed in all sections of the reactor. The temperature in the lower layers quickly enough due to the exothermic reaction (in a few tens of seconds) reaches the control value and again the damper is triggered - the next portion of the final product is unloaded.

From a certain temperature level, first in the lower layers, then higher, an exothermic reaction is activated, and at some point in time the temperature in the middle layers turns out to be higher than in the lower ones. The upper peak is observed on the temperature curve. At this moment, the unloading of the next portion of torrefied biomass from the lower layers into the cooling zone does not reduce the temperature at the control point, because layers with a higher temperature move into this region. To ensure the required temperature level at the control point, the frequency and volume of unloading automatically increases and the reactor is quickly filled with fresh "cold" portions of raw materials, which leads to an overall decrease in the temperature in the reactor. On the temperature curve, this moment is characterized by a temperature drop. Then, gradually, the heat wave rises up - there is a general rise in temperature. Low-frequency vibrations are formed.

Due to thermal inertia, the transition from the stage of initial heating to the working quasi-stationary mode is accompanied by thermal "swing" – low-frequency temperature fluctuations with a period of about 20 minutes and an amplitude of several tens of degrees. At the entrance to the reactor, the heat controller maintains a constant temperature of the coolant, and therefore in this area the amplitude of temperature fluctuations of the biomass is minimal and amounts to several degrees.

The heat wave reaches the upper layers of the reactor with a significant delay and the amplitude of temperature fluctuations here is much larger. In the presented version, the quasi-stationary operating mode is established after 2-3 periods of low-frequency oscillations, which is about an hour. In this case,
the specific energy consumption for the production of one kilogram of torrefied product was $\eta = 84$ kJ/kg.

The presence of low-frequency oscillations (thermal “swing”) in transient torrefaction modes is caused precisely by exothermic reactions that cause an avalanche-like local overheating of individual layers of biomass. Such a transient process is characterized by a positive feedback - a small increase in temperature leads to an exponential increase in the heating rate. Transient modes of thermal destruction of biomass from one state to another equilibrium state, in which the exothermic effect is not observed, are carried out without thermal “swing”.

Numerical experiments have shown that for a certain combination of operating parameters, when the exothermic overheating (the temperature difference at the control point and the coolant at the reactor inlet) exceeds a certain value, these oscillations can become persistent and the steady state is not achieved (Fig. 5).

**Figure 5.** Persistent temperature oscillations in transition mode from warming to cyclic discharge.

It can be seen that the temperature value in all layers along the height of the reactor fluctuates with an amplitude of up to 180 degrees and a period of about 20 minutes. At the same time, the specific energy consumption increases by one and a half times ($\eta = 117$ kJ/kg), and individual layers of biomass are not enough time at the torrefaction temperature (above 250 °C), not ensuring the uniformity of heat treatment of raw materials.

In the JIHT RAS stand, two control units are provided for controlling the torrefaction process using an exothermic reaction: maintaining the required coolant temperature at the reactor inlet and controlling the discharge of a certain volume of torrefied pellets with a focus of the progressing exothermic reaction.

To smooth out the thermal “swing”, the transient process must be carried out with variable operating parameters. Cyclic unloading after the heating stage should begin without exothermic overheating, i.e., when the temperature at the control point is equal to the temperature of the heating coolant, and with minimum volumes of the unloaded portion. Then, as the entire reactor warms up, the exothermic overheat and the volume of discharged portions can be increased, thereby increasing the energy efficiency and productivity of the stand.

Figure 6 shows the temperature change in various sections of the reactor during the transient mode after 700 seconds of the first heating stage with a smooth increase for 40 minutes in the discharge volumes from 0.5 to 3.5 liters and an increase in exothermic overheating (T5-T4 difference) from zero to 25 °C.
It can be seen that in this mode low-frequency temperature fluctuations in the upper and lower layers of the reactor are almost completely suppressed, in the middle part of the reactor the amplitude of such fluctuations is reduced to 50 degrees, and the transient process is limited to one wave. In addition, a smooth change in operating parameters makes the process more energy efficient. Specific energy consumption in this mode was less than 80 kJ / kg.

4. Conclusion

The results of the performed studies indicate that the exothermic reaction used in the presented technology has a "self-willed" character, causing an avalanche-like temperature rise that is difficult to control, and also thermal “swing” in transient conditions. Apparently, for these reasons, in existing torrefaction units, it’s tried to prevent the progressing of an exothermic reaction by limiting the operating temperature of the process and removing the released heat.

A mechanism for controlling the torrefaction process with an exothermic effect is proposed, which ensures an increase in the energy efficiency of the process and smooth transient modes of reactor operation without thermal “swing”. To use internal energy and control the exothermic reaction in the presented technology, two control units are used: control of the coolant temperature at the reactor inlet and control of the unloading period and the volume of the discharged portion of the final product. The plant automation controls not only the current temperature in the lower sections of the torrefaction zone, but also the temperature trend, taking into account the thermal inertia of the entire plant, smoothly changing the parameters at the inlet, the volume of unloaded products and the frequency of unloading.

5. References

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