Possibility of the use of exothermic-reactions heat from thermal destruction of biomass to increase the energy efficiency of the torrefaction process

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Abstract. New results of investigation of exothermic effects accompanying the process of plant biomass torrefaction are presented in this paper, which is a continuation of experimental research carried out on the model lab-scale test-bench and devoted to the study of the exothermic effect. A distinctive feature of this work is using of a large-scale pilot torrefaction unit as a test item. This unit operation as close as possible simulates the processes taking place during industrial torrefaction. At this work stage a truncated version of the torrefaction unit was used (the upper hopper was demounted). Experimental data obtained on a pilot torrefaction unit confirm the possibility of exothermic reactions heat usage for process intensifying. It is shown that such operation mode provides increased unit productivity on conditions that gas piston engine is operating at a constant power mode. The characteristics of the fuel obtained in the proposed process organization, as well as the fuel obtained as a result of torrefaction process excluding the influence of exothermic effect heat, are compared. As the main directions of further research, the problem of low-temperature pyrolysis volatile products utilization and the development of operating parameters at a full-scale torrefaction unit have been chosen.

1. Introduction
A promising technology for the pre-conditioning of solid hydrocarbon fuel from plant biomass is torrefaction. Torrefaction, or low-temperature pyrolysis, is a biofuel processing method, which consists in heating the biofuel in an oxygen-free environment up to temperatures in the range of 200–300 °C, followed by holding at such temperatures for certain time. The main pursued goal after such preliminary processing are increased biofuel consumer properties. As a result of torrefaction, moisture is removed from the initial material, and a partial thermal destruction of the main biomass components (hemicellulose, cellulose and lignin) takes place. End-product is a biofuel with clear-cut hydrophobic properties as well as increased specific combustion heat value (in comparison with initial material). The main torrefied biomass advantage is its considerable sameness to traditional energy coals by basic physicochemical and energy characteristics. And on such parameters as sulfur, heavy metal and ash content torrefied biomass exceeds fossil fuel.

A significant role in achieving the high quality of the torrefaction process is played by thermal processes accompanying the thermal destruction of the convertible biomass. The endo- and exothermic reactions accompanying biomass torrefaction process can appreciably influence the main operating parameter—torrefaction temperature. The main organic part components of any
plant biomass are hemicellulose, cellulose and lignin. Besides, the decomposition of hemicellulose and lignin shows a pronounced exothermic character, unlike cellulose, the destruction of which is accompanied by the occurrence of endothermic reactions [1–4]. On the example of various types of wood, a number of studies have been carried out, which have proved the presence of exothermic effect during biomass torrefaction. In Ohliger’s investigation [5], experimental data on the exothermic effect magnitude were obtained during birch chips torrefaction process in the temperature range of 270–300 °C, which formed a range from −199 to 148 kJ/kg. In the experiments with the fixed-bed torrefaction reactor (van der Stelt [6]) for three temperature ranges (230, 250 and 280 °C) there were obtained next value ranges of thermal effects: 425 to 1113, 22 to 1375, −1516 to 1160 kJ/kg respectively. Taking into account exothermic reactions heat when designing an industrial torrefaction plant can conduct process thermal efficiency increasing.

The lack of industrial torrefaction process implementation is currently associated with some technological difficulties, which greatly increase process cost. The problem of exothermic self-heating is often solved by increasing the flow rate of the heat carrier (with direct heating), or by including the cooling stage (with indirect heating).

This experimental work is a continuation of earlier studies, in which the small-scale cylindrical reactor model was used [7]. The initial stage in exothermic self-heating process large-scale study during torrefaction process was an experimental prototype. This experimental plant is a complex where combustion products of a gas reciprocating engine are used as a heat carrier for biomass direct heating.

2. Experiments at pilot torrefaction unit

The torrefaction unit includes gas piston power unit (GPU), gas-water heat exchanger (HE), vertical torrefaction reactor and afterburner. In figure 1 the simplified line diagram with main components of the torrefaction unit is shown. The total height of unit is 5.8 m.

The main economic effect of the use of GPU is expected from waste combustion products heat utilization when they are used as an inert heat carrier medium. The temperature of the combustion products at the GPU outlet is about 650 °C. Combustion products are divided into 2 streams, one of which directly enters the reactor mixing zone, and the second—after passing the heat exchanger. Thus, in the mixing zone (with the use of an automated throttle valve), a constant temperature of the heat carrier at the reactor inlet is ensured.

A feature of technology that is realized in this unit is torrefaction process thermal efficiency increasing by using of heat released during exothermic reactions passing (taking place while biomass components thermal destruction occurs). Initially, the raw material is supplied to the torrefaction reactor for heating up to the operating temperature by only external heat from the GPU combustion products. The temperature of the coolant is constant throughout the whole torrefaction process. When the raw material reaches the operating temperature, the self-heating of processed raw material is arisen. Under the influence of exothermic effect pellets are heated to temperature range of 300–350 °C, then they are unloaded into cooling zone. At the same time the pellets portion (located above) occupies place of the torrefied product. Pellets are heated to temperature higher than the coolant temperature therewith holding time is much shorter, than during classic torrefaction process (with exothermic effect cancellation). Thus, the process productivity increasing can be achieved. At the same time, the GPU during the entire torrefaction process operates in the rated power mode, thus achieving a significant process thermal efficiency increasing and a higher service life of the power units. In figure 2 torrefaction unit general view is shown.

In this work, experiments were performed on truncated torrefaction unit (without the upper-hopper feeder). The main purpose was more detailed investigation of the prerequisites for exothermic effect appearance and its characteristics. It should be noted that volatile pyrolysis
products after leaving the reactor enter the afterburner where they are neutralized. In the implementation of a direct heating reactor, direct use of pyrolysis gases is not possible, since pyrolysis gases are largely diluted with GPU combustion products. However, within the framework of the technology being implemented, the heat produced in the afterburner is used to preheat the “raw” pellets in the upper-hopper feeder.

3. Results and discussion
Experiments carried out on the pilot torrefaction unit of quasi-continuous operation confirmed the possibility of unit capacity increasing by using of biomass internal heat (exothermic effect). The tests were carried out on wood pellets with a full load (90 liters). The GPU electric power was constant and amounted to 25 kW, which corresponded combustion gas flow rate of 0.044 kg/s. The total productivity while proposed torrefaction process organization reached a value of 90 kg/h. Thus, while classic torrefaction process (with exothermic effect cancellation) organization, the productivity was about 30 kg/h. Figure 3 shows the temperature pattern changing along the torrefaction reactor height, provided with the processed products cyclic unloading.

As can be seen from the figure, the temperature in torrefaction zone is much higher than the coolant temperature at the inlet to the reactor. The temperature fluctuations in the reactor lower part (in the coolant mixing zone and unload zone) equipped with automatic device for maintaining a constant temperature (275 °C) are caused by the torrefied pellets periodic unload into the cooling section. Several engineering solutions allow to implement an efficient unloading of the treated biomass and to exclude significant uncontrolled overheating in torrefaction zone. It is reasonable to compare the characteristics of pellets obtained in proposed torrefaction mode with pellets obtained under suppression of exothermic reactions. The lower combustion heat value and elemental composition of two types of pellets proved to be almost identical. It should
be mentioned that torrefaction unit operation mode with the suppression of exothermic reactions is characterized by a temporary engine power increasing. This procedure is necessary for coolant flow rate increasing and, as a consequence, to intensify heat transfer (to exclude overheating zones). Consequently, the torrefaction process organization with cyclic pellets unloading, in which partial use of heat of exothermic reactions becomes possible, is energetically more effective.
4. Conclusion
As part of this research was experiment series on a pilot plant in order to study possible ways of thermal effects rational using. The implementation of the results obtained in experimental studies will reduce external sources heat consumption during the torrefaction process, which will greatly enhance the process energy efficiency. In future, it is planned to carry out experiments on a fully assembled unit, as well as to solve problems associated with the recovery of volatile torrefaction products.

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