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Thermal processing of biomass into high-calorific solid composite fuel

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ABSTRACT

Since the reserves of fossil fuels are gradually exhausting, the biomass inclusion in the energy balance is becoming an urgent issue and a major field for researchers. However, such biomass characteristics as high moisture content, low calorific value, friability, stickiness and others lead to the high operating costs for burning. Thus, biomass pre-processing is required to improve its properties. This work shows the results obtained through the development and substantiation of the parameters of the biomass processing technology in a high-calorie solid fuel for boiler units. Chips from a mixture of Siberian wood (birch, pine, and aspen) and peat of Kandinsky deposit were used as biomass sources. Thermal processing (low-temperature pyrolysis) allows increasing the calorific value of the updated raw materials and obtaining the basis for the binder. Liquid pyrolysis products together with dextrin were used for molding solid composite fuel in the form of pellets and briquettes. These solid fuels had lower heating values of 29.1 MJ/kg (wood chips) and 20.9 MJ/kg (peat), which is superior to most types of fuel briquettes and pellets and comparable to the highest-quality fossil fuels.

1. Introduction

As we know, the reserves of fossil fuels such as natural gas, coal, and oil are limited and, according to different forecasts, will be exhausted within a few centuries. In this regard, different measures have recently been taken aimed at refocusing the energy sector to use other energy sources [1]. Negative public opinion, caused by the accidents at Chernobyl and Fukushima nuclear stations, casts doubt on the prospects of nuclear energy development [2,3]. Thus, one of the most likely options to replace traditional energy based on fossil fuels is the use of renewable energy sources (sun, wind, water, biomass, etc.). Right now, the share of renewable energy is about 22% of the total electricity production, among which the hydropower share is approximately 17%, while the share of other types is about 5% [4–8]. Nonetheless, according to experts [4], the hydropower potential of major rivers in the world has already been utilized approximately by one third. The undeveloped part is concentrated mostly in the developing countries, which limits the further development of high-capacity hydropower. Another obstacle to the development of hydropower is the environmental cause, because the construction of hydroelectric power plants requires the flooding of large areas that significantly modifies the local biosphere. Therefore, the attention of the world scientific community is currently focused on such renewable energy sources as wind, sun, and biomass [4]. Hundreds of billions of dollars are invested annually in the development of renewable energy [9] to prove the high potential of this trend.

However, the use of the said renewable energy sources has a number of barriers to widespread introduction associated with some climatic and geographical factors [10,11]. The limited range of sources is a particularly topical issue for Northern countries, such as Russia, Sweden, Finland, Canada, etc., with short daylight hours in winter, frequent rainfall, wind obstacles (mountains, forests, etc.), low temperatures, and others. Heat extraction from the ground using heat pumps also has some limitations. This method requires large areas due to low air temperatures in winter and can cause fertile soils to freeze, which would make them unsuitable for agricultural use in the future. In this case, almost the only usable source of renewable energy is biomass (wood, household, agricultural and wood processing waste, etc.) [11]. For some countries with vast peat reserves and moderate mining activity, it can also be seen as a kind of renewable fuel feedstock. In Russia, for example, the reserves of peat are about 128 billion tons and growing, while in low demand by energy production. In this case, we can regard peat resources as virtually unlimited and include them in the concept of “slowly renewable biomass” [12].

The reason for the low percentage of biomass involvement in the energy balance is a number of properties that hinder bioconversion: high humidity, brittleness, friability and low calorific value. Due to high humidity, raw materials stick together and congeal during

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transportation in winter [13], requiring additional time and cash expenditures for heating carriages. Low strength and high friability of biomass are reasons for the high losses of the material due to its sifting through the grate. Therefore, its direct burning involves high operational costs and is extremely rare [14–17].

In the field of efficient use of biomass as an energy source, there have been various studies, mainly focused on its pre-processing into high-calorie fuels, such as gasification [18–20] briquetting [21–24], bioconversion [25–27], thermal modification, and synthesis of fuels [28–30].

The population density in the Northern countries is very low and many energy consumers are located away from the main highways. This imposes certain conditions on the organization of power supply: only local resources are used, the generating facilities are autonomous and have low capacity (e.g., boiler houses and individual consumers). These factors need to be considered when choosing the method of biomass utilization.

With respect to low-capacity power-generating facilities, one of the most common methods of biomass processing is briquetting. These objects use grate fuel-firing equipment operating on lump solid fuel. Therefore, the use of fuel briquettes with the desired size, strength and stable thermal performance, allows obtaining acceptable values of efficiency and operating costs regardless of the type and date of manufacturing the fuel-firing equipment. The replacement or modernization of the equipment usually implies long payback periods. This makes these measures unattractive for investment.

The briquetting of biomass and sub-standard fuels (brown coal, waste coal, etc.) has been known for over a century. To date, different dependencies and parameters have already been obtained and defined to provide high strength of the briquettes. The fuel and energy market offers a wide range of fuel briquette production lines: Nestro, Pini&Kay, RUF, etc. However, the following problems in this field still exist [31,32]:

- high energy intensity of production due to the use of energy-intensive pressure equipment;
- low humidity resistance of briquettes or none at all;
- the calorific value of briquettes depends on the characteristics of raw materials, which in some cases do not allow obtaining briquettes that would meet the standards (for example, the lower heating value (LHV) of poplar waste in the dried state does not exceed16.5 MJ/kg [33]).

These shortcomings increase the unit cost of fuel briquettes and reduce their competitiveness in comparison with coal. It is therefore advisable to use the available binders during pressing that will reduce the energy intensity of production and improve the physical properties of the produced fuel. In order to improve the thermal characteristics of fuel, it is possible to use the preliminary thermal processing of the raw materials. It allows reducing the amount of ballast components (*O, N*). Such processing results in increasing both the specific carbon content and the combustion heat in terms of 1 kg of fuel.

The purpose of this work is to develop and substantiate the parameters of resource-efficient biomass processing into high-calorie solid fuel to be used in grate-fired boilers. In order to achieve this purpose, the raw material was thermally pre-processed into a carbon residue and pyrolysis condensate (pyrogenetic moisture and pyrolysis tar). We used the pyrolysis condensate to produce binders by adding dextrin in different concentrations. These binders were mixed with the carbon residue to form such solid composite fuels as pellets 20 mm long and 20 mm in diameter and briquettes 50 mm long and 50 mm in diameter. In order to determine the drying parameters, the prepared fuel was heated at temperatures of 20–140 °C, cooled and tested for strength according to GOST 21289-75.

2. Experimental part

The principle of thermal processing involves the pyrolysis of biomass and production of briquettes and pellets called solid composite fuel (SCF) from the resulting products. It is advisable to use tar or pyrolysis condensate, which can be obtained in the same thermal processing of the biomass, as a binder to produce SCF. In order to develop the described technology, it is necessary to investigate the characteristics of the initial biomass, thermal processing and product formation, the characteristics of obtained products, as well as burning and strength characteristics of the produced SCF.

2.1. Initial biomass

The wood chips, consisting of a mixture, which includes birch, pine and aspen, and the peat from Kandinsky Deposit (Tomsk region, Russia) were chosen for the studies. The wood chips were taken from wastes of one of the largest wood processing plant in the Tomsk region. These wood chips were presented by the fractions sized 5–20 mm. The studied peat belongs to the group of fen peats with the medium degree of decomposition. It has brown color and high humidity. At Kandinsky field, clay and sandy gravel are currently being extracted from under a layer of peat. Thus, a large amount of peat is extracted and stored in open areas as ballast, in need of recovery.

The burning characteristics were determined in accordance with Russian standards (GOST). The humidity (W_t^r), ash content (A^d) and volatile yield of (V^{daf}) of the biomass were found using GOST R 52911-2013, GOST 55661-2013 and GOST 55660-2013, respectively. The lower heating value (Q_i^r) was investigated using an ABK-1 (RET, Russia) calorimeter according to GOST 147-2013.

The elemental composition of the biomass was studied using a Vario Micro Cube elemental analyzer (Elementar, Germany). The heating value of the biomass was derived from the elemental composition on a dry ash-free basis by Mendeleev's formula:

$$Q_i^{daf} = 340 \cdot C^{daf} + 1030 \cdot H^{daf} - 109 \cdot (O - S)^{daf}, \frac{kJ}{kg}.$$

The calculated heating value (after accounting for the effects of moisture and ash) was compared with the calorimetric data in order to check if the obtained results were correct. The values obtained by two independent methods were almost identical, which confirmed their validity.

2.2. Thermal processing of biomass

A special experimental setup (Fig. 1) was developed for the thermal processing of biomass. It consists of a reactor (1), a heater (2), an autotransformer (3), an ammeter (4), a voltmeter (5), a TM-902C thermometer (6), a type-K thermocouple (7), a heat-resistant insulated hose (8), a cooler (9), and a chilled water-jacketed tank (10) for collecting the condensed products.

The initial biomass was milled to 5–10 mm and then loaded into the reactor, which was hermetically sealed and placed in the heater. The heat was supplied to the reactor all along its cylindrical surface. The heating power was set using the autotransformer in accordance with the data of the ammeter and voltmeter. The thermometer and thermocouple were used to control the temperature of the process. They allowed determining the temperature both in the space over the bed and directly in the bed (center and periphery).

The raw material was heated at 10 °C/min. During the heating process, the volatile products (the vapors of pyrogenetic moisture