Granulated biofuels combustion efficiency

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Abstract. The article presents the results of experimental studies of the thermal and ecological performance of the Firematic 60 boiler manufactured by Herz Energietechnik GmbH. Wood pellets with diameter of 6 and 8 mm and biochar from hydrolytic lignin were used for combustion. The components of the boiler’s heat balance and the emission of harmful substances were determined during the burning of the biofuels. In the course of experimental work high energy and environmental performance of the Firematic 60 boiler was reached while working on granulated fuel which gives a reason to recommend this boiler for heat supply of low-rise buildings in the conditions of the Arctic region. Organized in Onega City production of biocahar from hydrolytic lignin allowed to obtain high-quality fuel from biomass that has remained in dumps for 40-60 years. Experimental data on the change in the apparent and bulk density, mechanical durability of wood pellets thermally pretreated for 90 minutes in an electric furnace without oxygen at temperatures of 200, 250, 275 and 300 °C was obtained. It has shown that with an increase in the temperature of wood pellet torrefaction all these parameters decrease. The influence of the torrefaction process parameters of the hydrolytic lignin on the sorption properties of the biochar has been studied; sorption properties have been compared for the granules produced from the hydrolytic lignin and coniferous wood.

Introduction

An effective way of the complex solution of energy and environmental problems while providing heating load of consumers is the use of modern devices operating on solid biofuel. The research papers on highly efficient domestic and foreign heating devices positioned in the market have great importance [1,2]. Also, the research is prospective as it aims studying of torrefaction biofuel [3].

Torrefaction of solid biomass is based on its thermal treatment without air access at temperatures of 200-330 °C. As the result of this process biochar which can be used in powder form or for the production of pellets or briquettes is obtained. Torrefaction process allows to bring the characteristics of biomass closer to characteristics of coal. Different degrees of thermal treatment lead to different yields and different calorific value of the finished product [4]. Theoretical calorific value of torrefied product is between 18 and 31 MJ/kg [5] (calorific value of biochar). Black pellets have good flowability and durability, they are hydrophobic and obeyed by the same laws of grinding as coals. High energy density determines the economic feasibility of their transportation over long distances. Black pellets excel the wood pellets in all characteristics.
Purpose and objectives

Purposes of this work are:
- experimental determination of energy and environmental performance of “Firematic 60” boiler while burning wood pellets with diameter of 6 to 8 mm as well as hydrolyzed lignin black pellets;
- study of torrefaction temperature influence on transport and processing characteristics of wood pellets;
- study of torrefaction process influence on sorption characteristic of biofuel.

Results and discussion

Researches were held in Scientific and Educational Center of Energy Innovations of Higher School of Power Engineering, Oil and Gas NArFU named after M.V. Lomonosov which is connected to a district heat supply system. The reserve source of the building heat supply is the “Firematic 60” boiler made by Herz Energietechnik GmbH. The boiler is designed to operate on pellets and chips [1]. Nominal capacity of boiler is 60 kW. Detailed description of the boiler is presented in the article [6].

Multi-method research of boiler operational efficiency was carried out in three stages. In the course of the first stage the balance experiments were carried out when wood pellets were fed into the boiler furnace. Wood pellets have the diameter of 8 mm, sufficient uniform granulometric composition [7] and the thermotechnical characteristics (Table 1, tests №1,2) that correspond with requirements of current standards. At the second stage wood pellets with the diameter of 6 mm (Table 1, tests №3,4) were burned in the boiler furnace. At the third stage of research the boiler was operated on hydrolyzed lignin black pellets produced by “OAO “Bionet” (Table 1, tests №5,6). There are results of only two tests for each fuel which describe the obtained energy and environmental performance of the boiler.

| Table 1. The main performance of the boiler burning wood pellets and hydrolyzed lignin black pellets |
|-----------------------------------------------|
| Value, dimension               | №1 | №2 | №3 | №4 | №5 | №6 |
| Heat capacity (kW)             | 64.0 | 103.5 | 71.3 | 83.5 | 87.2 | 91.4 |
| Outlet operating pressure of water (MPa) | 0.27 | 0.27 | 0.22 | 0.24 | 0.30 | 0.30 |
| Inlet water temperature (°C)   | 60.0 | 79.0 | 78.0 | 78.0 | 80.0 | 79.0 |
| Moisture of pellets as received basis (%) | 8.38 | 8.60 |       |       |       | 6.27 |
| Ash content of pellets as received basis (%) | 0.50 | 0.43 |       |       |       | 2.45 |
| Dry-and-ash-free volatile yield (%) | 85.10 | 84.75 | 84.75 | 84.75 | 63.85 |
| Lower calorific value as received basis (MJ/kg) | 17.30 | 16.97 | 16.97 | 16.97 | 21.34 |
| Flue gas temperature (°C)      | 106.0 | 151.0 | 154.0 | 155.0 | 160.0 | 157.0 |
| Excess air in flue gas         | 1.39 | 1.42 | 1.46 | 1.43 | 1.45 | 1.42 |
| Heat loss:                     |     |     |     |     |     |     |
| flue gas (%)                   | 4.17 | 6.71 | 7.68 | 7.61 | 6.88 | 6.60 |
| incomplete combustion (%)      | 0.02 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 |
| carbon (%)                     | 0.12 | 0.11 | 0.22 | 0.22 | 0.47 | 0.47 |
| external (%)                   | 0.47 | 0.29 | 0.42 | 0.36 | 0.34 | 0.33 |
| Gross efficiency (%)           | 95.20 | 92.87 | 91.67 | 91.80 | 92.25 | 92.55 |
| Total biofuel consumption (kg/h) | 14.0 | 23.0 | 16.0 | 19.0 | 16.0 | 17.0 |
| Emission of NOx (mg/MJ)        | 52.0 | 52.0 | 56.0 | 54.0 | 46.0 | 44.0 |
| Emission of CO (mg/MJ)         | 21.0 | 12.0 | 6.0 | 6.0 | 3.0 | 3.0 |
| Particulate matter emission (mg/MJ) |     |     | 4.84 | 4.39 | 9.59 | 9.34 |

The analysis of fuels was carried out with the use of the equipment of laboratory of thermal analysis and IKA C 2000 basic Version 2 calorimeter with LOIP FT-216-25 liquid cryothermostat. Study of the grain size distribution of granulated fuels and combustion residues was carried out with vibratory sieve shakers AS 200 Control and Microtrac S3500. The determination of velocity fields and
flue gas flows was performed with Pitot tube and micromanometer of “Testo-435” precision instrument. The results of study of velocity fields were used to determine the particulate matter concentrations at the flue gas after the boiler. In order to get that done it was used external filtration method which is applied via the “OP-442 TC” impactor, dust sampling probe, filter holder, etc. “Testo-350 XL” gas analyzer was used to determine content of combustion products. Fuel consumption was determined by equation of the indirect heating balance. Experimental data analysis was performed using multi-block program-methodological complex [8]. The main results of energy survey of the “Firematic 60” boiler is presented in Table 1.

After automatic start-up the period it takes to reach the rated load does not exceed 20 minutes. After 33-38 minutes the automated control system provides inlet boiler water temperature close to the optimum value (60 °C).

The analysis of thermal conditions has shown that heat loss with flue gas is 4.17-4.68 %, but it rises when load and inlet boiler water temperature increase (Table 1). A stage fuel combustion scheme and efficient mixing of secondary air with combustible components of fuel while keeping the excess air coefficient in furnace within the range from 1.39 to 1.46 allow to reach low values of heat loss due to incomplete fuel combustion (Table 1). Values of carbon oxide concentrations corrected to excess air coefficient of 1.4 are 8.0-58 mg/Nm³.

Carbon loss when boiler operates on all types of pellet has low range which is explained by homogeneity of grain size distribution of burning fuel, its low ash content and sufficiently high caloric value.

Prospective direction of improved biofuel production is manufacturing of black pellets [9]. Thus, pellets production from torrefied hydrolytic lignin allows to obtain (even on soft thermal treatment modes with the temperature of 180-200 °C) high quality fuel from biomass that has being remained in dumps for 40-60 years. The boiler switched from burning wood pellets with the diameter of 6 mm to hydrolyzed lignin black pellets has increased its efficiency (Table 1) despite the higher ash content of the latter (5.56 times more). In addition, minimal NOx and CO emissions have been achieved while burning hydrolytic lignin black pellets (Table 1).

External heat loss from the boiler of rated heat capacity (60 kW) does not excess 0.5 % (that is much lower than in Russian standards [10]), it is explained by moderate overall dimensions, high quality of lining and thermal insulation of materials. Losses due to temperature of bottom ash of the boiler did not excess 0.01 % while operating on wood pellets; did not excess 0.05 % while operating on black pellets. Energy survey of the boiler burning granulated fuels has shown that it could provide the efficient operation with a load much higher than rated.

Low emission of NOx (Table 1) is explained by middle level of maximum temperatures and excess air in combustion chamber as well as two stage combustion scheme. Sulfur dioxide in combustion products while burning biofuels on each boiler mode is absent.

A stage fuel combustion scheme and intensive mixing of secondary air and combustible components of fuel make it possible to ensure boiler’s efficient operation at low oxygen concentration of 4.0-6.0 %. The rise of oxygen concentration of higher than 6% leads to the increase dispersion of harmful substances to the environment. On this basis, the threshold value of the oxygen concentration in automated control system should be reduced to 4 %.

The results of soot particles emission research with the use of external filtration method under isokinetic conditions [11-13] of gas sampling have shown that soot emission factor is 1.74–5.95 g/GJ on 1 GJ of wood pellets heat (with a heat output of 72-104 kW). Soot emission factor PM 2.5 (with conversion coefficient of 0.14 [14]) is 0.243–0.834 g/GJ. When the boiler operates on hydrolyzed lignin black pellets the average soot emission factor is 2.467 g/GJ and soot emission factor PM 2.5 is 0.345 g/GJ. Research has shown that solid particles with dimension less than 15 μm are predominantly carried away to the atmosphere.

The research of efficient burning of improved fuels was carried out jointly with the research of change in apparent and bulk density as well as wood pellets durability in the process of torrefaction.
Wood pellets were supplied by “ZAO “Lesozavod 25” (Arkhangelsk city). Pellets consist of pine on 70% and spruce on 30%. Moisture of pellets is 6.9%.

Wood pellets torrefaction is performed in electrical furnace without oxygen with isothermal soaking for 90 minutes at temperatures of 200, 250, 275 and 300 °C.

The bulk density is determined in accordance with GOST 32987-2014 [15]. The apparent density of samples is determined by measuring of mass and volume by external measurement. Pellets without visible defects are selected, their edges are aligned on a grinding machine. Determination of durability are performed on lignotester NHP 100 in accordance with EN 15210-1 [16]. The results are presented in Table 2.

**Table 2.** Characteristics of hydrolyzed lignin black pellets.

| Sample | Torrefied product output (%) | Bulk density (kg/m³) | Apparent density (kg/m³) | Durability (%) |
|--------|------------------------------|----------------------|--------------------------|----------------|
| Starter pellets | - | 597.06 | 1261.20 | 97.97 |
| Pellets are torrefied at: | | | | |
| 200°C | 94.13 | 589.97 | 1246.35 | 97.81 |
| 250°C | 87.09 | 533.52 | 1127.28 | 93.11 |
| 275°C | 78.77 | 514.12 | 1110.40 | 89.84 |
| 300°C | 64.01 | 456.13 | 985.98 | 74.68 |

Based on the obtained data it is clear that loss of pellet mass increases as torrefaction temperature rises that is explained by thermal decomposition of main polymeric structures of the wood. Thus, hemicellulose begins to decompose at the temperature of about 190 °C. However, main breakdown of β-glucosidic bond proceeds at the temperatures ranging from 220 to 280 °C [17, 18]. Cellulose and lignin are more thermostable. Decomposition of cellulose occurs in the temperature range of 280-370 °C, and for lignin this value is in the range of 200-540 °C. During the torrefaction removal of moisture from wood occurs as well as volatiles which are formed in the process of hemicellulose breakdown and partial decomposition of cellulose and lignin. Considering the fact that quantity of lignin and cellulose into spruce timber is much higher than of hemicellulose (in 8.0 and 5.2 times accordingly) [19] the torrefaction process will be determined by the thermal decomposition of two main components (lignin and cellulose). Thus, mass of finished wood pellets while maintaining their shape and volume reduces in the torrefaction process, for which reason both the apparent and bulk densities decrease (Table 2).

Reduction of durability occurs with increasing temperature of pellets’ thermal treatment (Table 2). The main reasons of it are the uneven heating of pellets into depth during torrefaction because of low thermal conductivity that leads to thermal stresses and the side-by-side process of biomass thermal decomposition which is accompanied by vapor and volatiles emissions. In this case there is the parallel motion into pellet depth of two fronts: the evaporation and thermal decomposition of biomass organic components.

In addition, studies of sorption properties evolution of hydrolyzed lignin and its torrefied product obtained at various temperatures as well as wood pellets and hydrolyzed lignin black pellets have been carried out.

Such raw materials as spruce (50 wt%) and pine (50 wt%) consisting of chips (90 wt%) and sawdust (10 wt%) were used for production wood pellets with diameter of 8 mm.

The hydrolyzed lignin was sieved on a vibratory sieve shaker Retsch AS 200 Control. Fraction of 125-500 µm was sampled for the experiment. Torrefaction of hydrolyzed lignin was performed in electrical furnace without oxygen with isothermal soaking for 90 minutes at the temperatures of 200, 250, 275 and 300 °C.

The determination of water absorption of testing samples was carried out in accordance with GOST 16483.19-72 [20]. The samples were dried preliminary until absolute dry state in a weighing bottle in
an oven at the temperature of 105±2 °С. Then the sample bottles were inserted into a desiccator at the bottom of which there was a saturated sodium solution (Na₂CO₃·10H₂O). Samples had been in a desiccator for 60 days. Samples were weighted after 1, 2, 3, 6, 9, 12, 20 days and then every 10 days. Absorb moisture content was determined in accuracy of 0.1 %. Results of researches are illustrated in Figure 1.

Figure 1. Absorb moisture content change: 1– wood pellets, 2 – hydrolyzed lignin, 3 – hydrilyzed lignin black pellets; hydrolyzed lignin torrefied at °C: 4 – 250, 5 – 300, 6 – 200, 7 – 275.

Based on the obtained data wood pellets (11.9 %) and initial hydrolyzed lignin (11.2 %) have the highest absorb moisture content at the end of 60 days.

The dynamics of water absorption process in hydrolyzed lignin and its torrefied product are similar in all the cases: absorption of 80-84 % is in the first 3 days, then the velocity of this process decreases. The process of water absorption in wood pellets and black pellets proceeds more evenly, 76-86 % of all moisture are absorbed for the first 9 days. Various dynamics of water absorption process of milled samples and pellets are explained by larger surface area of the first one.

The torrefaction of hydrolyzed lignin samples leads to reduction in their sorption characteristics. Minimum value of water absorption for 60 days for hydrolyzed lignin torrefied at the temperature of 275 °C is 6.3 % which is on 4.9 % less in comparison with initial material.

Conclusions

A comprehensive energy survey has shown that the “Firematic 60” boiler provides high technical and economic performance and minimum emissions of harmful substances to the atmosphere while combusting wood pellets and hydrolyzed lignin black pellets. When burning the latter a high energy and environmental performance of the boiler has been reached wherein NOx and CO emissions were minimal. Pellets production from torrefied hydrolytic lignin allows to obtain high quality fuel from biomass that has being remained in dumps for 40-60 years.

The torrefaction process leads to the decrease in sorption characteristics of wood biomass which allows to reduce sufficiently the requirements for transportation and storage conditions of black pellets and to preserve their calorific value. However, torrefaction of finished pellets results in a reduction in their transport and processing characteristics such as apparent and bulk density and durability. Therefore, it is necessary to provide thermal treatment of initial material rather than a finished product to manufacture the pellets with high quality and processing characteristics.

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