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Influence of Preliminary Heat Treatment of Biofuel (Torrefaction Process) on the Combustion Process in Fluidized bed

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Abstract

For improvement of the combustion efficiency in a fluidized bed and decrease of carbon monoxide and nitrogen oxides emissions, biofuel is suggested to pre-heat treating (torrefaction). The experiments on burning of initial ("raw") and thermally processed pellets from sunflower husks were carried out in a pilot sample of a furnace with a bubbly fluidized quartz sand bed. The "raw" pellets had a lower calorific value of 16 MJ/kg and contained 75.6% volatile substances. After heat treatment in a specially designed reactor at a temperature of 250 °C (treatment time of 60 minutes), the tor - pellets had a lower combustion value of 20.7 MJ/kg and contained 54.8% of volatile substances. As a result of heat treatment, the carbon content in the pellets increased by 1.21 times, the nitrogen content increased by 1.36 times, the sulfur content boosted by 1.27 times, the calcium content improved in 1.66 times, the content of potassium raised in 1.74 times. It was experimentally proved that in a fluidized bed the intensive intralbed circulation of "Gulf Stream" type should be organized to reduce the probability of ash agglomerates formation. For the circulation of "Gulf Stream" type, a special air distribution grille was used, which provided a higher air velocity at the entrance to the bed near the vertical walls of the furnace and a lower air velocity in the center of the furnace. During the experiments with "VarioPlus" gas analyzer, the content of oxygen, carbon monoxide, and nitrogen oxides in the flue gases was measured. It was found that:

1. When tor-pellets are burned due to the higher heat of combustion, the oxygen content in the flue gases at the outlet from the fluidized bed is reduced by about 1.5 to 1.7 times, and the carbon monoxide content is reduced about 2 times.

2. When tor-pellets are burned due to the lower oxygen content of the flue gases, the nitrogen oxides content is reduced by about 1.7 times compared to "raw" pellets combustion.

Keywords: biomass combustion, sunflower husk, torrefaction.

1. Introduction.

The task of making high-efficiency heat-generating systems of small capacity (up to 50 MW), suitable for burning various types of solid fuels, including biomass and bio-waste, seems quite complex considering the wide range of characteristics of these fuels. The solution of this problem is possible due to the use of technologies such as combustion of fuel in the fluidized bed [1], that allows: 1) burn low-quality fuels with high ash content and low heat of combustion, 2) fix and remove sulfur of fuel directly in the combustion process, 3) reduce emissions of nitrogen oxides, 4) steadily burn fuel, the heat engineering characteristics of which fluctuate in a fairly wide range [2, 3]. However, this technology is not without a number of shortcomings, which are most noticeable when burning fuels with a high content of volatile substances, which include biomass and various types of biowaste. Self-segregation of hot biomass particles near the upper boundary of the fluidized bed significantly reduces the efficiency of the combustion process and the reliability of the boiler operation with the fluidized bed as a whole, as the volatile substances released from the biomass are burnt unorganized in the disengaging space, which also contributes to the increase in the temperature of gases at the outlet from the furnace, melting of ash particles and formation of dense ash deposits on the convective surfaces of boilers heating [4].

It was proposed to create in the bed the vortices that are comparable to the height of the fluidized bed (circulation ("Gulf Stream"), using an unusual gas distribution at the entrance to the bed in order to increase the efficiency of burning in the fluidized bed of fuels with a high content of volatile substances and to create intensive circulation of the solid and gas phases Merry and Davidson [5].

Another way to increase the efficiency of biomass combustion in the fluidized bed is to reduce the volatile matter content in it, which is possible as a result of preliminary heat treatment of biofuels (torrefaction) in low oxygen content at 250-300 °C. As a result of such heat treatment almost all moisture, some oxygen and hydrogen is liberated from the biomass, but the heating value of such biofuel increases by 20% or more and this biofuel acquires hydrophobic properties [6, 7, 8]. Moreover, as a result of torrefaction, the burning speed of the biomass can be reduced and approximated to the burning rate of fossil solid fuel [9].

The decrease in the burning rate of biomass, as well as the decrease in the content of volatile substances in biomass underwent the torrefaction, contributes to the completion of biofuels combustion in the combustion volume of the flue gases temperature approaching the calculated values, prevention of ash melting and formation of dense ash deposits on convective heating surfaces of coal and pulverized-coal fired boilers, which are usually converted to co-combustion of coal and biomass.

The joint effect of preliminary heat treatment and organization of circulation of "Gulf Stream" type on the process of burning biofuel in the fluidized bed has not been researched and this is the purpose of this work.

2. Experimental procedure for the "cold" model of the furnace.

At organization of the solid phase circulating of fluidized bed type "Gulfstream" the air or any other gas is supplied at a greater rate near the vertical walls defining bed, as shown in Figure 1. Such air distribution at the inlet to the bed results in preventing the formation of preferred sites for lifting of gas bubbles and facilitating large-scale circulation of the solid phase of the bed, as shown in Figure 1.

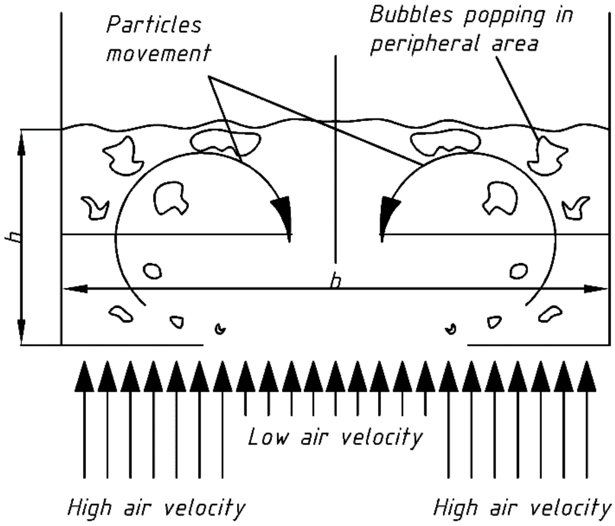

Figure 1. A pair of two-dimensional cells illustrating "Gulf Stream" type circulation mechanism.

In literature there is no justification of this particular gas distribution at the entrance to the fluidized bed, as shown in Figure 1. Meanwhile, a gas with a higher velocity can be fed not to the vertical wall bounding the bed, but at the center of the air distribution device. In fact, at the vertical wall the porosity of the bed is higher and, consequently, it can be assumed that with such air distribution arrangement, as shown in Fig. 1, a gas flow along the vertical wall can be observed without the necessary contact with the solid phase.

A comparative analysis of the hydrodynamic structure of the fluidized bed obtained with a "concave" input velocity profile of the gas (the velocity of gas at the entrance to the bed is higher in the bounding bed of the vertical walls, and at the entrance to the center of the bed is lower) and the gas "convex" input velocity profile (gas velocity at the entrance to the bed is higher in the center of the bed than at the wall-bounding walls) is also one of the objectives of this study.

Circulation "Gulf Stream" also contributes to a more intensive flow of heat exchange processes between the fluidized bed and the heat transfer surfaces within it [10]. Therefore, although the hydrodynamic structure of the fluidized bed can be studied by various methods, the results of studying the hydrodynamic structure of the bed are of undoubted practical interest on the basis of measuring the intensity of heat exchange between the bed and heat-exchange element within it in various areas of the fluidized bed. Heat transfer with the element in the bed simulates in a first approximation the heat exchange between the fluidized bed and the fuel particle, which is important for estimating the rate of heating and ignition of the fuel particle in the bed, and also for eliminating local bed overheating, melting fuel ash, and bed de-fluidization.

"Cold" model of a furnace with a fluidized bed was made to study the influence of the input air distribution methods on the hydrodynamic structure of the fluidized bed [11]. The scheme of the "cold" model of the furnace where the experiments were performed is shown in Fig. 2. The model consists of: filter (1) for the air cleaning in front of the blower (2); safety valve (3) and ball valves (4) for pressure relief and air flow control, flowmeter (5); - cylindrical tubes (9) diameter 180/172 mm and length 1000 mm, made of organic glass; - air inlet unit (6); - unit (7) of fixing the air distribution grid (8); - air outlet unit (11); - systems for measuring the pressure drop on grid and bed (10); - filter for exhaust air cleaning (12).

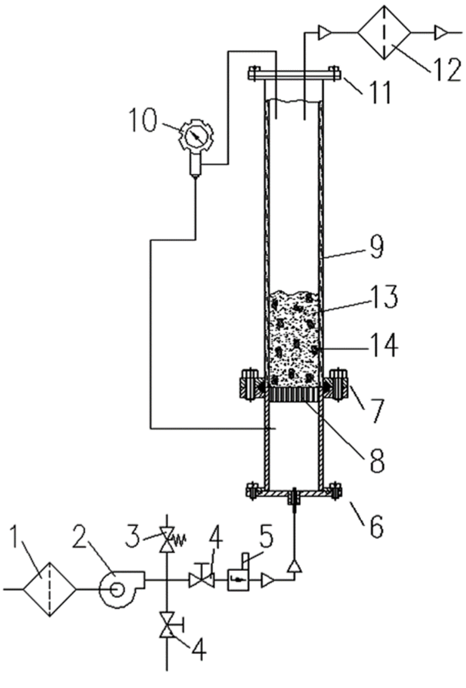

Figure 2. The scheme of furnace "cold" model.

SCL K06-MS-4 blower is used to create a fluidized bed, which provides an air flow rate of up to 300 m^3/h with a pressure of at least 0.0325 MPa. The air flow directed to the fluidization of quartz sand (as an inert material) is measured by a flowmeter (5), E771-AL1N050xKA, which operates on a thermal mass principle. The flow meter readings are shown at the built-in display, and analog and pulse signals are output to the computer.

The measurement of external heat transfer between the fluidized bed and the surface (copper ball D = 24 mm) was performed by a standard method of regular thermal conditions [12].

The thermocouple (type L) was soldered into the center of the ball that made it possible to continuously measure the temperature of the preheated pellet after being placed in a cold fluidized bed. The sensor circuit is shown in Figure 3. The sensor positioning system shown in Figure 4 was used to determine the distribution of heat transfer coefficients in the fluidized bed. The sensor positioning system in the fluidized bed chamber allows the copper ball to be positioned both on the chamber axis and at different distances x from the axis. The height of the ball position above the gas distribution grid h could be adjusted. During the experiments, the sensor was located at a height of 30 mm and 80 mm above the grate. Quartz sand with particle size 0.5-0.8 mm (d = 0.65 mm, u_{mf} = 0.26 m/s) was used as the dispersed material.

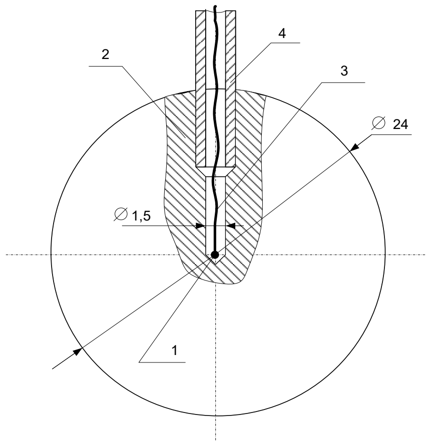

Figure 3. Scheme of sensor for determining of heat transfer intensity. 1 – thermocouple head, 1.2 mm in diameter, 2 – copper ball, 3 – thermocouple wires, 4 – connecting tube, 3.0 mm in diameter.

Three perforated grids were used for the organization of different types of inlet air distribution. The first variant of the grid has a uniform cross-sectional area (grid forms "flat" air velocity profile at the entrance to bed), the second variant provides a larger cross-section in the center (grid forms "convex" air velocity profile), and in third variant a larger section is located on the periphery (grid forms "concave" air velocity profile). The grating scheme is shown in Figure 5, and its characteristics are given in Table 1.

Table 1. Distribution of holes in various grids.

Equal area grid zones	Variant 1		Variant 2		Variant 3	
	Proportion of cross section, %	Number of holes with diameter 2 mm, *n*	Proportion of cross section, %	Number of holes with diameter 2 mm, *n*	Proportion of cross section, %	Number of holes with diameter 2 mm, *n*
S1 3919 mm^2	1.5	19	2.5	32	0.5	7
S2 3919 mm^2	1.5	19	2.0	25	1.0	13
S3 3919 mm^2	1.5	19	1.5	19	1.5	19
S4 3919 mm^2	1.5	19	1.0	13	2.0	25
S5 3919 mm^2	1.5	19	0.5	7	2.5	32

Before the measurement the copper ball was heated by a hot air source to a temperature of 200-240 °C, then the ball was put in the necessary point of the bed and the temperature of the copper ball was fixed until it equaled the temperature of the fluidized bed. All experiments were carried out at three different air filtration rates u = 0.49; 0.61 and 0.73 m/s to determine the effect of air velocity in the chamber.

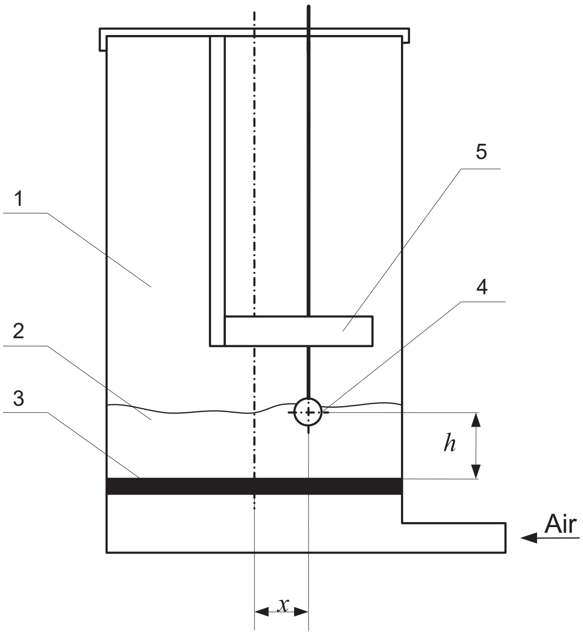

Figure 4. Scheme of sensor location for measuring of heat transfer intensity in fluidized bed.
1 – fluidized bed chamber, 2 – fluidized sand bed, 3 – gas distribution grid, 4 – sensor, 5 – sensor positioning system.

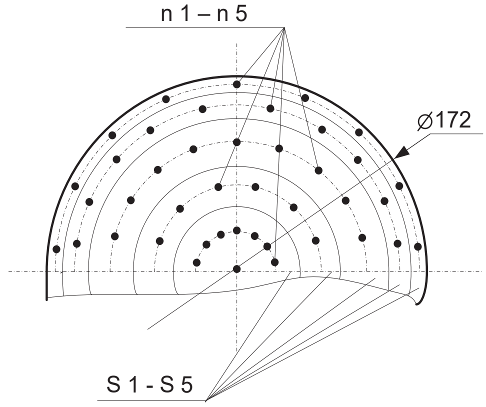

Figure 5. Scheme of gas distribution grid. n1 – n5 – number of holes in zones,

S1 – S5 – equal area zones.

3. Results of experiments on "cold" model and their discussion.

Figures 6-8 show average values of the heat transfer coefficients between the sensor and the fluidized bed for three types of air distribution grid and two values of the initial height of the bed (0.05 m and 0.1 m). With "flat" inlet air velocity profile (Figure 6) at initial bed height of 0.05m and air velocity of 0.49 m/s, the heat exchange rate of the equipment wall is 1.31 times higher than at the center of the apparatus. At the increase of the air velocity to 0.61 m/s, the heat transfer coefficient at half of radius of the apparatus is 1.19 lower than at the wall of the apparatus. Finally, at air velocity of 0.73 m/s at the center of the apparatus, the heat exchange rate is 1.16 times higher than in the other zones of the fluidized bed. With "flat" inlet air velocity profile with increase in the initial height of the bed to 0.1 m, the heat transfer in the center of the apparatus and at half of its radius is 1.1 - 1.35 times higher than in the peripheral zones of the bed.

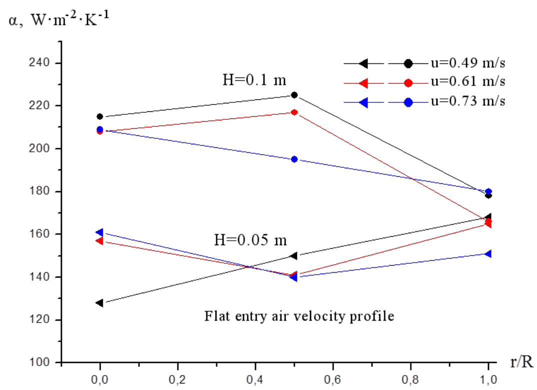

Figure 6. Dependence of coefficients values of heat exchange between the fluidized bed and heat exchange element on the air velocity with even inlet air distribution (Flat inlet air velocity profile).

With the “convex” input air velocity profile, the intensity of the heat exchange processes in the bed is substantially higher than for the “flat” air velocity input profile (Figure 7). At air velocity of 0.49 m/s, the heat exchange in the fluidized bed with initial height of 0.05 m is 1.5 to 1.6 times higher than for “flat” profile at the same air speed. However, at initial bed height of 0.05 m at half of radius of the apparatus, the heat exchange intensity is 1.3 – 1.4 times higher than at the center and at the apparatus wall, respectively. At increase in air velocity up to 0.73 m/s there will be a sharp increase, up to 400 W/m2 deg., in the intensity of heat exchange at about the middle of the radius of the apparatus, while in other areas of the bed the intensity of heat exchange remains the same.

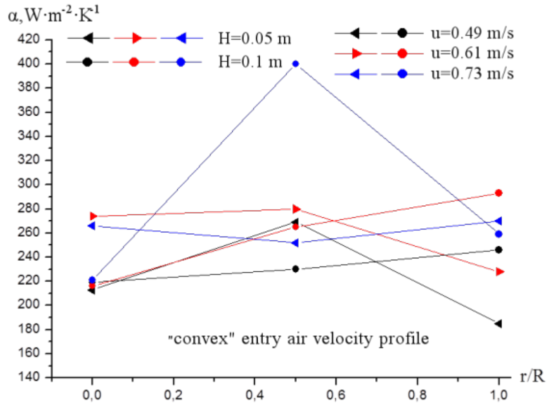

Figure 7. Dependence of values of heat exchange coefficients between the fluidized bed and heat exchange element on air velocity with “convex” input air velocity profile.

At “concave” inlet air velocity profile with the growth of the latter there is also an increase in the intensity of heat exchange in comparison with “flat” input air velocity profile (Figure 8). At increase in the initial height of the bed up to 0.1 m with a “concave” input air velocity profile, the values of the heat transfer coefficients fluctuate in a very narrow range about 230 to 260 W/m2 deg. Moreover, with “concave” inlet air velocity profile at 0.1 m bed height, the heat exchange rate is higher than the heat exchange rate in the bed with an initial height of 0.05 m in 1.5 –3.5 times.

It should be noted, that the “convex” inlet gas distribution provides a more intensive circulation than the “concave” input gas distribution if we accept that the increase in heat transfer rate between the fluidized bed and heat exchange element immersed in bed is connected due to the formation in the fluidized bed solids circulation circuit. On the other hand, the “concave” inlet air distribution provides practically the same intensity of the heat exchange processes in the entire volume of the bed. This suggests that the “concave” input gas distribution provides the same heat and mass transfer processes, as well as chemical reactions carried out in the fluidized bed.

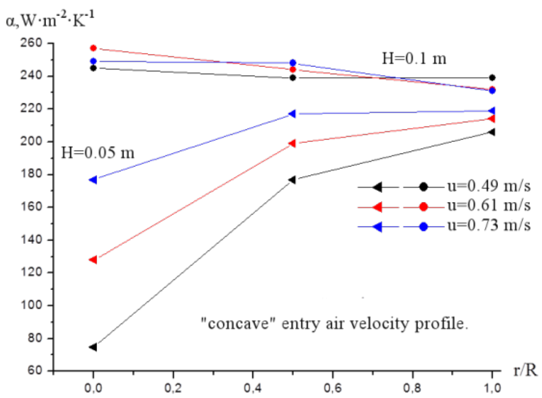

Figure 8. Dependence of values of heat transfer coefficients between the fluidized bed and heat exchange element on the air velocity with “concave” input air velocity profile.

4. The experimental procedure on the pilot sample of the combustion device.

Experimental verification of biofuel combustion, including pre-heat treated, in a fluidized bed furnace equipped with a gas distribution grid and forming “Gulf Stream” type circulation, was carried out on a pilot model of 500 kW boiler (Figure 9).

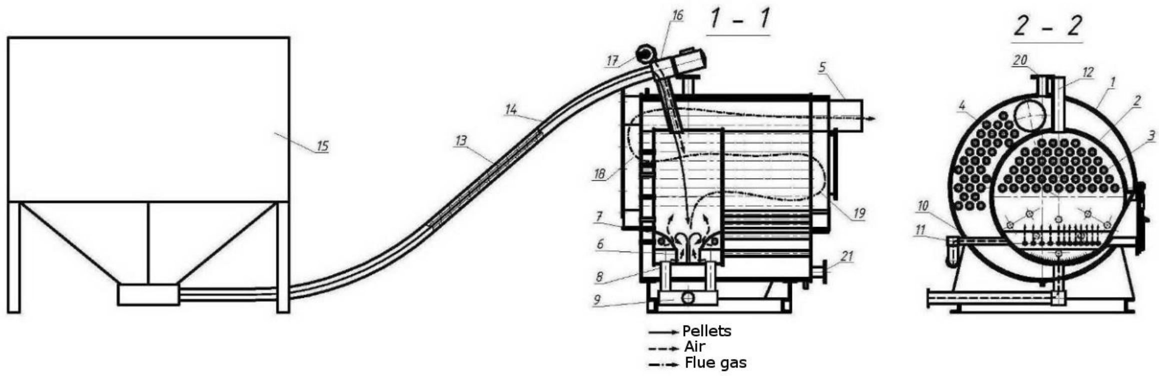

Figure 9. Diagram of boiler pilot model.

The boiler includes cylindrical body 1 where fire tube 2 is disposed which, through system of short and long fire tubes 3, 4, is connected to chimney 5 through which flue gases are removed from the boiler into the stack (not shown in the drawings). In the lower part of the flame tube 2 there is a fluidized bed of fuel. The fluidized bed in its lower part from the sides is bounded by an air distribution grid comprising lower side perforated profile 6 and upper perforated side and rounded profile 7. The lower profiles 6 are connected to an air blower via the first pipe system 8 through the first collector 9 (not shown in the drawings). The upper profiles 7 are connected to the secondary air supply fan via the second pipe system 10 through the second collector 11 (not shown in the drawings). In the upper part of the boiler there is a branch pipe 12 for feeding the pellets into the furnace of the boiler, which is connected to the system for feeding the pellets into the boiler. The fuel supply system is made in the form of a flexible screw 13, enclosed in a pipe 14, and is connected to a fuel storage bin 15. The fuel branch has a cover 16 in its upper part, where a fan 17 for supplying a tertiary blast is installed. The fuel branch 12 is installed at an obtuse angle to the longitudinal axis of the boiler in the direction of the smoke tubes 3. The front and rear rotary smoke boxes 18 and 19 are located on the front and rear walls of the boiler, respectively. In the upper part of the cylindrical body of the boiler 1 there is a connection 20 for evacuation of water heated in the boiler, and in the lower part of the cylindrical boiler body there is a conduit 21 for supplying water circulating through the boiler.

The experiments were carried out by burning pellets made from sunflower husks (Table 2). In this case, both ordinary (“raw”) pellets were used, as well as pellets after thermal treatment (torrefaction) in a low oxygen content medium at 250 ° C...

Table 2. Characteristics of pellets

Indicator	“Raw” pellets from sunflow er husks	Pellets from sunflower husks after torrefaction
Moisture wt % w.b.	11,4	6,7
Ash [550 °C] wt % d.b.	3,7	6,1
NCV MJ/kg w.b.	16,0	20,7
Volatiles wt % d.b.	75,6	54,8

The experiments were carried out at a boiler output of 380 - 520 kW. During experiments the height of the fluidized bed varied between 112 and 144 mm. The temperature of the fluidized bed varied between 660 and 861 °C, with the minimum value of temperature observed at the vertical walls of the furnace, and the maximum at the center of the bed. When carrying out the experiments with the gas analyzer “VarioPlus”, the content of oxygen, carbon monoxide, and nitrogen oxides in the flue gases was measured.

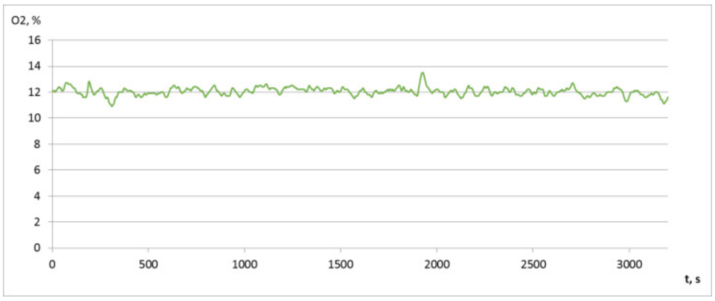

Figure 10. O_2 content change in flue gas at furnace exit during combustion of "raw" pellets.

As can be seen from Figure 10, the burning of "raw" pellets from sunflower husks is stable and the value of oxygen concentration in the flue gases comprises 12%.

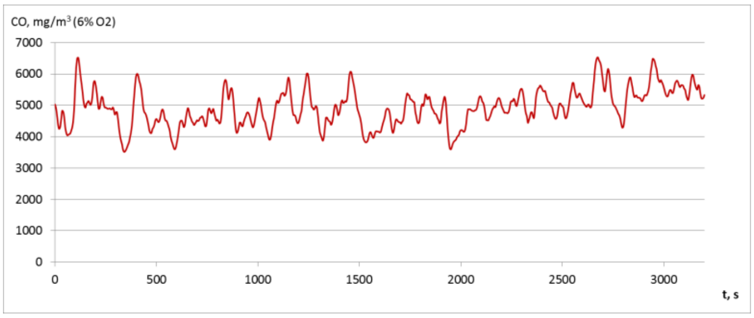

Figure 11. CO content change in flue gas at furnace exit during combustion of "raw" pellets

As can be seen from figure 11, the carbon monoxide emissions are large, reaching 6500 mg / m3. This means that "Gulf Stream" type circulation does not allow complete combustion of volatiles in the volume of the fluidized bed and in the volume of the furnace.

Emissions of nitrogen oxides are rather high and reach 1200 - 1300 mg / m3. These high emissions NOx can be explained by a sufficiently high content of nitrogen in the initial "raw" pellets (figure 12).

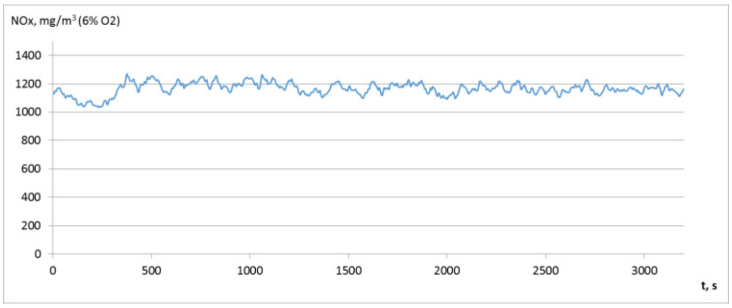

Figure 12. NOx content change in flue gas at furnace exit during combustion of "raw" pellets

During burning heat-treated pellets the concentration of oxygen in the flue gases is 1.5 – 1.7 times lower (Figure 13) than at "raw" pellets burning.

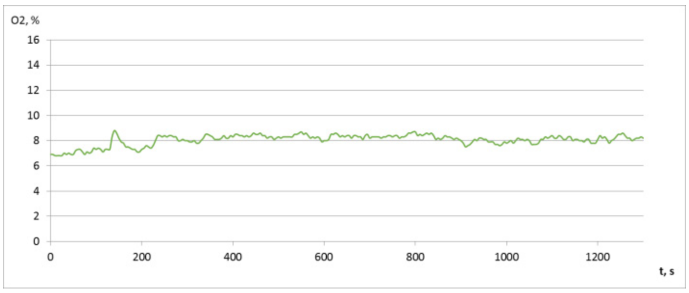

Figure 13. O_2 content change in flue gas at furnace exit during combustion of torrefied pellets.

The low concentration of oxygen in flue gases during the heat-treated pellets combustion can be explained by the higher heat of combustion of the latter and volatiles lower content than in “raw” pellets substances. The lower content of volatile substances in the heat-treated pellets and the higher value of their combustion heat ensure more complete combustion of the fuel in the volume of fluidized bed, which causes not only a lower oxygen content in the flue gases but also a lower carbon monoxide content in these gases (Figure 14).

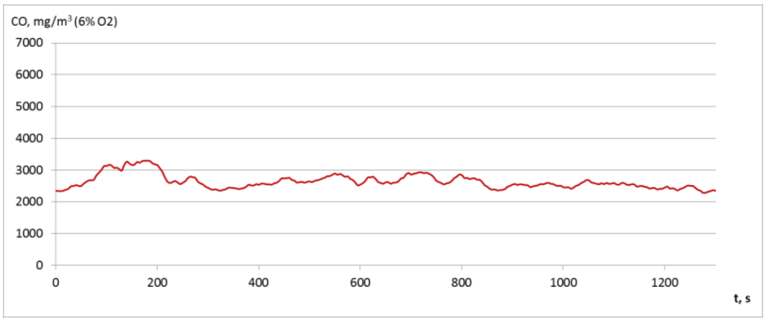

Figure 14. CO content change in flue gas at furnace exit during combustion of torrefied pellets

When burning heat-treated pellets from sunflower husks, the content of nitrogen oxides in the flue gases is about 1.7 times lower than at burning the “raw” pellets (Figure 15).

This fact requires explanation, because the higher heat of combustion of heat-treated pellets at first sight suggests an increase in emissions of nitrogen oxides. It is well known that many factors influence the emissions of nitrogen oxides during the combustion of solid fuels. However, the influence of these factors on the emission of nitrogen oxides is not the same. In work [13] an empirical dependence was obtained, although not for biomass, but for coal, which makes it possible to estimate the effect of these factors on the emission of nitrogen oxides. It turned out that the emission of nitrogen oxides is proportional to the coefficient of oxygen in the combustion zone in the degree equal to 2, 06411 and the content of volatile substances in the degree equal to 0.8375, but is inversely proportional to the amount of air required to burn one kilogram of fuel to the extent equal to 1.2441 (the amount of air required to burn 1 kg of fuel is proportional to the heat of its combustion). The value of the temperature in the combustion zone is taken into account in the denominator of the exponential and, since the temperature in the combustion zone in our experiments did not vary over a wide range, it could not significantly affect the emission of nitrogen oxides. Thus, the reason for a significant reduction in the emission of nitrogen oxides during the burning of heat-treated pellets is, a sharp decrease in the concentration of oxygen and a decrease in the amount of volatile substances in heat-treated pellets.

The conducted researches allow making the following conclusions:

Preliminary heat treatment of pellets (torrefaction) together with the organization of circulation of “Gulf Stream” type promotes a significant increase in the efficiency of burning biofuel and reduces harmful emissions.

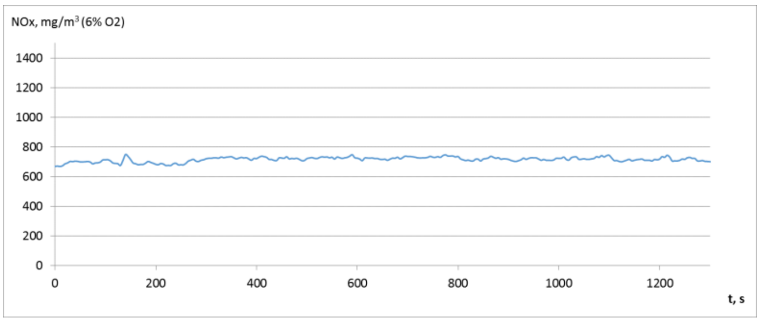

Figure 15. NOx content change in flue gas at furnace exit during combustion of torrefied

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