Comparative Studies of the Combustion of Raw and Heat-treated Straw and Combined Coal and Straw Pellets

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Abstract—**The main combustion process should be carried out in the regime of a fixed, forced ventilated bed for the efficient combustion of biofuel with low-melting ash in boilers with furnaces with a small height. After a certain period of time, a bed must be transferred into a state of turbulent fluidization, and then returned to its original state. So, the objective of the present work is to study the process of pellets combustion in such a bed (let's call it a pulsating bed). The suggested technology of combusting ensures prolonged steady combustion of fuel with moderate carbon monoxide emissions. Combined coal waste and straw pellets combust more stable with less carbon monoxide emissions than straw pellets. Preliminary torrefaction does not influence the stability of combustion, but allows reducing carbon monoxide emissions from the combustion of combined coal waste and straw pellets. Production of coal-straw pellets can apparently be considered as a new variant of the organization of coal and biomass co-combustion; and in the case of pellets torrefaction, it allows producing water-resistant fuel suitable for use not only in electric power stations, but also in small boiler-houses.**

Keywords-fluidized bed; fixed bed; straw pellets; coal's waste pellets.

I. INTRODUCTION

Analyzing the sources of raw materials for biofuel production, we came to the conclusion that the most accessible and annually renewable resource here is straw of different crops. Up to 120 million tons of straw of wheat, rye, oats and other cereal crops is annually gathered in Russia. As for winter wheat straw, we gather up to 60 million tons of it. Wheat straw is not used to feed cattle, but it is used in small quantities as bedding for the animals. Straw is often burned in the fields, as the value of its use as a fertilizer is questioned by many experts. According to our estimations, Russia can use up to 24 million tons of straw as fuel every year without harming either crop farming or agriculture. Straw as biofuel can be used for co-combustion with coal, including low-grade coal and coal waste (slurry). At the same time, we must bear in mind that straw is CO_2 – neutral fuel, i.e., the same amount of carbon dioxide is released during the combustion as the plant absorbs during its growth. Taking into account the low bulk density of straw and granulometric composition of slurry (the particles are of size up to 0.2 mm), it makes sense to process this fuel into pellets, which are easy to transport and store. The feeding of pellets into a boiler furnace can be easily mechanized and automated. Such coal-straw pellets can be used in low-power boilers (up to 1 MW).

However, straw differs from wood and wood wastes, which are now most frequently used as fuel, by a high content of chlorine, silicon, phosphorus, and potassium. The presence of these compounds in straw contributes to the formation of slag agglomerates in the furnace, coherent deposits on the boiler heating surface and corrosion under these deposits. Thus, about 80% of the ash, produced during combustion of straw, can form slag in the boiler furnace. At the same time, only 10% of the ash, produced from the combustion of wood bark, can form slag; and the ash from stem wood does not form slag at all [1].

Some problems with the formation of slag agglomerates arise both during the combustion of agropellets in a fixed bed [2][3], or during the combustion of agropellets in a fluidized bed of inert material [4][5][6][7].

The process of straw combustion in a fixed bed is largely influenced by the mass flow rate of blasting air, and the dependence of straw combustion rate in a fixed bed on the flow rate of blasting air has an extreme character [8]. This severely limits the range of power control of the furnace.

It is possible to increase the efficiency of biofuel combustion, including the increase of the flow rate of blasting air, by the organization of the combustion process in a fluidized bed.

Bhattacharya et al. [9] shows that the efficiency of combustion in a fluidized bed of such high-ash biofuel as rice husks (ash content of 14% or more) can reach more than 85%. Moreover, in contrast to the combustion of biofuel in a fixed bed, the efficiency of a process increases with the increase of the flow rate of primary air during the combustion in a fluidized bed.

However, as mentioned above, during the combustion of biogranules with low-melting ash in a fluidized bed, we observe gradual agglomeration around a burning granule of the particles of inert material, which ultimately leads to defluidization and cessation of a combustion process.

It is possible to prevent defluidization by increasing the gas velocity in the furnace and by transferring a bed into the turbulent fluidization regime.

The use of turbulent fluidization technology can provide significant advantages. So, the combustion of carbon spheres in the turbulent fluidization regime passes at the rate of 1.5-3

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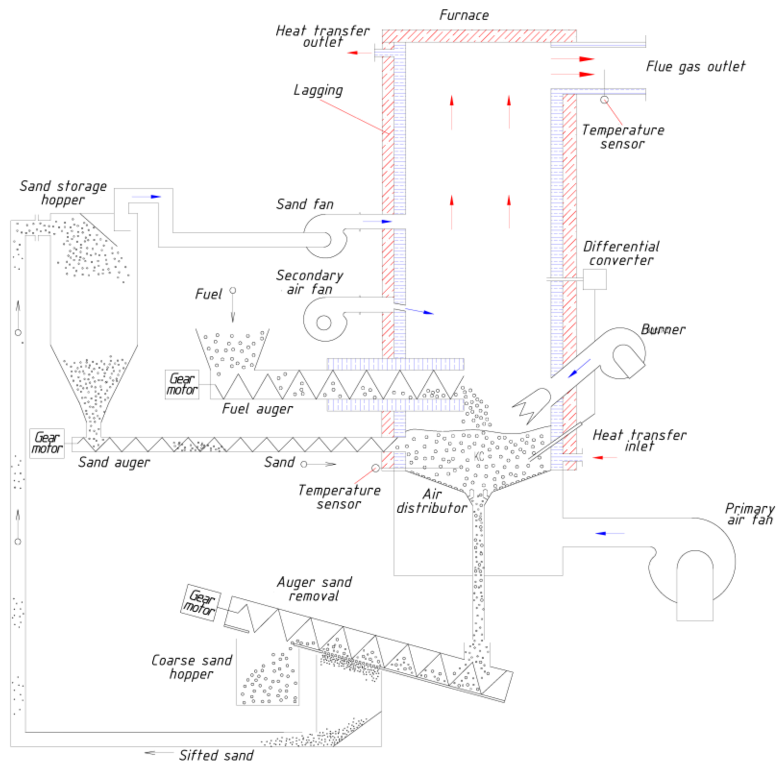

Figure 1. Functional scheme

times higher than in a bubbling fluidized bed [10], and it can be explained by significantly higher rates of mass transfer.

However, as applied to the technology of biofuel combustion in low- and medium-power boilers, i.e., in boilers with a small height of the furnace, the technology of combustion in the turbulent fluidization regime may be of limited use due to high fuel entrainment losses.

This implies the following proposition: the main combustion process should be carried out in the regime of a fixed, forced ventilated bed for the efficient combustion of biofuel with low-melting ash in boilers with furnaces with a small height. After a certain period of time, a bed must be transferred into a state of turbulent fluidization, and then returned to its original state. The transfer of a bed from one state to another can be implemented by changing the current frequency, energizing the drive of a blow fan. In this connection, the regulators of frequency can be programmed in a certain way, and the boiler operates automatically in both regimes, without operator's intervention.

So, the objective of the present work is to study the process of pellets combustion in such a bed (let us call it a pulsating bed).

II. The Experimental Unit

Figure 1 shows an outline of the experimental unit for studying the combustion of different types of solid fuel. The studies are conducted in the remote cylindrical furnace with inner diameter of 300 mm and height of 1000 mm above the air distribution grill. The furnace is water-cooled, and the cooling circuit of the furnace is inserted in the cooling circuit of the heat exchanger of flue gases.

The design of the furnace provides the tangential inlet of flue gases into the combustion can of the exchanger. This provides the post-combustion of volatile matters and the fallout of fuel and ash particles from gas flow.

The furnace is equipped with a hopper for solid fuel and with the device for fuel feeding in the furnace. Fuel inlet in the furnace is carried out at height of 350 mm above the air distribution grill.

The furnace is rested upon the air distribution grill; blasting primary air from the high-pressure fan is forced under this grill. The frequency of the electrical current, energizing the drive of the blow fan, is controlled, and it allows us to alter both the pressure of blasting air and blasting air flow rate by using a special program.

III. Methods and Materialse

In the course of the experiment, we combust pellets produced from straw, straw tor-pellets, combined coal slurry (70% by weight) and straw (30% by weight) pellets, and identical tor-pellets. Such a composition of pellets is conditioned by the fact that we want to get pellets with a maximum content of coal slurry. On the other hand, when the content of straw in the mixture is less than 30%, the obtained pellets are insufficiently strong. The cost of production of pellets from a mixture of coal slurry and straw is 60 euros/ton, and it is approximately equal to the cost of straw pellets production.

Torrefaction of pellets is carried out at temperature of 270°C during 30 minutes. In such a case, the weight loss of samples is the following: 85% for straw, 50% for coal slurry, and 60% for combined coal slurry and straw pellets.

The combined straw and coal slurry pellets have the following composition before torrefaction: sulfur – 1.2%, oxygen – 17.77%, hydrogen – 3.57%, nitrogen – 1.12%, carbon – 42.74%. After torrefaction these pellets have the following composition: sulfur – 1.27%, oxygen – 10.47%, hydrogen – 3.26%, nitrogen – 1.14%, carbon – 44.26%. The net calorific value of pellets increases by 17% and runs up to 19 MJ/kg by reducing the oxygen content and by increasing the carbon content. The hygroscopicity of pellets after torrefaction decreases from 11% to 7.1%.

As for straw pellets, the hygroscopicity of pellets decreases from 22% to 12% after torrefaction, and the calorific value increases by 18% and runs up to 18.3 MJ/kg.

Previously the authors of the following paper [11] determined the values of air flow rate, fed for the combustion in the same furnace as Figure 1 shows, where a bed, consisting of a mixture of straw pellets and solid combustion products, transits into a state of turbulent fluidization. The fractional composition of the bed is as follows: the fraction of particles smaller than 1 mm is 25%, the fraction of particles with the size from 1 mm to 2 is 27%, the fraction of particles with the size from 2 mm to 5 is 10% and the fraction of particles having a size from 5 to 6 mm is 38%.

We study the pressure drop pulsations in a bed during the combustion of pellets at different flow rates of blasting air. The measurement of the pressure drop in a bed is performed by means of the differential micromanometer "Testo – 525". The digital signal from the micromanometer "Testo – 525" is transmitted every 50 mcs to a personal computer, which allows storing the measured values and subjecting them to a statistical analysis The micromanometer "Testo – 525" has a measuring range from 0 to 3 kPa, the maximum duration of continuous measurements is 60 seconds, the measurement error is 0.0015 kPa.

Figure 2 shows the alteration of the mean square deviation of pressure drop in a bed with increasing the flow rate of blasting air.

As is well known [12][13][14][15], a sharp drop in the values of mean square deviation of pressure drop pulsation in a bed is typical to the transition of a bed into the turbulent fluidization regime. Hence, for our case (combustion of pellets in a bed of solid combustion products) a bed transits into a state of turbulent fluidization at air flow rate, divided by the cross sectional area of the empty furnace, of 2.0 – 2.5 m/s.

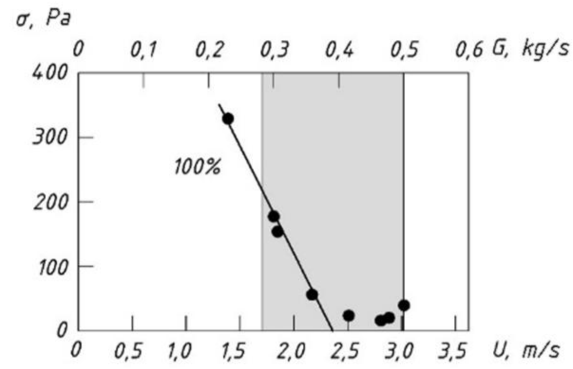

Figure 2. Mean square deviation of pressure drop in a bed vs. increase of flow rate of blasting air.

In the experiments, a bed is in a fixed state most of the time (flow rate of inlet blasting air in the furnace is 1.0 – 1.2 m/s), and then, as a result of increasing the current frequency, energizing the drive of a blow fan, a bed is abruptly transferred into turbulent fluidization (flow rate of blasting air is 2.0 – 2.5 m/s), and then a bed is again transferred into a fixed state. In the course of the experiments, we continuously measure the content of carbon monoxide, nitrogen oxide, carbon dioxide in flue gases, using the gas-analyzer VarioPlus; and we measure the content of sulfur oxides during the combustion of combined coal waste and straw pellets. The gas-analyzer VarioPlus provides the following accuracy: 0.2% for oxygen concentration, 0.02% for CO concentration measure, ± 5 ppm NO concentration measure.

The analysis of changes in the concentrations of the above mentioned substances in flue gases during the experiment allows us to evaluate whether the conditions for efficient combustion in furnace remain, and whether the formation of a significant degree of ash and slag agglomerates, preventing the normal combustion, does not occur. It is known, that the concentration of oxygen and carbon monoxide dramatically increases in flue gases and the concentration of carbon dioxide decreases during the formation of slag agglomerates and the cessation of normal combustion [4].

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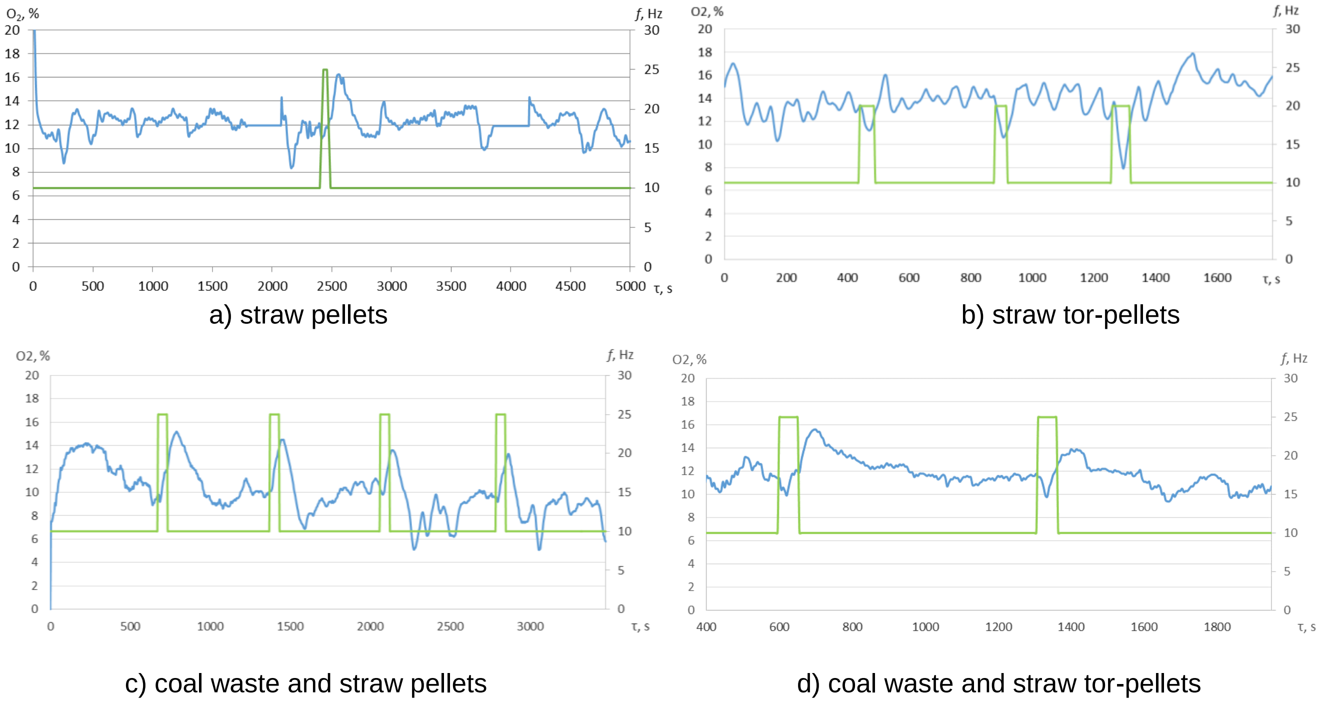


Figure 3. Changes in concentration of oxygen in flue gases from combustion of different pellets.

IV. Results and Discussion

Figure 3 shows the curves of changes in the concentration of oxygen in flue gases during the combustion of straw pellets (a) and straw tor-pellets (b), combined coal waste and straw pellets (c) and combined coal waste and straw tor-pellets (d).

As Figure 3 shows, the combustion of all types of fuel at a periodic transfer of a bed from a fixed state into a turbulent fluidized state is stable, and the combustion process does not cease. The peaks of oxygen concentration are observed only after increasing the flow of air (after increasing the current

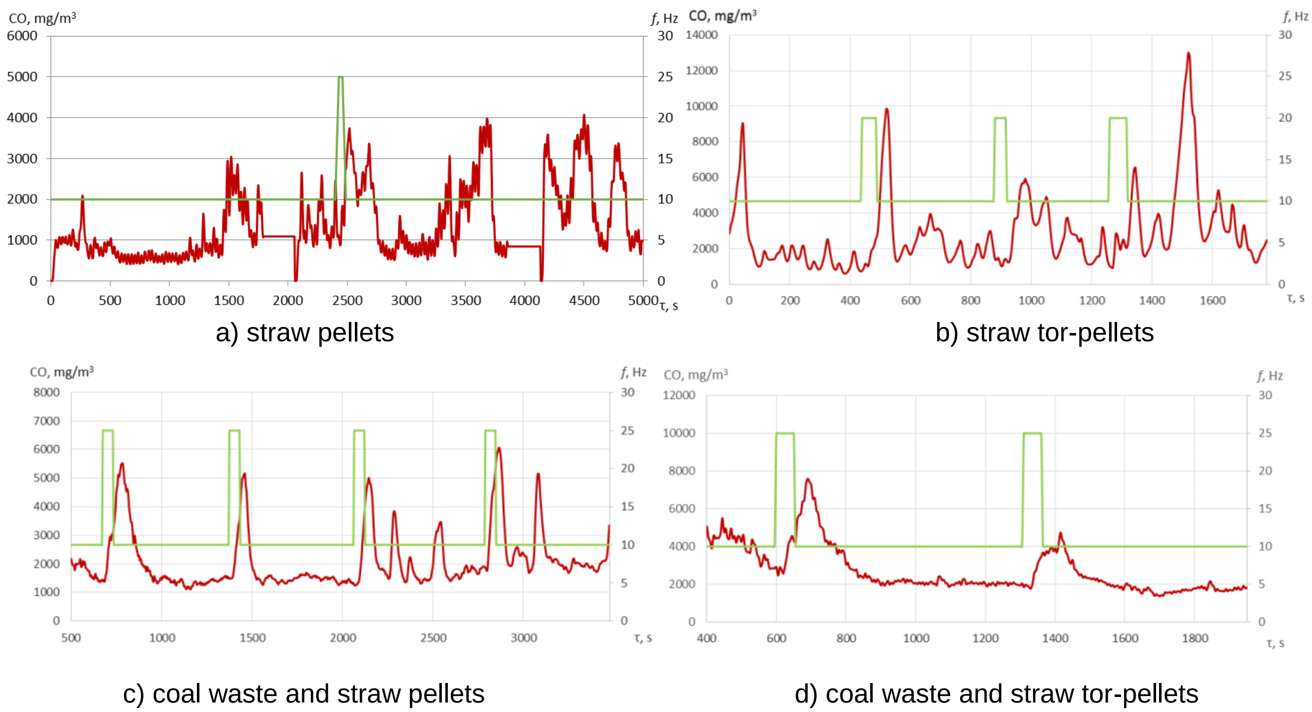
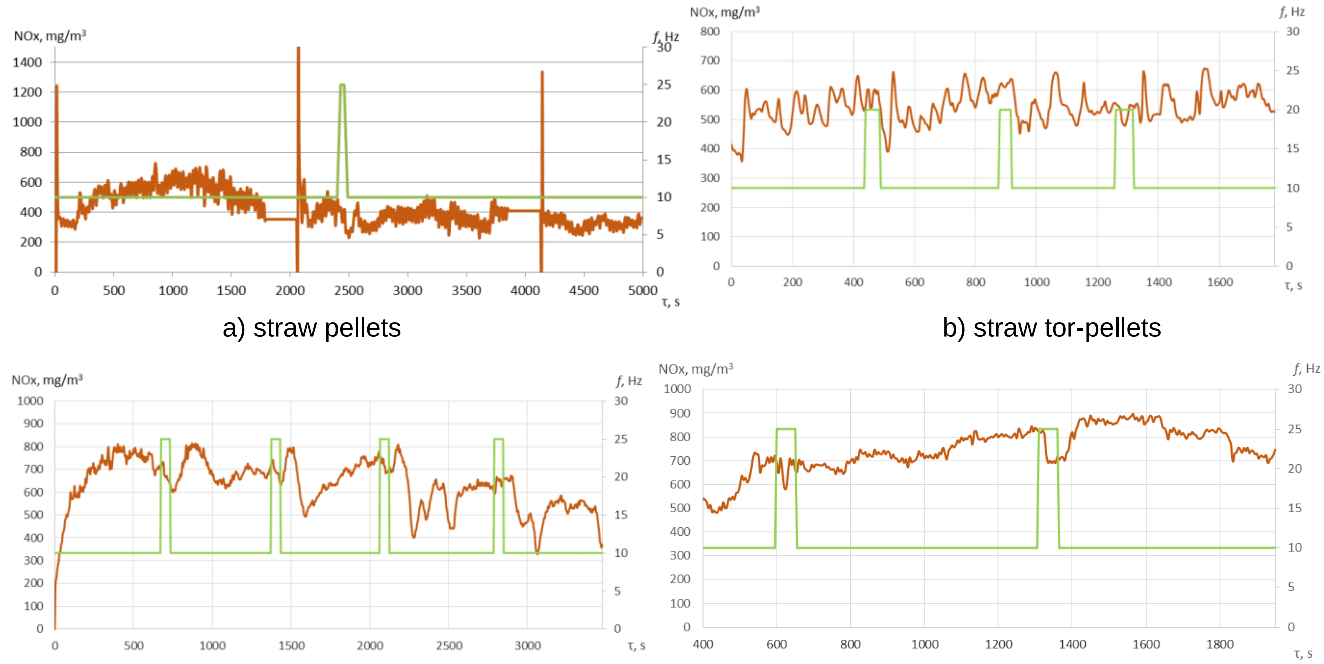


Figure 4. Changes in concentration of carbon monoxide in flue gases from combustion of different pellets.



a) straw pellets b) straw tor-pellets

c) coal waste and straw pellets d) coal waste and straw tor-pellets

Figure 5. Changes in concentration of nitrogen oxides in flue gases from combustion of different pellets (symbols are identical with the previous figures).

frequency, energizing the drive of a blow fan). Therefore, ash and slag agglomerates are not formed in the furnace or their formation does not prevent the normal combustion (this may be in case of formation of brittle porous agglomerates, through which air can freely flow to the fuel).

The lowest oxygen concentration fluctuations occur in flue gases from the combustion of combined coal waste and straw tor-pellets. Such pellets have a minimum yield of volatile matters, and may be combusted in a bed in an arranged way.

We observe the lowest concentration of carbon monoxide in flue gases from the combustion of combined coal waste and straw pellets and especially from the combustion of coal-straw tor-pellets (Figure 4 c, d). This can be explained by a low content of volatile matters in these pellets. During the combustion of these pellets, sharp carbon monoxide emissions are observed only with increasing the flow rate of blasting air at the moment when the bed is transferred into the turbulent fluidization regime.

As for straw pellets, torrefaction of pellets practically does not influence the emissions of carbon monoxide; it evidently can be explained by the slight reduction in the yield of volatile matters (about 13%) as a result of such processing.

As a result of torrefaction the nitrogen content of pellets does not practically change and remains equal to 0.14 – 0.15% for straw pellets and 1.12 – 1.14% for combined coal waste and straw pellets. Therefore, the emission of nitrogen oxides from the combustion of all the types of pellets (Figure 5) is approximately the same (the emission of nitrogen oxides during the combustion of coal-straw pellets is higher).

So, the following question is obvious: why the emission of nitrogen oxides is about the same during the combustion of coal-straw pellets, which contain about 8 times more nitrogen than straw pellets, as during the combustion of straw pellets? In our opinion, there is a partial reduction of nitrogen oxides to molecular nitrogen by carbon of fuel when the flue gases flow passes through it.

V. CONCLUSION

1) The suggested technology of combusting fuel with low melting temperature of ash (combustion in a fixed bed with a periodic transfer of a bed into the turbulent fluidization regime) ensures prolonged steady combustion of fuel with moderate carbon monoxide emissions.

2) Combined coal waste and straw pellets combust more stable with less carbon monoxide emissions than straw pellets.

3) Preliminary torrefaction does not influence the stability of combustion, but allows reducing carbon monoxide emissions from the combustion of combined coal waste and straw pellets.

4) Production of coal-straw pellets can apparently be considered as a new variant of the organization of coal and biomass co-combustion, which in the case of pellets torrefaction allows producing water-resistant fuel suitable for use not only in electric power stations, but also in small boiler-houses.

5) The results of the study can be used for the boilers with any power, equipped with furnaces with a fluidized bed. In this case, the furnace of a real boiler can be considered as consisting of several furnaces with the inner diameter of 300 mm (the furnace with such a diameter is used in this study).

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