

# Upgrading of consumer characteristics of granulated solid fuel from mixture of low-grade coal and biomass

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**Abstract.** Effect of torrefaction on consumer characteristics of fuel pellets made of low-grade and agricultural waste is shown. Data on the volatile content, ash content, calorific value and hygroscopicity for initial pellets and pellets, heat-treated at various temperatures are presented. The experimental study of the combustion process of initial and heat-treated pellets showed that torrefaction of pellets leads to a decreasing of the ignition temperature and an increasing of the efficiency of boiler plant.

## 1. Introduction

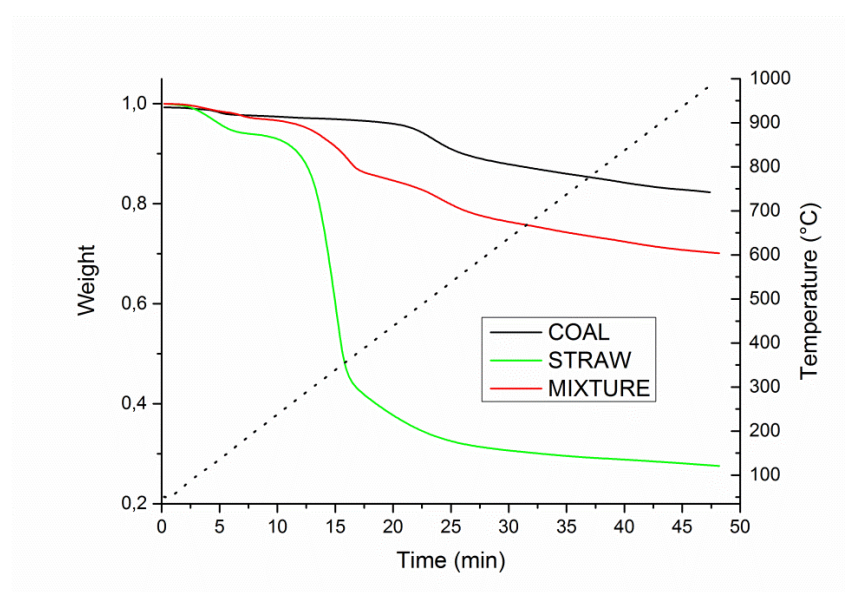
Currently in Russia, there are about 46 coal-preparation plants, which process more than 145 million tons of coal per year. Up to 15% (22 million tons per year) of this treatment capacity is mud coal—washery waste. Solid fraction of mud coal is a finely dispersed mass with the organic content of 25-40%. The composition of mud coal is very unstable: humidity ranges from 18 to 40%, ash content—45 to 75%, the content of particles having size less than 0.1 mm—from 45 up to 95%. Unclaimed mud coal is stored in ponds for years, polluting the environment. However, solid fraction of mud coal is fairly high-calorie fuel, but its usage in energy purposes is difficult, because existing and newly designed boiler installations are intended for burning of coal with an ash content of 20%, moisture content of 18% and dust fraction up to 12%. Low-grade coal (and mud coal especially) using leads to decreasing of boiler efficiency up to 55% or below. One of the ways to improve the combustion efficiency of this type of solid fuels is their co-firing with biomass [1]. Biomass is highly reactive fuel: it is highly flammable and burns stably. The heat, generated by the combustion of biomass, can provide a stable ignition and combustion of low-reactive coal waste. At the same time as fuel, biomass has several drawbacks (low bulk density, high humidity and relatively low combustion value), which complicate its utilization for energy purposes. Development of methods for co-firing of biomass and low-grade coal will compensate for disadvantages of each type of fuels and will promote solving the problem of their effective utilization.

Nowadays, one of the variants of co-firing of biomass and low-grade coal is producing of fuel pellets from these materials [2]. The paper discusses the possibilities of improvements of consumer characteristics of these pellets by means of their thermal treatment carried out in oxygen-free gas atmosphere, the so-called torrefaction (or low-temperature pyrolysis) [3–5].



**Table 1.** Contents of the sulfur, nitrogen, carbon, hydrogen and oxygen in pellets (on active state), wt%.

Element	Unit	Initial pellets	Torrefaction temperature, °C		
			230	250	270
Sulfur	%	1.20	1.19	1.18	1.27
Nitrogen	%	1.12	1.11	1.15	1.14
Carbon	%	42.74	42.91	44.06	44.26
Hydrogen	%	3.57	3.37	3.58	3.26
Oxygen	%	17.77	17.52	14.63	10.47

**Figure 1.** Temperature change during heating in nitrogen(dashed line) and TG curves for the samples of different raw materials (solid lines).

## 2. Experimental study

Laboratory investigations were carried out using thermal analyzer SDT Q600, which allowed determining the parameters of the test materials such as mass loss during the heat treatment associated with devolatilization, moisture content, ash content, and reactivity with respect to oxygen. The chemical composition of the initial pellets and pellets, heat-treated at various temperatures was explored in addition. As investigated materials there were used pellets containing 30% (by weight) of straw and 70% of low-grade coal (hereinafter referred to as straw-coal pellets). The elemental composition of the organic component of such pellets is given in table 1.

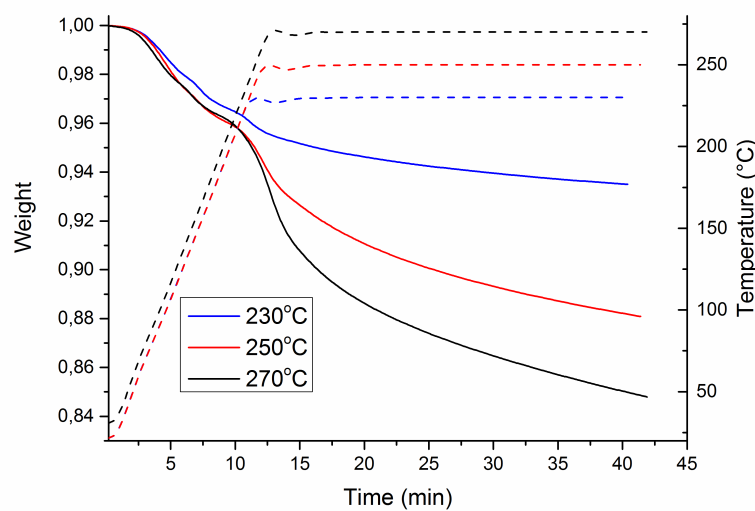
### 2.1. Heating in an inert gas atmosphere (pyrolysis)

Figure 1 shows the thermogravimetric (TG) curves characterizing the relative mass change of the samples from straw, coal and their mixture in the above proportions in the heating process. Heating was conducted in inert gas atmosphere (nitrogen) with the rate 20°C/min.

These TG curves shows that the straw has higher moisture content and is characterized by

**Table 2.** Characteristics of raw materials: mass fraction of volatile products (on active state) and ash content (on a dry basis).

Sample	Mass fraction of volatile products, %	Ash content, %
Mud coal	17.73	49.2
Straw	72.48	9.42
Mixture 30% straw–70% mud coal	29.92	41.57



**Figure 2.** Temperature profiles (dashed lines) and TG curves (solid lines) for straw-coal pellets during the torrefaction process.

substantially higher content of volatile products compared to coal (see table 2). From the TG curve for coal, shown in figure 1, it follows that when heating from 150 to 350°C, mass losses are not more than 1%. Thus, during torrefaction in which heating was carried to a temperature not higher than 300°C, the mass losses of straw-coal pellets, caused only straw thermal degradation, which is a part of the pellets.

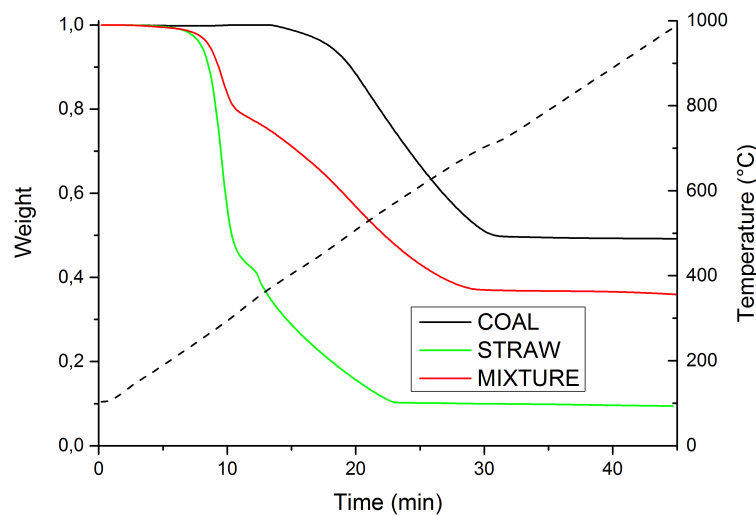
During laboratory investigations, the torrefaction process was modeled by using the thermal analyzer and consisted in heating of the raw material in an inert gas atmosphere (nitrogen) to a torrefaction temperature and subsequent holding at this temperature for definite time (see temperature profiles in figure 2).

Figure 2 shows TG curves characterizing the relative mass losses of straw-coal pellets during torrefaction process at different temperatures. From presented curves it follows that after 30 minutes keeping the samples at a fixed temperature, rate of mass losses is noticeably reduced. This fact was base for choose the timing of torrefaction process in subsequent experiments. Data on the yield of volatile products during torrefaction are shown in table 3.

The data shows, that increasing of the torrefaction temperature leads to a marked increase of mass losses due to devolatilization. Comparison of the data in tables 2 and 3 shows that in pellets, torrefied at maximum temperature of 270°C, and holding time of 30 minutes, the volatile content is halved.

**Table 3.** Effect of torrefaction temperature on the characteristics of straw-coal pellets: mass yield of volatile products (on active state) and ash content (on a dry basis).

Parameter	Torrefaction temperature, °C		
	230	250	270
Mass fraction of volatile products, %	6.5	11.91	15.21
Ash content, %	33.94	35.35	39.62

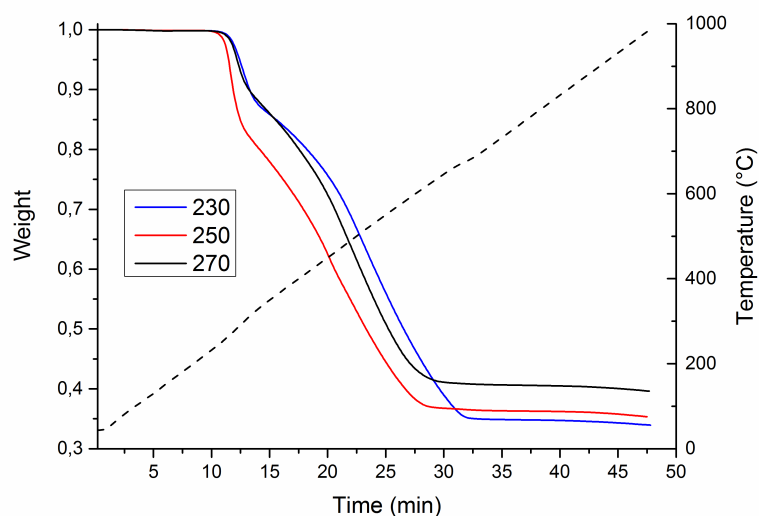


**Figure 3.** Temperature change (dashed line) and TG curves for the samples of different raw materials (solid lines) in the heating process in the air.

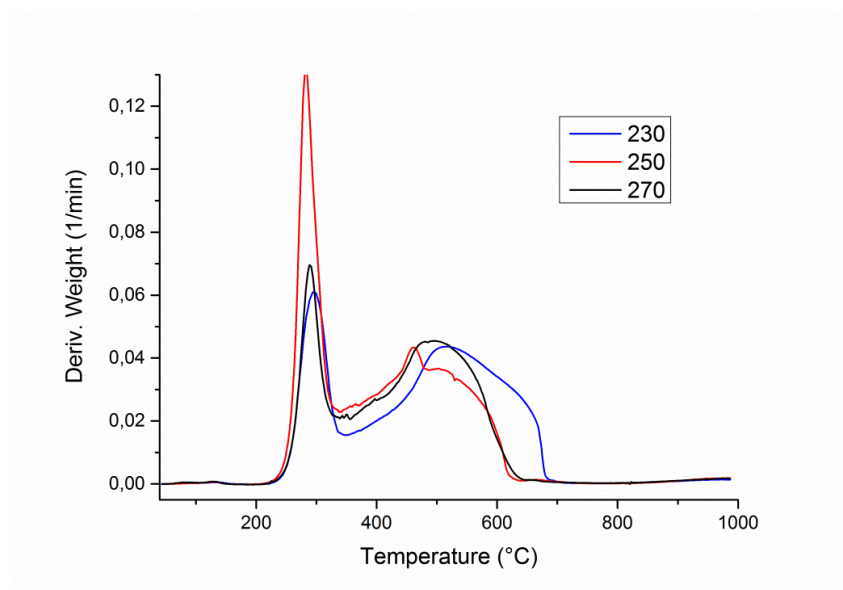
## 2.2. Heating in oxygen

Thermogravimetric and differential thermogravimetric (DTG) dependences, measured in the air, allowed to obtain information about the ash content of the test samples and to compare their reactivity in an oxidizing environment. Data on the ash content of different samples, studied in this work and derived from the TG curves shown in figures 3 and 4, are summarized in tables 2 and 3. From the data obtained it follows that the ash content of the coal is significantly more than that of straw and is about 50%. Thus, the straw additive reduces the ash content of pellets made of a straw-coal mixture. At the same time, torrefaction leads to increasing of the ash content of pellets due to thermal degradation of the organic part of the straw and yield of volatile products of torrefaction (see table 3).

As follows from a comparison of TG curves measured in the air for torrefied pellets at different temperatures (see figure 4), the torrefaction temperature increasing non-monotonically effects on the beginning and the rate of oxidation processes. Most clearly this difference is manifested in the DTG curves, presented in figure 5, from which it follows that for pellets, torrefied at the temperature of 250°C, oxidative process, associated with devolatilization, begins a little earlier and proceeds much more rapidly than for pellets, heat-treated at two other temperatures. This is evidenced by the first peak on the DTG curves in figure 5. Even more significantly, the influence of torrefaction temperature on the shift of the oxidation process beginning to low temperatures



**Figure 4.** Temperature change (dashed line) and TG curves (solid lines) for torrefied straw-coal pellets in the heating process in the air.



**Figure 5.** DTG curves for torrefied straw-coal pellets in the heating process in the air.

appears during the oxidation of the solid residue (the second peak on the DTG curves). This solid residue consists of coal and a solid residue formed after devolatilization of straw.

### 2.3. Combustion heat and the limit of hygroscopicity

During torrefaction a destruction of the pellet organic component and devolatilization occur. As a result, chemical composition of the processed raw material is changed. The results of ultimate analysis of initial pellets and torrefied at temperatures of 230, 250 and 270°C pellets are shown in table 1. From the presented data, it follows that torrefaction leads to an increase

**Table 4.** Heating value and limit moisture content (LMC) of initial and torrefied pellets.

Parameter	Unit	Initial pellet	Torrefaction temperature, °C		
			230	250	270
LHV on a dry ash-free basis	MJ/kg	25.0	24.9	27.0	29.2
LMC	%	11	11	9	7.1

in carbon content, slight decrease in hydrogen content and marked decrease in oxygen content. Naturally, changing of pellets chemical composition effects on their heating value. The last can be calculated on the base of results of ultimate analysis using Mendeleev formula, according to which the lower heating value (LHV)  $Q_L$  of solid fuel is

$$Q_{LHV} = 33.9[C] + 103[H] - 10.9([O] - [S]),$$

where [C], [H], [O], [S]—mass fraction of carbon, hydrogen, oxygen, and sulfur in solid fuel. LHV calculated for the initial pellets and torrefied at different temperatures pellet are shown in table 4. As can be seen from the presented data the LHV (on a dry ash-free basis) increases with increasing of the torrefaction temperature. For pellets, torrefied at 270°C, LHV is 17% higher than the similar parameter for the initial pellets.

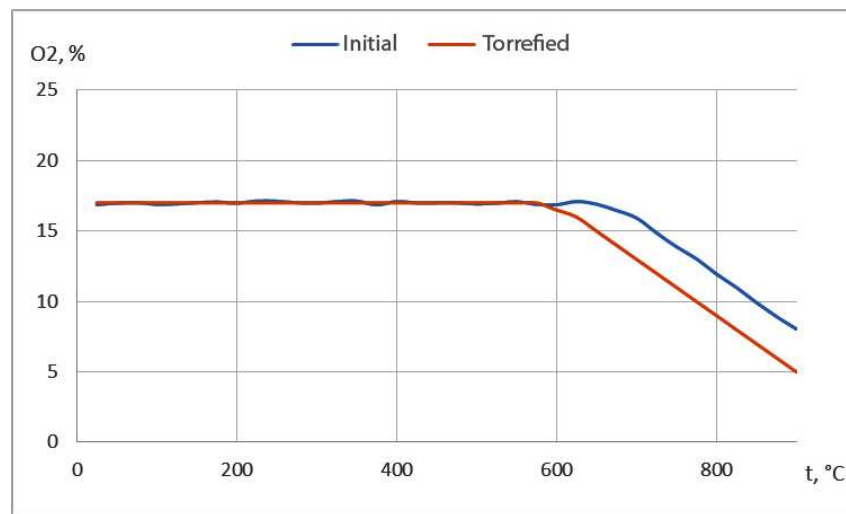
Humidity significantly effects on the heating value of solid fuel. Humidity of solid fuel depends on the temperature and relative environment humidity. The limit value of the moisture absorbed by the material from the ambient air, expressed in weight percentage relative to the weight of dry material, called the limit moisture content (LMC). The experimental LMC is determined at a relative humidity of air close to 100%. Torrefaction significantly effects on the hygroscopicity of various kinds of biomass, including the straw. Torrefaction leads to the appearance of hydrophobic properties, thereby reducing the limit hygroscopicity. In this paper LMC of the initial pellets and torrefied pellets was determined from changing of their weight after being in the air with almost 100% humidity at a temperature 22°C. Holding time under these conditions was equal to 48 hours. The measurement results are shown in table 4. Based on these data, it follows that LMC of torrefied at 270°C pellets reduced by more than 1.5 times.

#### 2.4. Ignition temperature and boiler efficiency

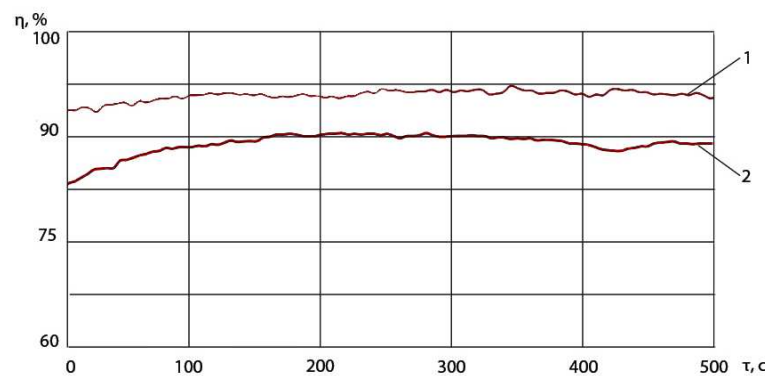
Study of the effect of torrefaction process on ignition temperature of straw-coal pellets and boiler efficiency when burning these pellets were carried out on a boiler designed to burn granulated fuel in a fluidized bed [6]. Rated heat power of the boiler was 100 kW. In the experiments straw-coal pellets, torrefied on the laboratory stand at 250°C, were used. To determine the ignition temperature the portion of 300 g pellets was placed into the boiler furnace. Pellets were placed on a layer of glowing coal, formed at combustion of the previous portion of pellets. After enable of blow fan via the gas analyzer VarioPlus the concentration of oxygen in the flue gases was measured continuously. At the same time, measurement of the temperature in the layer of pellets was carried out. A sharp drop of the oxygen concentration in the flue gas was interpreted as the beginning of the pellets ignition. Figure 6 shows that torrefaction of straw-coal pellets reduces the temperature of their ignition to 100°C.

Based on data of the analyzer VarioPlus the efficiency of the boiler was calculated by:

$$\text{Eff} = 100\% - (T_g - T_a) \times \left( \frac{A}{O_{2max} - O_2} + B \right), \quad (1)$$



**Figure 6.** Changes of the oxygen content in the flue gas during the combustion of initial and torrefied straw-coal pellets.



**Figure 7.** Boiler efficiency during combustion of initial (2) and torrefied (1) straw-coal pellets.

where  $T_g$ —flue gas temperature,  $T_a$ —air temperature,  $A$  and  $B$  coefficients of fuel,  $O_{2max}$ —oxygen content in the air (20.9%),  $O_2$ —oxygen content in the exhaust gases. Figure 7 shows the time dependences of the efficiency of the boiler during combustion of the initial and torrefied straw-coal pellets. From the dependences it is follows that usage of torrefied pellets leads to increase of boiler efficiency by about 5%.

### 3. Conclusion

As a result of experimental studies data characterizing volatile content, ash content, heating value, limit moisture content and ignition temperature of straw-coal pellets and similar pellets, torrefied at different temperatures, were obtained. It is shown that the thermal processing of straw-coal pellets improves consumer properties of such pellets and increases the efficiency of the boiler, designed for burning granular solid fuel. Torrefied straw-coal pellets can be recommended for using as a solid fuel for facilities of distributed energy that will favour the rational usage of rational using of natural fossil resources, utilization of agricultural waste and improvement of environmental conditions.

## Acknowledgments

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