Torrefaction is a promising technology of poultry (chicken) litter conversion into a solid fuel

Ekaterina Artiukhina, Panagiotis Grammelis, Vladimir Kosov, Vladimir Sinelschikov, Dmitry Klimov

***Abstract*—**Effect of torrefaction on thermochemical properties of chicken litter pellets was investigated. Untreated pellets were subjected to torrefaction at temperatures T_t= 230, 250 and 270 °C during 1 hour in the nitrogen or oxidizing atmospheric conditions. Thethermogravimetric and differential scanning calorimetry analyses of chicken litter pellets undergoing torrefaction at different temperatures in the nitrogen or oxidizing atmospheric conditions were performed. The original and torrefied chicken litter pellets were characterized by proximate and ultimate analyses. As a result, the data on the influence of torrefaction on volatile matter, ash, fixed carbon content and combustion value of the chicken litter pellets were obtained. In addition, hygroscopic properties of initial and torrefied material were measured. It was observed that pellets torrefied at temperature of 270 °C remained stable and hydrophobic after 140 hours presence in a desiccator. This simplifies the storage and transportation of torrefied pellets and increase its shelf life. The aforementioned characteristics of chicken litter pellets are compared with similar characteristics of the wood pellets. Torrefaction of chicken litter pellets is considered as a promising technology for its conversion into a solid fuel. It was shown that the torrefied chicken litter pellets can be used as a solid fuel for autonomous heating systems.

***Keywords*—**Chicken litter pellets, TGA, torrefaction, ultimate and proximate analyses

I. INTRODUCTION

RISISNG demand for poultry products, which has consistently increased at about three times the rate of population growth over each of the past five decades [1], [2], leads to the rapid growth of this industry, causing excessive manure production.

Poultry litter is a mixture of poultry manure, feathers, spilled feed and bedding materials, typically consisting of wood shavings, sawdust, wheat straw, rice or peanut hulls [3], [4] and other low-cost organic materials. It represents a significant part of agricultural wastes generated yearly. Each bird produces around 5 tons of manure per year [5]. Chicken litter contributes to soil, water and air contamination by emitting and releasing ammonia, greenhouse gases, hazardous pathogenic bacteria. Chicken manure typically has the following composition: water – 50-70 %, organic matter – about 25%, nitrogen – 0.7-1.9 %, phosphoric acid – 1.5-2.0 %, potassium oxide – 0.8-1.0 %, lime – 2.4 %, magnesium – 0.8 %, sulfur – 0.5%. It also contains valuable microelements such as copper, manganese, zinc, cobalt, boron, as well as active ingredients. Content of nitrogen and phosphorus in chicken manure is 4 - 5 times more than in cattle manure [6]. The upper layer of the soil, on which litter is stored, contains about 4950 kg/ha of mineral nitrogen (including 2500 kg/ha of the nitrate), which is in 17 times higher in comparison with uncontaminated soil.

Application of agricultural waste for energy purposes would solve not only the problem of its utilization, but also would significantly increase the power availability of agricultural sector by domestic resources. In addition, utilization of agricultural waste contribute to solving a number of environmental concerns associated with agricultural production. Last circumstance is primarily concerned with waste of livestock and poultry breeding.

There are few ways of chicken litter utilization: e.g. to use it as fertilizer and as a feedstock for fuel production.

Poultry litter is primarily applied to land because it is an excellent source of organic nutrients for crop production. Stricter regulations for land application of poultry litter due to environmental and increasing energy demand have lead to the research on the potential use of poultry litter for energy applications.

Biogas and bio-fertilizer are two products of the chicken litter processing technology, based on anaerobic fermentation. Such kind of technologies are widespread. It is possible to produce up to 6 m^3 biogas from 1 m^3 of raw biomass applying specific process parameters such as optimal fermentation temperature, continuous mixing of raw materials, and well-timed loading and unloading of the raw material in a reactor. Biogas typically consists of methane (60-70%), carbon dioxide (30-40%), hydrogen sulfide (0-3%) and hydrogen impurities, nitrogen oxides and ammonia. Calorific value of biogas

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reaches 25 MJ/m^3 that is equivalent to combustion of 0.6 liters of gasoline, 0.85 liters of spirit, 1.7 kg of wood or use 1.4 kWh of electricity.

Apart from the energy generation, the bioconversion process allows to solve another problem. Fermented chicken litter, when used in agriculture as fertilizer, helps increasing crop yield by 10-15% compared with the unfermented chicken litter. This is explained by the fact that during the anaerobic treatment, the mineralization and nitrogen fixation occur [6].

Chicken litter can also be used as a solid fuel. Production of solid fuel from chicken litter requires preliminary pelletization. Chicken litter pellets can be used as an intermediate product for further processing, or directly as a solid fuel. In the first case gasification of chicken litter pellets can be proposed for the production of gaseous fuel. This technology allows to convert chicken litter pellets into gaseous fuel with combustion value about 5000 kJ/m^3 [7]. Composition of gaseous fuel, received by this technology is shown in Table 1.

The main drawback of this technology is the high content of nitrogen and carbon dioxide in the produced gas mixture that leads to decrease of it combustion value.

As a solid fuel chicken litter pellets can be used for burning in the pellet boilers. It is also possible to use them for co-firing with straw, wood chips or coal.

Table 1. Composition of gaseous fuel produced from chicken litter pellets

Gas component	Volume content, %
CO	15-22
H_2	16-22
CH_4	1.0-2.5
CO_2	11-15
N_2	45-48

The main disadvantage of chicken litter pellets is its low heating value. So we encounter the need to raise the combustion heat of chicken litter pellets. One way of solving this problem is thermal treatment of pellets in neutral gas environment. This process is well known as a torrefaction and is widely used for processing different types of lignocellulosic biomass into solid fuel [8], [9]. During torrefaction not only the moisture removal from an initial raw material, but also partial thermal decomposition of an organic constituent of biomass takes place [10]. As a result a solid hydrophobic product is formed. In addition its specific combustion value surpasses a similar value for raw material [9].

The present paper is devoted to an investigation of influence of the torrefaction conditions on specific combustion value, hygroscopicity properties and chemical composition of chicken litter pellets.

II. Experimantal Conditions

The pellets were heated in the inert atmosphere conditions at different torrefaction temperatures Tt = 230, 250 and 270 °C with the rate of 10 °C/min and residence time of 60 min. Fig.1 illustrates the temperature profiles during torrefaction.

Due to partial devolatilization the mass loss of pellets takes place during torrefaction. The thermogravimetric analysis (TGA) of chicken litter pellets was carried out to measure the quantitative characteristics associated with mass loss of raw materials during the heating. For this purpose, the thermogravimetric analyzer SDTQ 600 was used. The SDTQ 600 was capable also to perform the differential scanning calorimetry (DSC), and it was used for investigations of the influence of torrefaction on the combustion value of granulated biomass fuel.

The chicken litter pellets were characterized after and prior to torrefaction process by ultimate and proximate analyses. All results were presented on a dry basis. Lease submit your manuscript electronically for review as e-mail attachments.

III. Results and Discussion

A. Heating in Neutral Gas Environment (Nitrogen)

As mentioned above, the release of volatile matter, caused by thermal decomposition of the organic constituents of raw material, takes place in the torrefaction process. The thermogravimetric (TG) curves describing mass losses of samples during torrefaction at different temperatures are shown on Fig. 1.

The TG curve demonstrating the mass loss due to pyrolysis at 800 °C is also presented on the aforementioned figure. After the sample temperature reaches the value of Tt the rate of mass losses decreases because of reduction of sample mass. It can

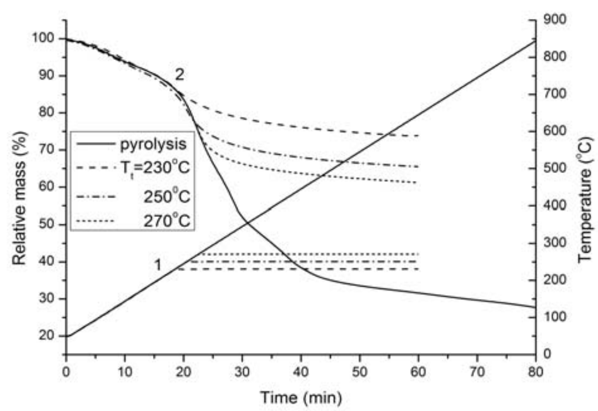

Fig.1. Change of temperature (1) and relative mass (2) of chicken litter pellets during pyrolysis and torrefaction at different temperatures Tt.

be seen from the Fig. 1, mass losses account for 27, 34 and 37 % at torrefaction temperatures 230, 250 and 270 °C, respectively. From a comparison of curves, shown in Fig. 1, follows that these losses are noticeably less than total content of volatile matter in the initial sample.

Since wood sawdust is a part of chicken litter it is interesting to compare the yield of volatile matter from both of them. Volatile matter content in the chicken litter pellets is 73.5 % (in terms of the dry basis). A similar parameter for sawdust is 82 %. Fig. 2 presents data on the rate of mass loss as function of temperature, so-called differential thermo gravimetric (DTG) curves for wood sawdust and chicken litter pellets.

The DTG curve, corresponding to wood sawdust, has three representative knees (are marked by arrows) associated with

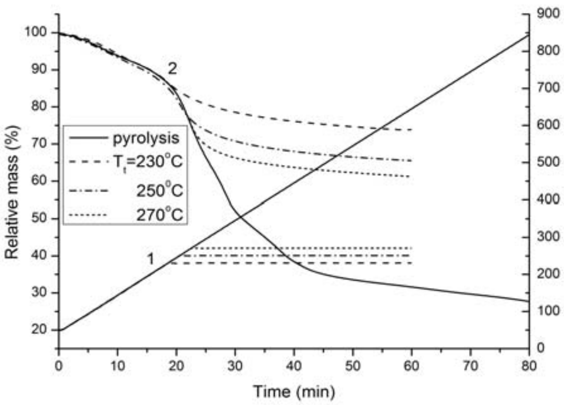

Fig.2. Rate of mass loss of wood sawdust and chicken litter pellets during heating in nitrogen at the rate of 10 °C/min.

thermal decomposition of hemicellulose (1), cellulose (2) and lignin (3). On the DTG curve, corresponding to the chicken litter pellets, the beginning of devolatilization is shifted to

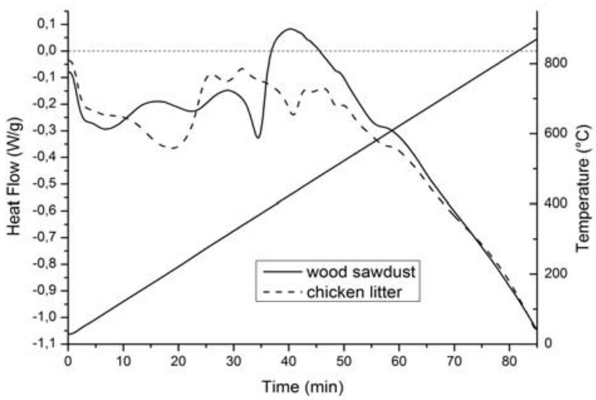

Fig.3. DSC curve of wood sawdust and chicken litter pellets in nitrogen at the heating rate of 10 °C/min.

lower temperatures. The representative knees, associated with thermal decomposition of hemicellulose, cellulose and lignin, are persisted, although their amplitudes are varied considerably.

Noticeable qualitative and quantitative differences are observed for the DSC curves that describe the heat flow required to maintain given heating rate of wood sawdust and chicken litter pellets (see Fig. 3). The first endothermic effect for chicken litter pellets is observed in the temperature range 120 – 270 °C. For sawdust the maximum of the first endothermic effect, associated with the decomposition of cellulose (see Fig. 2), falls on temperature of about 360 °C. In the temperature range 390 – 480 °C exothermic effect, caused by decomposition of lignin, results in change of sign of heat flow in the case of sawdust. At temperatures above 650 °C, DSC curves for wood sawdust and chicken litter pellets coincide practically.

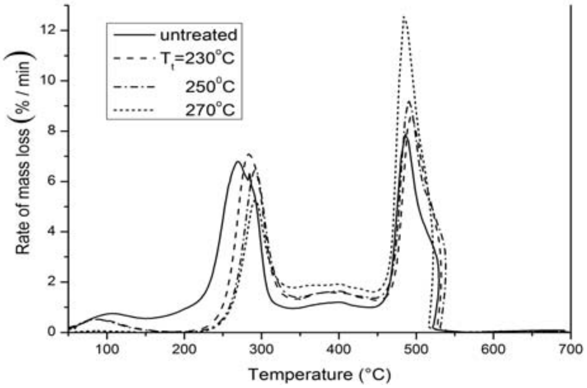

Fig.4. Rate of mass loss of untreated and torrefied chicken litter pellets during heating in air at the rate of 10 °C/min.

B. Heating in Oxidizing Gas Environment (Air)

DTG curves, measured in oxidizing gas environment and in particular in air, differ considerably from similar curves, measured in a neutral gas environment. This difference is primarily due to the fact that heterogeneous oxidation reactions occur in air. In Fig. 4 DTG curves measured in air for initial and torrefied chicken litter pellets are shown.

On the DTG curve measured in nitrogen, the basic mass loss is observed only in the temperature range 200 - 450 °C and is connected with devolatilization (see Fig. 2).

On the DTG curve, measured in air, in the temperature range 450 - 530 °C the second peak of mass loss is observed that is associated with the oxidation of char residue. Shift of first maximum towards higher temperatures for the DTG curves corresponding to the samples, processed at higher torrefaction temperatures (see Fig. 4), is explained by decreasing content of least thermostable organic component,

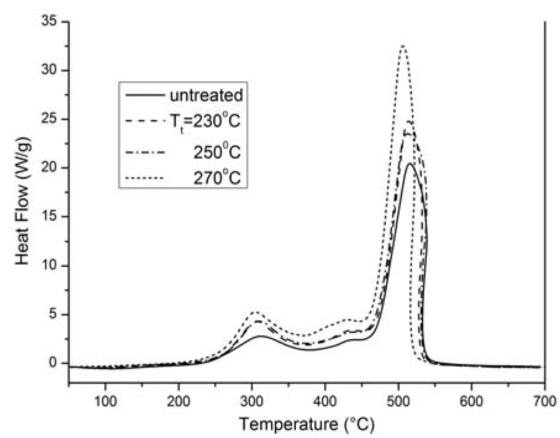

Fig.5. DSC curve of untreated and torrefied chicken litter pellets in air at the heating rate of 10 °C/min.

namely hemicellulose, in their composition.

DTG curves, shown in Fig. 4, correlate well with the DSC curves describing the heat generation caused by oxidation reactions proceeding during heating pellets in the air (see Fig. 5).

The first maximum in the DTG curves shown in Fig. 5 is associated with the oxidation of the volatile matter, the second – with oxidation of the char residue. As it can be seen from

Fig. 5, an increase of torrefaction temperature leads to an increase in the amplitude of both peaks. This behavior is explained by the fact that with increasing Tt the combustion value of volatile matter (the first peak) and the relative fraction of the char residue (the second peak) are increasing also. As a result, the combustion value of torrefied pellets exceeds the combustion value of initial pellets and increases with increasing torrefaction temperature.

C. Thermochemical Characteristics of Chicken Litter Pellets

The chicken litter pellets were characterized after and prior to torrefaction process by ultimate and proximate analyses. All results are presented on a dry basis. Ultimate analysis results of untreated and torrefied chicken litter pellets are given in Table 2.

The ultimate analyses of original and torrefied pellets demonstrate changes in elemental composition of biomass due to thermal treatment. The carbon content is increased with increasing degree of torrefaction, while the oxygen and hydrogen contents are decreased. The carbon content of pellets subjected to torrefaction at 230, 250 and 270 °C increased by 9.8, 18.1 and 23 % correspondingly. The decrease of oxygen content by 16.3, 27.6 and 35.3 %, and hydrogen content by 12.2, 15.9 and 20.4 % compared to untreated biomass was observed at torrefaction temperatures 230, 250 and 270 °C respectively.

Table 2. Ultimate analysis of untreated and torrefied chicken litter pellets on dry ash-free basis.

Characteristics	Untreated pellets	Pellets torrefied at		
		230 °C	*250 °C*	*270 °C*
Carbon, %	48.03	52.74	56.72	59.16
Hydrogen, %	6.66	5.85	5.6	5.3
Nitrogen, %	5.93	8.3	9.02	9.84
Oxygen, %	38.72	32.42	28.04	25.04
Sulphur, %	0.66	0.69	0.62	0.66

Torrefaction decreases the atomic O/C and H/C ratios of chicken litter pellets as illustrated by Fig. 6.

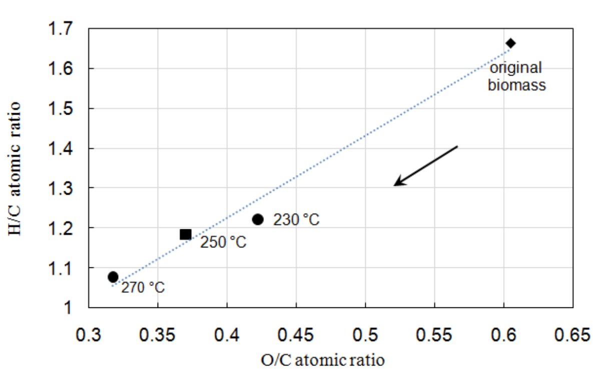

Fig.6. The atomic H/C ratio versus atomic O/C ratio in pellets, torrefied at different temperatures.

Fig. 6 demonstrate that the highest value of atomic O/C ratio – 0.6, corresponds to untreated biomass, while the lowest atomic O/C ratio – 0.32 corresponds to the biomass torrefied at a temperature of 270 °C. The same trend is observed for the atomic H/C ratio. The atomic H/C ratio decreased from 1.66 for original biomass to 1.08 for biomass subjected to torrefaction at 270 °C.

It can be seen that with the increase of torrefaction severity the pellets composition is shifted from original pellets closer to coal in terms of relative concentrations of oxygen, hydrogen and carbon, following the pathway shown by arrow on Fig. 7.

The result of this is an increase in energy content.

Table 3 presents proximate analysis results of the original and torrefied chicken litter pellets at different temperatures. It follows from the presented data that increase of torrefaction temperature results in appreciable increase of specific combustion value.

Table 3. Proximate analysis of untreated and torrified chicken litter pellets on dry ash-free basis

Characteristics	Untreated pellets	Pellets torrefied at		
		230 °C	*250 °C*	*270 °C*
Relative combustion value	1	1.32	1.41	1.65
Ash content (dry basis), %	13.7	16.6	18.6	20.8
Volatile matter (dry basis), %	73.5	63	58.7	56.6
Fixed carbon, %	12.8	20.4	22.7	22.6

Fig. 7 illustrates changes in volatile matter, fixed carbon and ash content of chicken litter pellets exposed to torrefaction under different temperatures.

The proximate analysis demonstrates significant decrease of volatile matter content and increase of fixed carbon content with increase of torrefaction temperature. It can be observed that volatile matter content decreased by 14.3, 20.1 and 23 % for chicken litter pellets subjected to torrefaction at temperatures 230, 250 and 270 °C, respectively, compared to untreated biomass. As volatiles causing an equipment slagging,

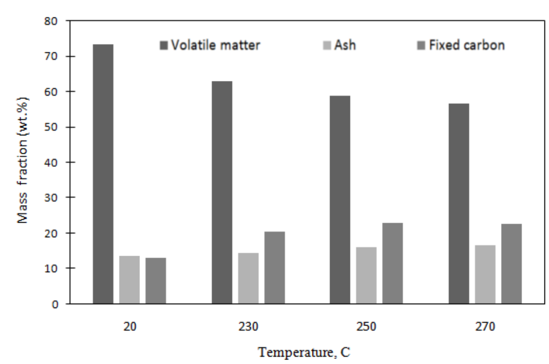

Fig.7. Changes in volatile matter, fixed carbon and ash content of pellets undergoing torrefaction at T = 230, 250 and 270 °C compared to untreated ones.

corrosion, fouling [11]–[14] are partly removed from the torrefied pellets, they become more suitable for combustion and gasification. At the same time fixed carbon content of chicken pellets exposed to torrefaction at temperatures 230, 250 and 270 °C increased by 20.4, 22.7 and 22.6 % respectively comparing with untreated pellets. Unfavorably, the ash content of chicken litter pellets, that is several times greater than in peat and in wood pellets, increased by 21.2, 35.8 and 51.8 % for pellets subjected to torrefaction at 230, 250 and 270 °C correspondingly.

Another important characteristic of any solid fuel is its hydrophobicity. To determine the effect of torrefaction on it the corresponding measurements were carried out. During measurement, a test sample was placed into a desiccator, in which 100 % humidity at a temperature of 26 °C was maintained. Periodically measurements of test sample mass were carried out. Results of experiments are presented in Fig. 8.

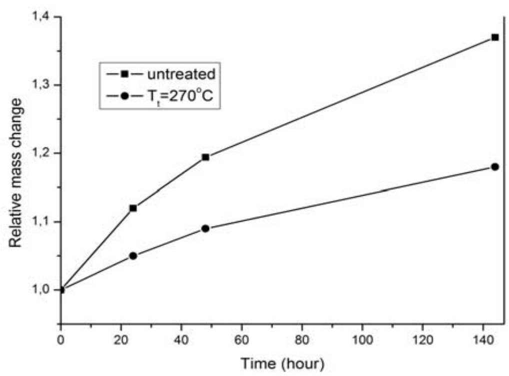

Fig.8. Relative mass change of initial and torrefied (at temperature 270 °C) pellets as a result of water vapor uptake.

The presented data show that the initial sample absorbs water vapor from the air considerably faster than the sample torrefied at temperature of 270 °C. It is necessary to note that untreated chicken litter pellets swelled and fell apart after 140 hours presence in a desiccator. At the same time, pellets torrefied at temperature of 270 °C remained stable and hydrophobic, conserving their shape. This simplifies the storage and transportation of torrefied pellets and increases its shelf life.

From these data one can see that the torrefaction allows to improve essentially the hydrophobic properties of granulated biomass fuel. The limit moisture content of pellets torrefied at Tt = 270 °C is practically half in comparison with untreated pellets.

IV. Conclusions

The influence of torrefaction on the properties of chicken litter pellets processed under inert or oxidizing atmospheric conditions at temperatures 230, 250 and 270 °C was examined. The thermogravimetric and differential scanning calorimetry were performed and the original and torrefied chicken litter pellets were characterized by proximate and ultimate analyses as well. The pellets composition is shifted from original pellets closer to coal in terms of relative concentrations of oxygen, hydrogen and carbon with an increase of torrefaction temperature. It was shown that torrefaction of chicken litter pellets allows to improve its consumer properties, namely, to increase the energy content and to obtain hydrophobic properties. It was observed that pellets torrefied at temperature of 270 °C remained stable and hydrophobic after 140 hours presence in a desiccator. The torrefaction of chicken litter pellets is considered as a promising technology of its conversion into a solid fuel that can be used for autonomous heating systems conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

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