Effect of temperature process at chicken litter
torrefaction on properties of products obtained

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Abstract. In connection with the situation with the environment and energy in the world, it
is necessary to study the possibility of using biological waste as an energy resource. The method
of thermochemical treatment of organic waste is investigated in this paper. The chicken litter
in the form of pellets is used as a raw material. The experimental studies of the torrefaction
temperature influence on the thermotechnical characteristics of chicken litter and the yield of
products were conducted in lab-scale system. The five temperature regimes of torrefaction (220,
240, 260, 280, and 300 °C) with holding time determined with thermogravimetric analysis are
studied. The thermotechnical characteristics of the initial and torrefied material as elemental
composition, the lower calorific value, hygroscopicity limit, and bulk density are determined.
The properties of non-condensable gases (specific volume yield, chemical composition, and
calorific value) are investigated. The material balance for each of the temperature regimes
is calculated. The conclusion about the optimum temperature regime for torrefaction of chicken
litter based on the results of experimental studies is made.

1. Introduction
Chicken manures are formed on poultry farms as a by-product along with waste from slaughter,
incubation, processing of poultry, feathers and down. Chicken manure can be obtained in two
forms, depending on the way the poultry is kept: floor and cellular. The flooring is carried out
on a litter, where wood dust, peat, sunflower husks, straw and other materials can be used as
litter material [1]. With this method of maintenance not pure chicken manure, but the litter
mass which has a moisture content of not more than 30 wt % is utilized [2,3]. With the cellular
method of maintenance from the decks located under the cells clean chicken manure is removed
with the help of scrapers [4]. When chicken manure is removed, it is often diluted with water in
order to avoid sticking of the mass to the working parts of the scraper plants. As a consequence,
the manure has moisture content up to 85–90 wt % [4]. Currently, the main way to utilize
chicken manure and litter mass from the poultry farms is to export to fields where they are used
as a fertilizer because of the high content of nitrogen, phosphorus and potassium [4].

The main problems of storing chicken manure, in addition to its large amount, are the loss
of nitrogen, phosphorus and potassium, as well as the development of pathogenic microflora.
According to the World Health Organization, chicken manure is a factor of the more than 100
pathogens of infectious and invasive disease transmission, and it can be a favorable environment
for the development and long-term survival of pathogenic microflora, contains an increased
number of pesticides, medicines, weed seeds and other contaminants [5]. In quantitative terms,
the accumulations of chicken manure represent thousands of tons of organic waste, which are a huge source of environmental pollution. On the other hand, these types of bio-waste have a great energy potential.

Despite the higher ash content on dry weight (20–30 wt % [6]) in comparison with the plant biomass, the chicken manure has a higher calorific value of about 13 MJ/kg (on a dry basis) [7]. For comparison, the higher calorific value for a dry mass of wood waste is about 18 MJ/kg [7]. Landfill of chicken manure, in addition to alienating suitable for use in agriculture, leads to a loss of energy source which can be put on one level with plant biomass.

The thermal methods, such as pyrolysis, gasification and combustion are used for the chicken manure energy potential extract. Each of the thermal treatment methods requires that the moisture content of the mass is not more than 25–30 wt % which obliges to use the drying stage. At the same time, in order to prevent the material from accumulating moisture again, it is necessary either to include the drying stage directly in the process of thermal processing, or to create special conditions for storing the dried chicken manure. The difficulty of design such conditions forces farmers to create small-scale thermal processing plants directly on the territory of a poultry farm, excluding the possibility of cooperating with other enterprises. An exception is the combustion process. Chicken manure burning plants have great productivity. But in this case, it is required to add material such as coal and biomass with a high melting point of ash due to the low ash melting temperature of chicken manure, which limits the application of this technology to small farms.

Creating material that can be stored and transported in the open air will enable poultry farms to reduce the cost of exporting this waste and use it for their own needs for generating heat and electricity. Such a material can be created using torrefaction technology. It is low-temperature pyrolysis, carried out in the temperature range of 220–300 °C. Compared to other thermal processing methods, torrefaction is a less energy-consuming and easily accessible method in terms of equipment and conditions [8]. It was also proved in [9] that, in relation to plant biomass (wood, straw), torrefaction improves the fuel properties of the material. Most torrefaction studies are conducted with plant biomass currently used as fuel. Biomass of animal origin is less commonly seen in studies, and often under more severe conditions [10]. However this technology will make it possible from chicken litter to obtain fuel with low hygroscopicity limit and calorific value increased as compared with the initial raw material. It will create favorable conditions for the development of the process of chicken manure treatment. In addition, due to the growing annual number of generated waste, including agricultural waste, producers are forced to look for ways of their economical utilization. Studies of the torrefaction process in relation to this type of waste will expand the raw material base and improve the ecological situation in problem areas. In this paper, the temperature regime of the chicken litter torrefaction, which is optimal from the point of view of improving the fuel properties of the resulting solid product was determined.

2. Material and methods
2.1. Material
In this work a chicken litter (a mixture of chicken manure and plant biomass) in the form of pellets was used as initial raw material. The material was dried to a moisture content of 1 wt % before experimental studies. Characteristics of the feedstock are shown in table 1.

The table shows that the chicken litter has a high carbon content, which leads to the lower calorific value of more than 17 MJ/kg. The ash content of the chicken litter is more than 15 wt %. Chicken manure has an ash content of 33 wt % usually [7]. The decrease in ash content is achieved through the use of litter material of plant origin.
Table 1. Characteristics of chicken litter (on dry basis).

| Parameter                  | Value  |
|----------------------------|--------|
| Ultimate analysis (wt %)   |        |
| C                         | 42.86  |
| H                         | 5.70   |
| N                         | 3.76   |
| S                         | 0.72   |
| O                         | 31.89  |
| Ash                       | 15.07  |
| Lower calorific value, $Q^d_L$ (MJ/kg) | 17.03 |
| Bulk density (kg/m$^3$)    | 597.0  |

2.2. Experimental procedure in lab-scale system

An experimental study of the torrefaction process of the chicken litter has been carried out in a laboratory setup, the scheme of which was presented previously [11]. The installation consists of a torrefaction reactor, into which the raw materials are put, and a condenser, where the torrefaction tar is accumulated. The maximum mass of the feedstock that was placed into the reactor during the series of experiments was 192.5 g, the average backfill mass was 150 g. Experimental studies were carried out for five temperature regimes of torrefaction (220, 240, 260, 280 and 300 °C) with a holding time determined using thermogravimetric analysis. The holding time for all five temperature regimes was 40 min.

The solid residue, tar and non-condensable gases are the products of the torrefaction process. The mass of the torrefaction tar was determined by weighing the condenser before and after the experimental study. To determine the properties of the gas, the experiment for each temperature was carried out in 2 stages. At the first stage, the volume of non-condensable torrefaction gases was measured with a gas meter. At the second stage, the gas mixture obtained during the experiment was collected in a gas-holder. A gas analyzer was connected to the gas-holder. So the integral composition of the mixture was determined.

2.3. Methods of torrefaction product characteristic investigation

Methods for determining the characteristics of the torrefaction products and the equipment used for this are presented in table 2.

3. Result and discussion

3.1. Mass balance

The results of the material balance calculation for each torrefaction temperature are presented in figure 1.

According to calculations, the mass loss in the torrefaction process increases by more than 2.5 times in the range from 220 to 300 °C. At 220 °C, mass loss reaches a value of 16%, and at a process temperature of 300 °C, it is a 43.5%. With a rise of the torrefaction temperature, the mass yield of the torrefaction liquid significantly increases. The yield of non-condensable gases is grown less intensively. The divergence of mass balances is not more than 1.5%.
Table 2. Methods and devices for definition of torrefaction products.

| Definable parameter                              | Determination method or device                                      |
|-------------------------------------------------|-------------------------------------------------------------------|
| Holding time (min)                              | Thermal analyzer SDT Q600                                         |
| Initial raw material and solid residue          |                                                                   |
| mass, $m$ (g)                                   | Laboratory scales Acom JW-1                                       |
| ultimate analysis: C, H, N, S (wt %)            | Element Analyzer “Elementar Vario Macro Cube”                     |
| ash content, Ash (wt %)                         | ASTM E1755-01                                                    |
| oxygen content, O (wt %)                        | Moisture Analyzer Ohaus MB45                                      |
| moisture content, $W$ (wt %)                    |                                                                   |
| lower calorific value on dry basis, $Q^d_L$ (MJ/kg) | $Q^d_L = 0.001(339C + 1030H - 108(O - S))$                        |
| lower calorific value on dry ash free condition, $Q^d_{Laf}$ (MJ/kg) | $Q^d_{Laf} = Q^d_L/(1 - Ash/100)$                                  |
| hygroscopicity limit (wt %)                     | GOST 16483.32-77                                                 |
| bulk density (kg/m$^3$)                         | ACTM E873-82                                                     |

Non-condensing gas

- composition of gas: CO, CO$_2$, CH$_2$, NO, NO$_2$, SO$_2$, H$_2$S (vol %)
- volume of gas, $V$ (l)
- specific volume yield, $V_{sp}$ (l/kg)
- calorific value (kJ/m$^3$)
- density, $\rho$ (kg/m$^3$)

Gas Analyzers Vario Plus Industrial “SYNGAS” and “OPTIMA 7”

3.2. Properties of the non-condensing gas

The composition and thermal properties of the gas mixture obtained as a result of chicken litter torrefaction are presented in table 3. Regardless of the torrefaction temperature, carbon dioxide is the main component of the gas mixture, but as the temperature rises, the proportion of combustible components (CO and CH$_4$) increases, which leads to an increase in the calorific value of this mixture. The gas contains impurities of sulfur and nitrogen compounds, the value of which remains almost constant in the range of regime temperatures of torrefaction. The growth of the specific volume yield is insignificant, which was noted in figure 1 already. In this way, a mixture of non-condensable torrefaction gases is not interesting from the point of view energy application. It has a low calorific value and is contaminated with sulfur-containing impurities.

3.3. Characteristics of solid residue

The change in the appearance (size and color) of the chicken litter depending on the torrefaction temperature is presented in figure 2. With growth of the torrefaction temperature, an increase in the degree of pellet charring can be noted. The higher the processing temperature, the more crushable the pellets become. This can be explained by the formation of a larger number of open pores due to the yield of volatile products with increasing torrefaction temperature. Characteristics of chicken litter at different torrefaction temperatures are presented in table 4.
Figure 1. Mass balance of chicken litter torrefaction at different temperatures regime.

Table 3. Characteristics of the gas released from the material as a result of torrefaction.

| $t_t$ (°C) | 220 | 240 | 260 | 280 | 300 |
|-----------|-----|-----|-----|-----|-----|
| CO$_2$ (vol %) | 88.8 | 85.9 | 83.0 | 82.5 | 79.5 |
| CO | 8.7 | 11.5 | 14.4 | 14.9 | 17.8 |
| CH$_4$ | 0.4 | 0.6 | 1.0 | 1.1 | 1.4 |
| O$_2$ | 0 | 0 | 0 | 0 | 0 |
| N$_2$ | 0 | 0 | 0 | 0 | 0 |
| NO | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 |
| NO$_2$ | 0.9 | 0.8 | 0.6 | 0.6 | 0.5 |
| SO$_2$ | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 |
| H$_2$S | 0.6 | 0.5 | 0.4 | 0.4 | 0.4 |
| Total | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Specific volume yield (l/kg) | 22.0 | 28.2 | 40.7 | 53.5 | 54.5 |
Density (kg/m$^3$) | 1.91 | 1.89 | 1.87 | 1.86 | 1.84 |
Calorific value (kJ/m$^3$) | 782 | 1248 | 1640 | 1722 | 2178 |

The chicken litter under the influence of the torrefaction process, leads itself to be similar to the plant biomass. The torrefaction process promotes the growth of carbon in the feedstock. Carbon goes out with volatile components, but the rate of mass loss of raw material is higher
than the rate of carbon release. The increase of carbon content occurs up to 280 °C, at which it reaches a value of 54.28 wt %. The material torrefied at 300 °C has a lower carbon content. As the temperature rises, the amount of hydrogen decreases. Hydrogen is released as part of non-condensable hydrocarbons (CH₄). In the form of H₂ hydrogen is observed only after 400 °C. At \( t_t \) = 300 °C oxygen is 2.1 times less compared to \( t_t \) = 220 °C, and almost 3 times less than in the initial raw material. Based on the composition of non-condensable gases (see table 3), oxygen is released together with CO, CO₂, NOₓ and SO₂. In this connection, the decrease of oxygen in the composition of torrefied material is so significant. All this leads to the fact that at a torrefaction temperature of 280 °C the maximum lower calorific value is observed for chicken litter (22.14 MJ/kg). This value is 30% higher than that of the initial raw material.

With a growth of temperature, the amount of ash content increases, but this does not affect the calorific value, as in another type of waste–sewage sludge [11].

Figure 3 shows the changes in the main thermal characteristics under the influence of the torrefaction temperature as compared with the initial raw material.

When the calorific value growth was studied [figure 3(a)], it can be noted that the maximum calorific value for dry ash-free mass was not reached, which indicates a significant energy potential inherent in chicken litter. At 280 °C for dry ash-free state, the lower calorific value is 27.86 MJ/kg, which is even higher than that for wood pellets [12].

The hygroscopicity limit decreases with rise of temperature from 21% for the feedstock to 9% at 240 °C [figure 3(b)]. And then the hygroscopicity limit remains constant.

Table 4. Characteristics of torrefied chicken litter (on dry basis).

| \( t_t \) (°C) | 220 | 240 | 260 | 280 | 300 |
|---------------|-----|-----|-----|-----|-----|
| Ultimate analysis (wt %) |       |     |     |     |     |
| C             | 49.06 | 49.75 | 51.52 | 54.28 | 53.30 |
| H             | 5.73  | 5.39  | 5.26  | 5.03  | 4.63  |
| N             | 4.25  | 4.42  | 4.49  | 4.95  | 5.35  |
| S             | 0.73  | 0.87  | 0.92  | 0.93  | 1.02  |
| O             | 24.51 | 22.52 | 19.06 | 14.29 | 11.60 |
| Ash           | 15.72 | 17.05 | 18.76 | 20.52 | 24.10 |
| Lower calorific value, \( Q^d \) (MJ/kg) | 19.97 | 20.08 | 20.92 | 22.14 | 21.69 |
| Hygroscopicity limit (wt %) | 11   | 9    | 9    | 9    | 9    |
| Bulk density (kg/m³) | 546.4 | 517.8 | 485.2 | 474.3 | 444.7 |
Figure 3. Change in lower calorific value (a) and hygroscopicity limit (b) of chicken litter at five temperatures of the torrefaction.

Bulk density is an important indicator in the supply implementation of biofuels in volumetric units and along with the lower calorific value allows estimating its specific energy consumption. Information on bulk density makes it possible to calculate the required capacity of vehicles for transportation of fuel and storage facilities. With an rise of the torrefaction temperature, a decrease in the bulk density is observed. When the raw material is torrefied at 300 °C, this value is decreased by 25% compared to the initial one.

4. Conclusion
Experimental studies of the torrefaction process of the chicken litter in the temperature range from 220 to 300 °C were carried out. The results of the study showed that, in relation to this type of organic waste, the torrefaction temperature of 280 °C is optimal. The lower calorific value increases by 30%, the hygroscopicity limit decreases by 2.3 times, the value of the bulk density is reduced by 25% compared with the initial raw material. These characteristics are the basic, if the chicken litter is considered as a fuel.

At a temperature of 280 °C, the mass loss is 35%, while non-condensable gases have a low mass and volume yield. The main component of the gas mixture is carbon dioxide, and therefore the calorific value of non-condensable gases is only 1722 kJ/m³. With such characteristics, non-condensable gases find no energy application.

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