Energy characteristics of the char obtained by two steps pyrolysis of chicken manure

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Abstract. The thermal treatment of chicken manure is an ecological alternative of neutralizing this kind of waste with energy recovery. In this regard, a two-stage pyrolysis process was chosen, the first stage having the purpose of preheating and moisture elimination. The drying process up to the starting point of volatile matter release, about 200-250°C was taken into consideration. As a result of the moisture elimination in the first step of the pyrolysis process, a gas fuel rich in CO, CH₄, H₂ will be obtained. The experimental determinations consisted in the proximate and ultimate analysis of the initial residue and tests of the pyrolysis process in a pilot plant that allows the pyrolysis of a quantity of waste in range of 40-200g. A sample of a 140 g was subjected to the pyrolysis process at 500°C and the char (an organic, solid, consistent and odourless product) was obtained. The carbon (C), nitrogen (N), hydrogen (H) and sulphur (S) contents of the final product of pyrolysis were determined by a Costech 4120 Elemental Analyser that allows us to calculate the Lower Heating Value (LHV) of the char. For the evaluation of the energy potential, a theoretical balance of the energy consumption in the process of pyrolysis and the energy developed by combustion of the char, has been made. This theoretical balance was verified by determining the energy developed by combustion of char based on the composition determined in the laboratory. The laboratory results confirmed the existence of an energy potential of the pyrolysis product, which offers a technological alternative.

1. General considerations
As the waste from poultry is significant, two main questions arise - first regarding ecology and the second - the possibility of energy generation.

In the past, these wastes have been used as agricultural fertilizers, especially in the field of vegetable crops, but their storage creates problems related to groundwater and odours in the atmosphere, especially odours resulting from the high ammonia content.

Experience has shown that the most difficult process is to handle waste when it is intended to be incinerated due to its very high moisture content (on average 50%).

In the agricultural production sector, if a hay bed or wood chips placed above the floor are used, the handling capacity of poultry manure is increased (generally, this bed represents about 10-12% of the manure weight) as well as the general energy characteristics. Three technologies can be considered for energy production: direct combustion in steam or hot water boilers, pyrolysis and gasification.

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The authors of the paper conducted theoretical studies regarding the direct combustion conditions in a boiler furnace and experimental studies on pyrolysis. Taking into account the physical characteristics of poultry manure, gasification appears to be the least applicable.

2. Physical-chemical and energy characteristics of poultry manure

These characteristics have been determined in the laboratory of the Department of Thermodynamics, Engines, Thermal and Refrigeration Equipment, Faculty of Mechanical Engineering and Mechatronics of Politehnica University of Bucharest, Romania. There have been made determinations of both, pure and mixed poultry manure with solid biomass bed, in a mass ratio of 10-14%. Experimental determinations have been performed for poultry manure from the central region of Moldova and from the central region of Muntenia.

Figure 1 and 2 show the general aspects of the poultry manure obtained from a local intermediate storage area compared to storage with cereal straw bed.

![Figure 1. The aspect of pure poultry manure.](image1)

![Figure 2. The aspect of poultry manure with cereal straw bed.](image2)

A small difference between the average density of pure poultry manure compared to the poultry manure with biomass bed have been noticed. The values are presented below:
- Bulk density of pure poultry manure: 88-142 kg/m³;
- Bulk density of poultry manure with straw bed: 79-127 kg/m³;

Water content is very high, averaging 35-50%.

The technical analysis of poultry manure is presented in Tables 1 and 2.

**Table 1.** The results of the technical analysis for poultry manure with biomass bed.

| Characteristics         | UM | Test I | Test II | Test III | Test VI | Test V |
|-------------------------|----|--------|---------|----------|---------|--------|
| Moisture content, Wᵢ   | %  | 35.2   | 36.2    | 37.4     | 39.1    | 40.2   |
| Volatile matter, Vᵢ    | %  | 50.3   | 48.2    | 47.2     | 45.7    | 46.1   |
| Ash content, Aᵢ         | %  | 6.8    | 6.2     | 6.7      | 6.1     | 6.1    |
| Fixed carbon, Cᵢ         | %  | 7.1    | 8.8     | 8.1      | 9.1     | 7.6    |

**Table 2.** The results of the technical analysis for pure poultry manure.

| Characteristics         | UM | Test I | Test II | Test III | Test VI | Test V |
|-------------------------|----|--------|---------|----------|---------|--------|
| Moisture content, Wᵢ   | %  | 37.1   | 37.2    | 36.9     | 37.2    | 36.9   |
| Volatile matter, Vᵢ    | %  | 50.2   | 50.2    | 49.9     | 50.1    | 50.4   |
| Ash content, Aᵢ         | %  | 6.2    | 6.1     | 6.3      | 6.2     | 6.2    |
| Fixed carbon, Cᵢ         | %  | 6.5    | 6.5     | 6.9      | 6.5     | 6.5    |

Index “i” refers to the initial state considered in the intermediate storage warehouse.
The tests indicate a small amount of combustible solid mass in the form of fixed carbon and a high ballast content (sum of water content and ash).

The high content of ballast, in range of (43-46.3)%, shows a difficult application of direct combustion technology indicating that two-stage pyrolysis technology is applicable (the first stage representing only the elimination of moisture).

### Table 3. Ballast content of poultry manure.

| Characteristics                              | UM   | Test I | Test II | Test III | Test VI | Test V |
|---------------------------------------------|------|--------|---------|----------|---------|--------|
| Ballast content of pure poultry manure      | %    | 43.3   | 43.2    | 43.2     | 43.4    | 43.1   |
| Ballast content of poultry manure with      | %    | 42.6   | 43.0    | 44.1     | 45.2    | 46.3   |
| biomass bed                                 |      |        |         |          |         |        |

### Table 4. Elemental analysis.

| Type of sample                              | C    | H     | N     | S     | O     | A     | Wt   | LHV  kJ/kg |
|---------------------------------------------|------|-------|-------|-------|-------|-------|------|--------|
| pure poultry manure                         | 12.1 | 16.1  | 4.3   | 4.9   | 1.6   | 1.8   | 34.5 | 36.2   |
| poultry manure with biomass bed             | 12.3 | 22.5  | 4.3   | 5.2   | 1.4   | 2.3   | 35.1 | 37.4   |

LHV is the main indicator of the efficiency of energy recovery for this type of waste and is calculated basis on the elemental analysis with the following relation:

$$LHV = 339C' + 1029.1H' - 109(O' - S') - 25.1W', \quad \text{kJ} / \text{kg}$$ (1)

The results presented in table 4 show low values of LHV for both samples, which implies the need of a fuel support (gas or liquid) for direct combustion.

### 3. Experimental pyrolysis test

The tests have been performed using a chamotte furnace equipped with a thermometer and thermostat, according to the solution presented in Figure 3.

![Figure 3. The scheme of the pyrolysis installation.](image)
The poultry manure samples had a weight of (120-160) g and were placed on a 60 x 120 mm tray type device. The char was obtained by heating the samples for 2 hours at (500-580)°C. The char was obtained by heating the samples for 2 hours at 900°C.

Figure 4. The aspect of char obtained from poultry manure.

The char obtained is environmentally friendly, does not smell and does not adhere to the surfaces it comes into contact with. The drying process was carried out at temperatures of (200-250)°C, in order to reduce the time. Furthermore, burning experiments were carried out with the produced char.

4. Determinations of pyrolysis char composition

For the characterization of the biochar obtained from poultry manure, the following instrumentation has been used: a COSTECH ECS 4010 analyzer to perform the ultimate analysis of the samples, for determination of the content of elements such as Carbon, Hydrogen, Nitrogen and Sulphur (Standard deviation: 0.1% abs, CHNS simultaneously for 2-5 mg sample).
Figure 5. CHNS chromatograms of poultry manure char.

Table 5. CHNS elemental analysis for poultry manure char.

| Type of sample       | C (%) | H (%) | N (%) | S (%) |
|----------------------|-------|-------|-------|-------|
| Poultry manure char  | 23.81-24.71 | 1.37-1.45 | 2.11-2.16 | 0-0.1 |

A very small amount of sulphur was detected. It is noted that in the pyrolysis process, an increase of C content occurred concurrently with the H loss. Also N content in the char increased in pyrolysis process, related to the raw feedstock. Ash content of the biochar from poultry manure has been determined using a Nabertherm furnace.

5. The energy balance of the semi-pyrolysis process
The heat balance was performed for a two-stage semi-pyrolysis fuel unit, the first stage comprising of only the heating and the removal of water content.

As the gas exhausted in the pyrolysis process has a high amount of moisture, the placement of a dryer before the pyrolysis reactor is recommended, while the temperature in drying process does not exceed the 250ºC value. In this case, the temperature in the reactor is maintained in the range (450-580)ºC. Figure 6 represents the scheme of the low temperature pyrolysis process with the dryer.

Figure 6. The pyrolysis process with preceding drying.

The flow rate of the material (fuel) subjected to pyrolysis is \( B \), kg/s. The heat for the drying process will be determined by the equation:
where $\Delta t_1 = t_i - t$, and $t_i$ is the initial temperature. The last term of the equation is the heat of water vapour released to the temperature $t_i$.

$$B_2 = B_1 \cdot \frac{100 - W_t^i}{100}, \text{ kg/s}$$

(3)

$$B_w = B_1 \cdot \frac{W_t^i}{100}, \text{ kg/s}$$

(4)

The resulting char quantity respects the following relation:

$$B_c = B_1 \cdot \frac{100 - W_t^i - V_t^i}{100}, \text{ kg/s}$$

(5)

The quantity of fuel gas will be:

$$B_g = B_1 \cdot \phi \cdot \frac{W_t^i}{100}, \text{ kg/s}$$

(6)

It was considered that in the pyrolysis phase the devolatilization has been realized in parts marked with $\phi$. For a temperature above 550°C, the devolatilization value is (0.65-0.8).

It is stated that the volatiles contained in the initial matter were not released during the drying phase.

The heat consumed for the pyrolysis:

$$Q_2 = B_2 \cdot c_c \cdot \Delta t_2$$

(7)

with $\Delta t_2 = t_2 - t_i$. A calculation regarding the energy efficiency for processing of mass unit of fuel indicates that the specific heat consumed in the drying process was assimilated with that of the peat, a fuel that is similar to the poultry manure:

$$c_1 = 0.01 \cdot W_t^i \cdot c_w + \left(1 - 0.01 \cdot W_t^i\right) \cdot c_c, \text{ kJ/kg}$$

(8)

where $c_c = 1.2$ for temperatures above 250°C. For poultry manure with $W_t^i = 40\%$ and $V_t^i = 27\%$, the result is:

$$c_1 = 0.01 \cdot 40 \cdot 1.2 + \left(1 - 0.01 \cdot 40\right) \cdot 1.2 = 2.4 \text{ kJ/kg·K}$$

For $\Delta t_2 = 250 - 20 = 230^°C$, the result for the heat consumption for the dryer, with the considered mass flow rate $B_1 = 1 \text{ kg/s}$, was the following:

$$Q_2 = 2.4 \cdot 230 + 2510 \cdot \frac{0.40}{100} + 1.3 \cdot 230 \cdot \frac{0.40}{100} = 1670 \text{ kW}$$

The mass flow rate of waste entering the pyrolysis reactor will become:

$$B_2 = 1 \cdot \frac{100 - 40}{100} = 0.6 \text{ kg/s}$$
The mass flow rate of combustible gas exhausted from the pyrolysis reactor:

\[ B_B = 0.6 \cdot 0.75 \cdot \frac{27}{100} = 0.12 \text{ kg/s} \]

The solid mass flow rate of pyrolysis waste (the char rate) will be:

\[ B_c = B_B \cdot \frac{100 - W^i_v - V^i}{100} = 0.33 \text{ kg/s} \]

The heat consumed for the pyrolysis, based on the data:

\[ \Delta t_2 = t_2 - t_1 = 540 - 250 = 290^\circ C \]
\[ c_2 = 1.4 \text{ kJ/kg·K} \]

obtained from the case of the anhydrous peat at \( t_m = 400^\circ C \):

\[ Q_2 = 0.33 \cdot 1.4 \cdot 290 = 134 \text{ kW} \]

For the entire pyrolysis process, the consumed heat will be:

\[ Q = Q_1 + Q_2 = 1670 + 134 = 1804 \text{ kW} \]

The heat produced by burning the char containing ash in the percentage \( A^i = 7\% \), will be:

\[ Q_{char} = B_c \cdot H_c = 0.33 \cdot 30000 \cdot \frac{100 - 7}{100} = 9200 \text{ kW} \]

The theoretical value is confirmed by the calorific value determined based on the composition of the char: \( C^i = 23.81\% \), \( H^i = 1.37\% \), \( LHV^i = 9481.3 \text{ kJ/kg} \)

The amount of biochar will be:

\[ B_{char} = B_c + \frac{A^i}{100} = 0.33 + \frac{7}{100} = 0.4 \text{ kg/s} \]

For this quantity of char obtained from poultry manure, the thermal power becomes:

\[ P_t = 0.4 \cdot 9481.3 = 3800 \text{ kW} \]

Even if the energy value of the resulting combustible gas is not considered. It should be noted that the energy value of the heat produced by the burning of the char obtained from poultry manure is greater than that consumed for the heating. This results in technical and economic feasibility in using the pyrolysis technology of the poultry manure.

6. Conclusions

The paper is a continuation of a series of experiments and analyses regarding the possibility to use the pyrolysis as a technology for energy capture from the poultry manure.

The previous experimental data were the foundation for the numerical application regarding the energy efficiency of the pyrolysis process.

The numerical application has evidently demonstrated the existence of an active thermal energy with respect to the consumptions imposed by the pyrolysis process.

Measurements on the composition of char obtained from poultry manure confirmed the existence of a positive thermal potential in energy consumption for the internal pyrolysis process even if it is lower than the theoretical predictions.
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