Experimental researches on poultry manure combustion in co-combustion with biomass

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Abstract. Combustion of pure avian waste is strongly affected by its humidity content. According to the results of composition analysis, the initial humidity reaches up to 50%, inhibiting direct combustion initiation and development. Drying of poultry waste is an alternative, but simple relatively long-term storage or thermal pre-processing, complicates the technological process of energy recovery and increases the associated costs. Co-combustion represents a promising solution to enrich the heating value of raw poultry manure. Experiments using biomass (in a mass fraction of up to 30%) led to positive results in terms of efficiency. It is highlighted that the process depends on the quality of the woody biomass used for the mixture, but also on its bulk density, which causes an accelerated diffusion of air and influences the burning speed. This paper presents the experimental investigations on the co-combustion of poultry manure and woody biomass, performed on a 55 kW pilot boiler equipped with a post-combustion grate. The focus of the analysis is on the influence of the biomass bulk density and its heating value on the co-combustion process. The results obtained favor the development of a technology that is easy to apply and has a reduced cost. The technology investigated here is suitable for onsite applications in poultry farms, enabling meeting the energy demand based on co-combustion of resulting poultry waste.

1 Introduction

For the past decades, research interest in the energy field focuses on harmful emissions abatement and renewable energy technologies development and integration [1], [2]. It is remarked as, according to statistics released by the International Renewable Energy Agency, renewable energy sources (RES) almost doubled their cumulated generating capacity over the last decade [3].

One important but still less exploited RES is represented by the renewable waste [4]. For instance, waste mixtures resulting from bird houses operating cycles are characterized by increased soil restoration potential, so an alternative for their management is by spreading them as fertilizers [5], [6]. However, limitations regarding nitrogen content in agricultural areas imposed by 91/676/CEE Directive emphasize the need to intensively consider other management approaches such as treatments with energy recovery potential [7]. Combustion of poultry manure on site of poultry farms can be a solution for heating the halls, even to a certain extent, together with another fuel [8], [9].

The research developed in this paper aims to evaluate the efficiency of poultry manure co-combustion in combination with different types of solid biomass, such as forestry or agricultural. The approach presented meets also the objective of reducing the consumption of hydrocarbons (liquid or gaseous), according to the Paris Agreement. Specifically, the research refers only to the combustion of wet poultry manure, thus reducing the drying phase, usually naturally (which may be a polluting source by prolonged exposure to soil). The energy valorization of dry poultry manure has been previous research and achievements [4], [5], [10]. A mass participation of a maximum of 30% for poultry waste, which is fed above the burning biomass layer (only the fixed layer combustion technology for solid biomass) is envisaged.

The rest of the paper is structured as follows. Section 2 details the energy characteristics of poultry manure and the biomass which serves as thermal support.

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2 Energy characteristics of poultry manure

Solid biomass is a category of fuels characterized by a high volatile content, which involves a high ignition capacity, a low ash content, a very high oxygen content and a strong dependence of calorific value on moisture content [11], [12]. Usually, the humidity is required to be below 30%, in which case the calorific value becomes higher than 12 000 kJ/kg, superior to lignite [13].

In the present research, the solid biomass considered is represented by wood waste, while the agricultural biomass included vine ropes and tree branches.

The energy characteristics are assessed based on the elementary analysis, which includes the mass participations for carbon (C), hydrogen (H), sulfur (S), oxygen (O), nitrogen (N), water (W) and ash (A), according to eq. (1). The index *i* refers to the initial state, and the humidity is the total (W_t^i).

$$C_i + Hi + S_c^i + Oi + N_i + W_t^i + A_i = 100 \quad (1)$$

The calorific value can be calculated based on the elementary analysis. Flue gas emissions and air demand are determined by the stoichiometric relationships of combustion reactions. If only the lower calorific value H_i^i is in MJ/kg, the carbon content C, employing eqs. (2-4):

$$C = 0.0548929 + 0.023736\, H_i^i \quad [kg/kg] \quad (2)$$

$$V_g^o = 1.57933 + 0.217974\, H_i^i \quad [m_N^3/kg] \quad (3)$$

$$V_{CO_2} = 0.101619 + 0.043991 H_i^i \quad [m_N^3/kg] \quad (4)$$

Table 1 presents the energy characteristics of the biomass considered for the experimental tests.

Table 1. Energy characteristics of some solid biomass varieties.

Biomass	Ci	H_i	O_i	N_i	W_t^i	A_i	H_i^i
	%	%	%	%	%	%	MJ/kg
Dry wood	46.7	5.1	33.6	0.6	10.5	3.5	17.15
Wood with medium humidity	32.9	4.6	28.6	0.7	30	3.2	12.01
Sunflower stems	37÷42	4.1÷5.2	35÷40	1.2÷1.7	11.1÷17.1	3.3÷5.5	13.6÷15.2
Branches	36.7	5.2	30.8	0.6	25.2	1.5	13.80
Vine ropes	40÷43	3.7÷4.9	35÷42	0.6÷2.5	10÷26	2.5÷4.5	14.7÷15.8
Corn cobs	36÷39	3.6÷5.1	35÷44	1.4÷3.8	11.5÷17.1	3.7÷5.7	13.2÷15.0

In the experimental investigations, the poultry manure is pure or mixed with solid biomass, according to the operating conditions in the breeding halls.

The elementary analysis for biomass bed manure resulted within the ranges:

$C_i = 12.4 \div 22.6$ %
$H_i = 4.4 \div 5.4$ %
$S_c^i = 1.8 \div 2.1$ %
$O_i = 34.8 \div 37.6$ %
$N_i = 1.4 \div 2.4$ %
$A_i = 6.2 \div 12.8$ %
$W_t^i = 33.8 \div 38.8$

Subsequently, the lower calorific value is equal to $H_i^i = 3\,840 \div 5\,950$ kJ/kg

The elementary analysis of pure manure resulted within the ranges:

C_i = 12.4 ÷ 22.6 %
H_i = 4.4 ÷ 5.4 %
S_c^i = 1.8 ÷ 2.1 %
O_i = 34.8 ÷ 37.6 %
N_i = 1.4 ÷ 2.4 %
A_i = 6.2 ÷ 12.8 %
W_t^i = 33.8 ÷ 38.8

The lower calorific value is evaluated in this case at H_i^i = 3 750 ÷ 5 870 kJ/kg. It is noticeable that these values are slightly lower (less than 2%) than the ones calculated in the previous case.

It is remarked that, according to the lower calorific value for poultry manure, it is required their combustion with a thermal support. In the present research, the thermal support comes from biomass, which has a calorific value about three times higher.

3 Solid fuels combustion in fixed layer

Fixed layer combustion is characterized by a concentration of it in a very small volume compared to the general size of the hearth. The result is a difficult penetration of air into the fuel layer, which leads to an excessive increase in pyrolysis - gasification processes, the resulting combustible gases continuing to burn in the rest of the hearth area [14]. Consequently, the overall combustion process depends outside the energy characteristics of the fuel and the porosity of the layer (the volume of voids in the fuel layer) [11].

However, the porosity responds positively to particles of a shape that can be approximated with a sphere and a strict particle size distribution. The higher the granulation, the lower the porosity of the fuel layer, as follows (the porosity was denoted by m).

- Particle size 2 ÷ 25mm, m = 0.46 ÷ 0.48
- Particle size 25 ÷ 50mm, m = 0.42 ÷ 0.45

For biomass with shapes and sizes which are very far from spherical in shape (such as branches, vines, wood in the form of perches), it is proposed to replace the air intake criterion represented by porosity with the criterion "fuel layer density", ρ_c in kg/m^3.

An oxygen-deficient fuel layer leads to a two-stages combustion mechanism, the first stage comprising the phase of gasification pyrolysis, with strong CO emission, the second stage leading to the final oxidation, with the formation of CO_2 [15]. Figure 1 shows the physical model for two-stage combustion, the avian waste being attached to the second stage of combustion.

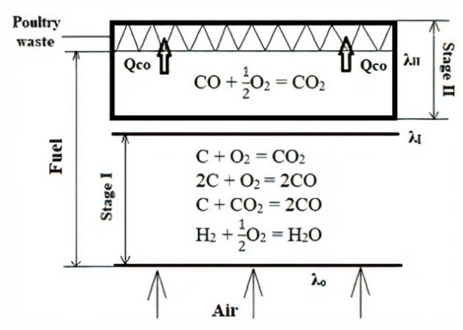


Fig. 1. Combustion scheme in a fixed layer of fuel with low porosity (high density), with two combustion steps

In stage I, the reactions take place:

$$C + O_2 = CO_2 \tag{5}$$
$$2C + O_2 = 2CO$$
$$C + CO_2 = 2CO$$
$$H2 + \frac{1}{2}O_2 = H_2O$$

The reactions with formation of CO are a consequence of the air deficit. It can be considered that at the end of the first combustion stage the excess air is λI ≈ 0.5λo (λo being the total excess air for the combustion in the layer). As for the combustion in the layer, the excess air λo ≈ 2, we can consider λI = 1 (stoichiometric combustion). An estimative calculation for biomass having the lower calorific value equal to H_i^i = 14MJ/kg, indicated the following combustion results:

- The volume of CO_2 will be:

$$V_{CO_2} = 0.5 \cdot (0.101619 + 0.043991 \cdot 14) = 0.358 \quad [m_N^3/kg] \quad (6)$$

- Volume of stoichiometric flue gas (λ = 1) emitted by burning the entire quantity of fuel:

$$V_g^o = 1.57133 + 0.217974 \cdot 14 = 4.63 \quad [m_N^3/kg] \quad (7)$$

- The concentration of CO_2 in the stoichiometric volume of carbon gas is:

$$CO_2 = \frac{V_{CO_2}}{V_g^o} = 0.077 \frac{m_N^3}{m_N^3} = 7.7\% \quad (8)$$

- The excess air λo allowed will be self-distributed to the second combustion stage. The concentration of CO in the second stage depends on the degree of oxidation of carbon to CO_2, and analytically for 1 kg of carbon is represented by the relation:

$$CO = 34.7 - 1.65CO_2 \quad [\%] \quad (9)$$

- The heat released by burning CO in the second combustion stage will be:

$$Qco = \frac{CO}{100} \cdot H_{i,CO}^i \quad [\frac{kJ}{m_N^3}] \quad (10)$$

where $H_{i,CO}^i$ is the lower calorific value of CO, resulting in:

$$Qco = \frac{34.7 - 1.65CO_2}{100} \cdot H_{i,CO}^i \quad [\frac{kJ}{m_N^3}] \quad (11)$$

- For a fuel with a C_i/100 carbon content, the equation becomes:

$$Q_{CO}^r = \frac{C^i}{100} \cdot \frac{34.7 - 1.65CO_2}{100} \cdot H_{i,CO}^i \quad [\frac{kJ}{m_N^3}], \quad (12)$$

Q_{CO}^r represents the actual amount of CO released when a solid fuel is burned.

The low heat input released by the second-stage combustion of CO, to support the combustion of poultry waste, leads to heavy ignition and entry into a gasification regime, with an excessively large extension of the total combustion time.

For the concentration of CO_2 = 7.7% achieved in combustion stage I, the heat released by burning CO will be equal to:

$$Q_{CO}^r = (0.0548929 + 0.023736H_i^i) \frac{34.7 - 1.65 \cdot 7.7}{100} \cdot 12644 = 995.8 \frac{kJ}{m_N^3}$$

This heat obtained by combustion of CO and is released at the same time as the combustion of the upper layer of poultry waste, but representing an insufficient thermal support. Thus, stoichiometrically, for the biomass considered having the lower calorific value equal to H_i^i = 14MJ/kg, the volume of flue gases having the value of $4.63 m_N^3/kg$, the total heat accumulated by combustion will be 3 023.7 kJ/m_N^3. The thermal participation of CO combustion in the second combustion stage results $\frac{995.8}{3023.7}$ = 0.32 = 32%, supporting the combustion of poultry manure.

The second stage combustion solution involves a low density of fuel in the layer (ρ_c < 250kg/m_N^3). If the correspondence with the porosity coefficient m is considered by the relation:

$$m \approx \frac{\rho_c}{\rho_o} \quad (13)$$

where ρ_o= 1 000 kg/m^3 is the absolute density for biomass, the porosity results in this case less than the value m = 0.25 enabling an easy penetration of air. The physical model of combustion is shown in Figure 2.

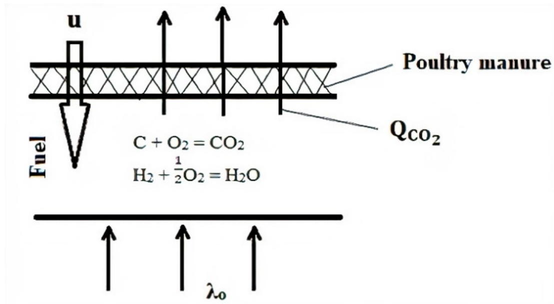


Fig. 2. Combustion in a fixed bad of fuel with high density (porosity).

The combustion rate u, in m/s, represents the rate of decrease of the fuel layer height. The higher it is, the more the heat released by combustion is transmitted directly to the upper poultry manure layer.

The combustion rate is determined by the lower calorific value H_i^i of the fuel and the density of the fuel layer ρ_c, as given in eq. (14):

$$u = f(H_i^i, \rho_c) \qquad [m/s] \tag{14}$$

Based on this observation, the law of heterogeneous combustion velocities q, can be expressed as in eq. (15):

$$q = \frac{C_o}{\frac{1}{k} + \frac{r_o}{D}} \qquad [m/s] \tag{15}$$

As a physical interpretation, the lower calorific value is attached to the combustion rate constant k [m/s] and the molecular diffusion density D [m^2/s]. With r_o [m] was noted the radius of the fuel particle and C_o represents the initial concentration of the oxidizing medium. The corresponding variation of the combustion rate u results, compared to the combustion parameters, H_i^i and ρ_c, is shown in Figure 3.

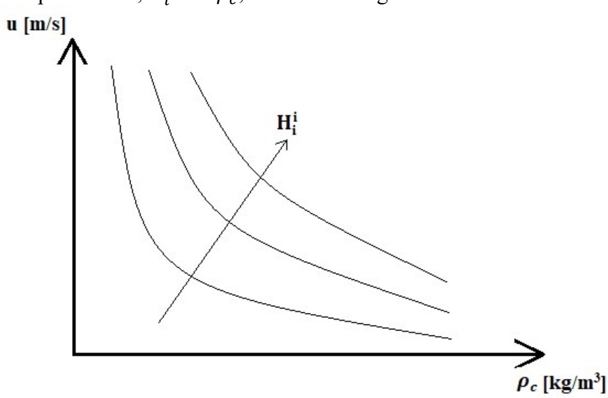


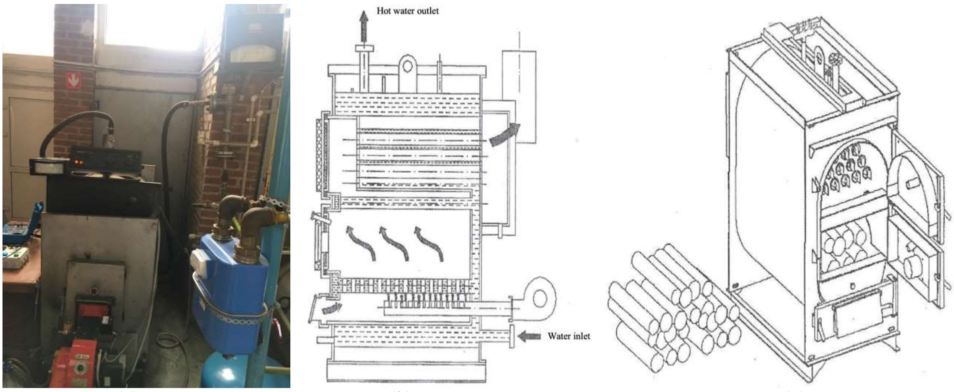
Fig. 3. Law of variation of combustion rate in a fixed layer of fuel

4 Experimental investigation on poultry manure – solid biomass co-combustion

The experiments conducted in this research aim to determine the efficiency of the co-combustion process depending both on the biomass quality and its bulk density. In reference to the moisture of the manure, it is highlighted that the investigations are conducted at very high humidity content of poultry manure. The combustion speed and the air diffusion behavior depending on the bulk density is observed.

4.1 Equipment and methodology of research

The experiments are performed at laboratory scale, employing a pilot installation comprising a boiler equipped with a fixed grill of 55 kW, set in the Thermotechnical Laboratory of the Faculty of Mechanics and Mechatronics, Polytechnic University of Bucharest.



(a) (b) (c)

Fig. 4. Pilot installation, 55 kW boiler: (a) Overview; (b) Cross-sectional diagram; (c) Front diagram.

The 55 kW pilot boiler has the following dimensions of the hearth:

- length: L_{hearth} = 750 mm; width: l_{hearth} = 550 mm; height: h_{hearth} = 600 mm;
- hearth volume: V_{hearth} = 0.25 m^3;

The hearth is equipped with a fixed bars grill with the following dimensions:

- length: L_{grill} = 520 mm;
- bars width: l_{grill_bars} = 15 mm;
- space between bars: s = 15 mm;
- grill surface: S_{grill} = 0.286 m^2;
- active surface of the grill: S_{active_grill} = 0.19 m^2;

4.2 Experimental cases

The tests are performed in three sets of conditions. The fuel used consists of a mixture of poultry manure (collected directly from the poultry house bedding), which is spread over the fixed layer of solid biomass (wood or agricultural), in a controlled proportion. The energy characteristics of the solid biomass used for the experimental tests are analyzed according to the relevant standard methods and presented in Table 1.

4.2.1 Case 1

The fuel mixture used is represented by:

- 70% forest biomass, wood mixture of different species (beech, oak, hornbeam) in the form of boards of size (2 x 5.5 x 25)cm^3, with humidity 25%, lower calorific value 13 200 kJ/kg and mass 5.3 kg;

Fig. 5. Solid forest biomass in the form of planks – 1.

- 30% poultry manure, with 50% humidity, calorific value 4 100 kJ/kg and mass 1.59 kg. In this scenario, the lower calorific value results:

$H_i^i = 0.7 \cdot 13\,200 + 0.3 \cdot 4100 = 10\,470$ kJ/kg

The volume of the fuel mixture placed in a fixed layer on the hearth grill was (40 x 30 x 25) cm^3, the fuel layer being characterized by a low density, ρ_c = 226.6 kg/m^3.

(a) (b) (c)

Fig.6. Experiment 1 - Images of the burning process inside 55 kW pilot boiler at different times of the process
a) the 3th minute; b)the 12th minute; c) the 17th minute.

The burning time of the sample was 1080 s, leading to a burning speed of 0.231 mm/s.

4.2.2 Case 2

The fuel mixture used is represented by:

- 80% forest biomass, wood mixture of different species (beech, oak, hornbeam) in the form of boards of size (3.5 x 7 x 25) cm^3, maximum humidity of 25%, the calorific value 13 400 kJ/kg and mass 5.0 kg.
- 20% poultry manure, 50% humidity, calorific value 4 250 kg/m^3 and mass 1.0 kg.

Fig. 7. Solid forest biomass in the form of planks – 2.

The calorific value of the biomass-poultry manure mixture result in this case:

H_i^i = 0.8 · 13400 + 0.2 · 4250 = 11 570 kJ/kg

The volume of the fuel mixture placed in the fixed layer on the hearth grill is (40 x 30 x 25) cm^3, the fuel layer being characterized by a lower layer density than in Case 1, specifically ρ_c= 200 kg/m^3. Figure 8 shows the images of the combustion process.

(a) (b) (c)

Fig. 8. Experiment 2 - Images of the burning process inside
55kW pilot boiler at different times of the process a) first minute; b) the 7th minute; c) the 9th minute.

The burning time of the sample was 1050s, leading to a burning speed of 0.238mm/s.

4.2.3 Case 3

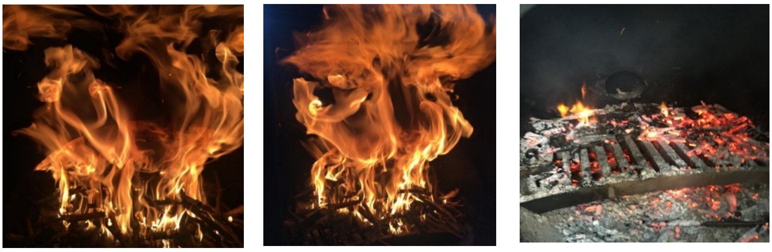
The fuel mixture used in this case is represented by:

- ≈ 85% agricultural biomass, mixture of vines and branches with tree bark, in the form of furrows 25 cm long, and different thicknesses between 4 and 17 mm, maximum humidity of 20%, calorific value 13700kJ/kg and mass 4 kg;
- ≈ 15% poultry manure, 50% humidity and mass 0.75 kg.

The calorific value of the biomass-poultry manure mixture results:
H_i^i = 12270 kJ/kg

Fig. 9. Solid agricultural biomass in the form of firewood and twigs

The volume of the fuel mixture placed in the fixed layer on the hearth grill is (40 x 30 x 30) cm^3, with the density of the fuel layer much reduced compared to the first two experiments, which facilitated rapid ignition and very intense combustion. The density of the fuel mixture was ρ_c = 132 kg/m^3.



(a) **(b)** **(c)**

Fig. 10. Experimentul 3 - Images of the burning process inside 55 kW pilot boiler at different times of the process; a) first minute; b) the 3th minute; c) the 18th minute.

The burning time is reduced to 980s, and the burning speed increased to 0.306 mm/s.

4.3 Results and discussions

Table 2 specifies the experimental parameters for the fuel mixture used in each of the three experimental tests.

Table 2 – Experimental parameters of the fixed layer fuel mixture

Parameters / No. exp.	Fuel mixture composition Solid biomass [%]	Fuel mixture composition Poultry manure [%]	Fuel mixture composition Solid biomass [kg]	Fuel mixture composition Poultry manure [kg]	Fuel layer volume [m^3]	Burning time [s]
Experiment 1	70 Wood	30	5.3 Wood	1.59	0.3	1080
Experiment 2	80 Wood	20	5.0 Wood	1.0	0.3	1050
Experiment 3	85 Agricultural	15	4.0 Agricultural	0.75	0.36	980

Variables / Exp. No.	u [mm/s]	ρ_c [kg/m^3]
1	0.231	226.6
2	0.238	200
3	0.306	132

The graph in Figure 11 shows the influence of the burned fuel density (ρ_c) containing a certain proportion of poultry waste in the technology of fixed layer combustion on the combustion rate (u). Poultry waste is fed to the top of the fuel layer.

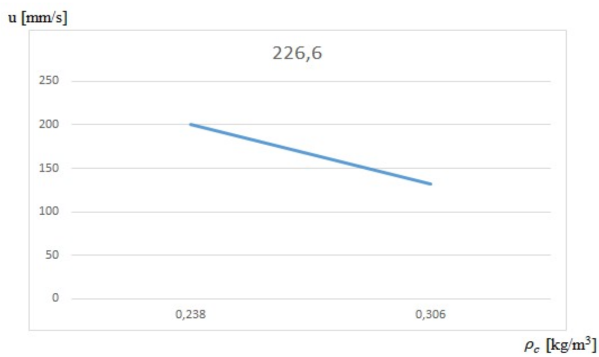


Fig. 11. The influence of fuel layer density on combustion rate

5 Conclusions

The co-combustion process shows great complexity, being influenced of several factors, such as: time, spatial distribution, flow currents, flue gases, (controlled) combustion rate and convection conditions. In all three experimental test conditions, the combustion (without prior mixing of fuels), is stationary, three-dimensional, with turbulent flow and unfolds in a heterogeneous environment.

The combustion of volatiles, including CO, took place in the volume between the biomass pieces and at the surface of the layer, as shown in Figures 6, 8 and 10. The time of drying and release of volatile matter reaches only 10% of the biochar burning period. The amount of heat released in the combustion process is largely determined by the combustion of the biochar residue. The normal development of the combustion process is still conditioned by the design of the air supply in the biomass co-combustion layer.

A comparative analysis between the three experimental tests highlights the decrease of the burning speed with the increase of the wood pieces dimensions (Case 2), but also an increase with the decrease of the fuel density in the layer. There are no significant differences between the use of wood or agricultural biomass.

The experimental test conducted in this research highlighted the possibility of energy recovery from poultry waste by means of combustion with solid biomass.

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