COMBUSTION OF POULTRY MANURE WITH SOLID BIOMASS – AN ALTERNATIVE FOR ENVIROMENTAL PROTECTION AND LOCAL ENERGY PRODUCTION

Rodica-Manuela GRIGORIU[1], Gheorghe LAZAROIU[2], Iulia SIMION[3]

This research aims to demonstrate experimentally that pollution by burning poultry waste mixed with wood biomass in optimal mass holdings can be reduced so as to fall between the upper and lower assessment thresholds for pollutants. These characteristics were determined in the laboratory of the Department of Thermotechnics of the Faculty of Mechanics and Mechatronics, Polytechnic University of Bucharest. Determinations were made on both pure manure and those mixed with the solid biomass bed, which was in a mass proportion of 10-14%, the samples being taken directly from the poultry hall. The experimental determinations were performed for poultry manure from the central region of Muntenia. The research highlighted the possibility of burning highly polluting poultry manure along with solid biomass. The developed co-combustion technology has responded positively both in terms of energy and environment. Solid biomass co-combustion was used based on the energy characteristics of the bird droppings, which have a high humidity and a low calorific value. The proposed combustion has solved the problems of high combustion speed, which is very low for wet bird droppings, while respecting the limits of environmental pollution. The performance of the co-combustion was also a consequence of a controlled mass dosing, in accordance with their energy characteristics, represented mainly by humidity and calorific value.

Keywords: Combustion; Poultry manure; Biomass; Local energy production; Environmental protection solution

1. Introduction

To meet current food needs, the world's poultry production recorded in 2018 reached 122,5 million tons, compared to the quantity of 120,5 million tons in 2017, representing a modest increase of 1,6 %.

World poultry production increased from 41,0 million tonnes of carcass equivalent in 1990 to 120,5 million tonnes in 2017. Out of a total of 120,5 million tonnes of poultry produced worldwide, the chicken broiler represents 89,19%. In 2018, the total production of poultry meat in the EU-28 was 15,8 million tons, increasing by 18% compared to 2013. The main poultry meat is chicken, with a total production of 12,8 million tons in 2017 [1].

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[1] PhD Student, Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail: manuela.grigoriu.1968@gmail.com

[2] Prof., Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania

[3] PhD Student, Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania

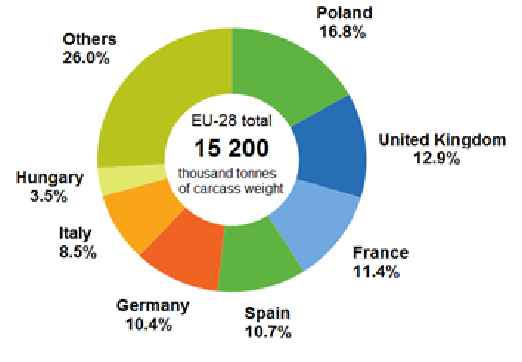
The European Environment Agency's EEA-Europe 2020 report, published in November 2020, shows that although emission levels for most air pollutants have fallen in the EU in recent decades (see Fig. 1.1.), air pollution remains a significant problem [2].

Based on previous results [3] - [10], this research aims to demonstrate experimentally that pollution by burning poultry waste mixed with wood biomass in optimal mass holdings can be reduced so as to fall between the upper and lower assessment thresholds for pollutants. These pollution thresholds are set out in Directive 2008/50 / EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality [11].

Poultry production takes place mostly in the EU on poultry farms, as specially designed and built units. they produce broilers. According to data published by Eurostat, the total number of broiler farms in the EU-28 was about 2,1 million in 2013. However, only 20000 are professional farms with more than 5000 broilers. The number of broiler farms per population is extremely high in Romania, Poland, Greece and Portugal.

The European Union produced 15,2 million tonnes of poultry meat in 2018, a new record at the time. This represents a cumulative rise of about one quarter or 3,2 million tonnes since 2010.

As shown in Fig. 1.1, in 2018, about 70% of EU poultry meat came from just six Member States: Poland (16,8%), the United Kingdom (12,9%), France (11,4%), Spain (10,7%), Germany (10,4%) and Italy (8,5%).



Note: shares do not sum to 100% due to rounding

ec.europa.eu/eurostat

Fig. 1.1. Poultry production in the EU, 2018

Poultry meat production in Romania - Romania produced in 1999, in an intensive industrial system, 104000 tons of poultry meat equivalent to carcass, and in 2018, 413 thousand tons of carcass equivalent, so more than triple over a period of 18 years (Table 1.3, UCPR -2019). Meat production obtained in alternative systems, increased from 1,54% in 2017 to 2,06% in 2018. [1]

Table 1.3.

Poultry meat production in Romania

Specification		2005	2019	2014	2015	2016	2017	2018
Live poultry meat (thousands of tonnes)		375	476	493	520	559	607	609
Live poultry meat, industrially produced (thousand tonnes)		282	406	427	461	468	497	530
Poultry meat equivalent to carcass (thousand tons)		293	371	384	406	436	473	475
Poultry meat equivalent to industrially produced carcass (thousand tons)		220	317	333	360	365	388	413
Import of meat and poultry preparations (thousands of tonnes)		161	98	131	133	149	158	155
Export of meat and poultry preparations (thousands of tonnes)		7,0	63,5	66,8	78	78	70	84
Internal consume	Total (thousand tons)	447.0	405.5	448.2	461	507	561	546
	Per capita (kg)	22.4	20.3	22.4	23.1	25.3	28.0	27.3
EU 27 poultry meat consumption (kg / capita)		-	23,8	22,0	22,5	22,7	24,1	-
Degree of self-sufficiency (domestic production / total consumption)		65.5	91.5	85.7	88.1	86.0	84.3	86.9

Source: UCPR, MADR, INS, AVEC, 2019 [1]

Global livestock growth is projected to grow by 2050, with human population growth projected to reach 9.6 billion by 2050. Poultry is expected to grow the most, by about 121% (Mottet, 2018). A recent report published in the Netherlands (Rabobank, 2018, quoted by Horne - 2018) estimated that the EU market share for "alternative meat" will double in the next seven years from 15 to 20% in 2025 [1].

2. Pollution caused by combustion

2.1. General aspects

Combustion pollution is a consequence of fuel composition and chemical combinations resulting from high temperatures. A fuel is presented for its composition by elemental analysis, according to Eq.(2.1):

$$C_i + H_i + S_c^i + O_i + N_i + A_i + W_t^i = 100[\%], \qquad (2.1)$$

where the index „*i*" represents the ratio to the initial state of the fuel, *C* being the carbon content, *H* - the hydrogen content, S_c - the fuel sulfur, *N* - the nitrogen content, S_c - the ash content, W_t - the total humidity, with mass proportions presentation.

Pollutants from combustion processes can be classified into:

a. Pollutants harmful to the human body Nitrogen oxides (NO_x), Sulfur oxides (SO_x) Carbon monoxide (CO);
b. Pollutants affecting vegetation: sulfur dioxide (SO_2) and combinations of Cl and H_2;
c. Persistent pollutants in the soil, which accumulate over time and become harmful (heavy metals);
d. Climate pollutants (CO_2 and N_2O) by triggering the greenhouse effect and destroying the ozone layer.[12]

2.2. Nitrogen oxide emission control

Nitrogen oxides, generically denoted NO_x, refer to NO, NO_2 and N_2O. Nitrogen oxides are pollutants that occur even when burning a "clean" fuel (eg hydrogen), the combustion of which produces only water vapor. The explanation lies in the fact that nitrogen combines with oxygen at high temperatures, the source of nitrogen oxides being represented by nitrogen in the air.

It turns out that two conflicting requirements come into play:

a) raising the adiabatic combustion temperature which increases the combustion efficiency, the threshold beyond which NO_x formation becomes important is 1500 °C;

b) reduction of the adiabatic combustion temperature to decrease the NO_x emission.

In the reaction environment of a flame, two areas are distinguished: the oxidation zone or the flame front and the area of the combustion products.

Oxygenated free radicals (O, OH, HO_2) are found in both areas, and the oxidation zone is also characterized by the presence of hydrocarbon radicals (CX) and hydrocarbon fragments that disappear very quickly and are no longer found in the area of reaction.

Of the four possible combinations of two nitrogen sources and two reaction media, the specific mechanism of NO formation is shown in Fig. 2.1. [13].

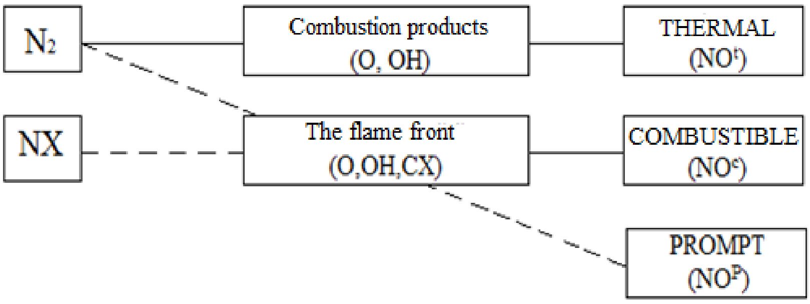


Fig.2.1. Mechanisms of NO formation

As noted, there are also chemical interconnections between these mechanisms. However, their kinetic aspects give them their own individuality, which at the application level, makes them dependent on parameters such as temperature and composition of the reaction mixture.

The thermal mechanism (Zeldovich) is the synthesis of the phenomenon and is based on the reactions represented by Eqs. (2.1 - 2.6), that take place at high temperatures during combustion, between nitrogen and oxygen in the air. These reactions are:

$$O + N_2 \overset{k_1}{\rightarrow} NO + N \qquad (2.2)$$

where, $k_1 = 1.8 \cdot 10^{14} \cdot e^{-\frac{318}{RT}}$ $[cm^3/mol \cdot s]$ (2.3)

$$N + O_2 \overset{k_2}{\rightarrow} NO + O \qquad (2.4)$$

where, $k_2 = 6.4 \cdot 10^{9} \cdot e^{-\frac{26}{RT}}$ $[cm^3/mol \cdot s]$ (2.5)

$$N + OH \overset{k_3}{\rightarrow} NO + H \qquad (2.6)$$

where, $k_3 = 3.8 \cdot 10^{13}$ $[cm^3/mol \cdot s]$ (2.7)

The decisive reaction is represented by Eq. (2.2). The atoms in the N_2 molecule are joined by a triple bond, which explains the high activation energy of the reaction (E_a = 318 kJ/kmol). For this reason, reaction represented by Eq. (2.2) becomes important only at high temperatures (above 1500 °C). The formation rate for NO is obtained based on the three reactions, in the form of:

$$\frac{d[NO]}{d\tau} = 2k_1 \cdot [O] \cdot [N_2] \qquad (2.8)$$

It follows from Eq. (2.8) that in order to reduce the formation of NO, the concentrations of monoatomic oxygen or nitrogen must be reduced, or the value of the constant k_1 must be reduced by reducing the temperature.

The instantaneous mechanism (Fenimore) / Prompt NO shows the formation of instantaneous formation of nitrogen monoxide and was discovered in 1979 by C.P. Fenimore from the General Electric Research and Development Center in Shenectady, NY [14], [15]. He observed significant NO formation in combustion regions where the Zeldovich mechanism could not function, namely in "cold" areas of the flame. Fenimore (who proposed the term prompt NO) explained the formation of NO in these areas by the reactions between nitrogen and the CH and CH_2 radicals in hydrocarbons:

$$N_2 + CH \rightarrow NCN + H \qquad (2.9)$$

$$N_2 + CH_2 \rightarrow HCN + NH \qquad (2.10)$$

The Fenimore mechanism is favored by fuel-rich flames. The activation energies of the reactions of this mechanism are lower than for reaction represented by Eq. (2.2). For example, reaction represented by Eq. (2.9) has an activation energy of 75 kJ/mol, almost 4 times lower than reaction represented by Eq. (2.2), which means that NO is generated at temperatures lower than the Zeldovich mechanism (starting at 730 °C).

Studies on the kinetics of N_2O formation have revealed a number of elemental reactions. Of these, the most important for the formation of N_2O are the reactions represented by Equations (2.11) and (2.12):

$$NH + NO \leftrightarrow N_2O + H \tag{2.11}$$

$$NCO + NO \leftrightarrow N_2O + CO \tag{2.12}$$

It can be seen that almost all the amount of N_2O formed in the combustion of gaseous fuels comes from the reaction of NO with nitrogenous intermediate species typical of the NO fuel mechanism: the amounts of nitrous oxide emitted by the combustion of gaseous fuels are very small, in order of ppm. Nitrogen oxide is formed when burned at low temperatures.

Formation mechanism of the formation of nitrogen (from organic mass) - The mechanism of formation of NO from the formation of nitrogen is based on the pyrolysis of fuels containing aromatic hydrocarbons or polyaromatic compounds with one or more nitrogen atoms in the molecule (coal, fuel oil, coke , waste oils, biomass). These compounds decompose directly to NO in the process of volatile release. Nitrogen oxides, called "fuel", are thus formed. These compounds do not form in gaseous fuels.

The mechanism of NO_2 formation is based on the reaction of nitrogen monoxide with a peroxide radical (RO_2) shown in Eq. (2.13):

$$NO + RO_2 \rightarrow NO_2 + RO \tag{2.13}$$

2.3. Reduction and control of nitrogen oxide emissions

There are two main methods of reducing nitrogen oxide emissions, generically known as primary and secondary methods.

The primary methods act on the thermogasodynamic processes in the flame and the hearth, so that the emission of nitrogen oxides is minimally possible.

Secondary methods group the multitude of technologies for the absorption of nitrogen oxides emitted by combustion.

Currently, in order to comply with the emission rules, it is mainly done through primary methods [16].

Combustion (reduction of NO_x in the hearth) **-** This method (fuel admitted in steps in the hearth) is often also considered a secondary measure, as long as the aim is to reduce the nitrogen oxides that are already formed.

The technique involves injecting fuel into the hearth above the main combustion zone, thereby forming a substoichiometric secondary combustion zone. Part of the combustion air is added upstream of this area to complete the combustion.

Burning can be considered divided into three zones, as shown in Fig. 2.2. In the primary area the main fuel is burned in poor fuel conditions.

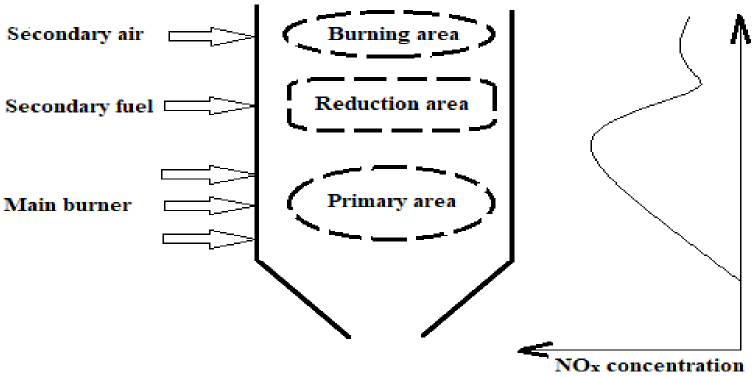


Fig.2.2. The principle of combustion with reduction zone in the hearth

2.4. Ammonia combustion

Not all fuels contain ammonia, or lead to its formation through the induced thermal field. Poultry waste is rich in ammonia, so by combustion, this pollutant is removed.

Ammonia is a chemical compound made up of one nitrogen atom and three hydrogen atoms. The state of aggregation of ammonia is gaseous, having the chemical properties of a base, toxic with a pungent odor, lighter than air.

The burning of ammonia in nitrogen and water is exothermic. Dinitrogen is the thermodynamic product of combustion: all nitrogen oxides are unstable in relation to N_2 and O_2, the principle behind the catalytic converter. Combustion of ammonia in air is very difficult in the absence of a catalyst (such as platinum or hot chromium oxide) because the flame temperature is usually lower than the ignition temperature of the ammonia-air mixture. The flammable range of ammonia in the air is 16-25%. There are no concentrations in this range for avian waste, with concentrations below 3%. A platinum electrode will be inserted to control the ammonia.

As shown in Eq. (2.14), ammonia does not burn in the air, but burns in oxygen; water and nitrogen result:

$$4NH_3 + 3O_2 \rightarrow 6H_2O + 2N_2 \quad (2.14)$$

In the presence of catalysts (platinum or platinum-rhodium) and by heating (750 – 800 °C), the oxidation of ammonia leads to the formation of nitrogen oxide:

$$4NH_3 + 5O_2 \rightarrow 6H_2O + 4NO \quad (2.15)$$

The solid biomass bed acts as a catalyst, the high temperature allowing combustion according to Eq. (2.15).

The caloric power of ammonia is $H_i^i \cong 18{,}6\ MJ/kg$, which indicates a low caloric intake. It is also worth noting that the burning of ammonia produces heat without emitting CO_2.

3. Pilot-scale experimental research on fixed-layer combustion of solid biomass avian manure

3.1. Determination of physico-chemical and energy characteristics of poultry manure

These characteristics were determined in the Laboratory of the Department of Thermotechnics of the Faculty of Mechanics and Mechatronics, Polytechnic University of Bucharest. Determinations were made on both pure manure and those mixed with the solid biomass bed, which was in a mass proportion of 10-14%, the samples being taken directly from the poultry hall.

The experimental determinations were performed for poultry manure from the central region of Muntenia. The average density of manure differs very little for pure poultry manure and those with biomass bed, with the values:

- bulk density of pure poultry manure: 87 - 141 kg/m^3;
- bulk density of poultry manure with straw bed, 80 - 126 kg/m^3.

Humidity has very high values, on average 35-50%.

The thermal energy analysis of poultry manure is presented in Tables 3.1. and 3.2.

Table 3.1.

The results of the technical analysis for biomass bed manure

Test / Characteristic	I	II	III	IV	V
Humidity, W_t^i, %	35.1	36.3	37.4	39.0	40.3
Volatile, V^i, %	50.2	48.3	47.7	45.8	46.2
Ash, A^i, %	6.9	6.7	6.8	6.2	6.0
Fixed carbon, C_f^i, %	7.2	8.7	8.1	9.0	7.7

Table 3.2.

The results of the technical analysis for pure manure

Test / Characteristic	I	II	III	IV	V
Humidity, W_t^i, %	37.2	37.3	36.8	37.2	36.8
Volatile, V^i, %	50.1	50.3	49.8	50.2	50.5
Ash, A^i, %	6.3	5.9	6.4	6.1	6.3
Fixed carbon, C_f^i, %	6.4	6.5	7.0	6.5	6.4

The „i” index refers to the initial condition, considered at the sampling point in the hall. The tests show a low amount of solid fuel in the form of fixed carbon, and a high ballast content, represented by the sum of moisture and ash. The high content of ballast, defined by the sum of moisture and ash, according to the data in Table 3.3., is in the range of 42,0 – 46,3%, indicating a difficult application for direct combustion technology, with the imposition of humidity.

Tabelul 3.3.

Ballast content of poultry manure

Test Ballast, %	I	II	III	IV	V
Pure manure ballast	42.0	43.0	44.2	45.2	46.3
Manure ballast with solid biomass bed	43.5	43.2	43.2	43.3	43.1

Table 3.4.

The results of the elemental analysis of manure

Results Characteristic	for ballast with biomass bed, in a mass proportion of 12%	for pure manure
Carbon, C^i, %	12.3 – 22.5	12.1 – 16.1
Hydrogen, H^i, %	4.3 – 5.2	4.3 – 4.9
Sulfur, S_c^i, %	1.7 – 2.0	1.6 – 1.8
Oxygen, O^i, %	35.1 – 37.4	34.3 – 36.2
Nitrogen, N^i, %	1.4 – 2.3	1.6 – 1.8
Ash, A^i, %	6.1 – 12.9	6.1 – 6.8
Humidity, W_t^i, %	34.0 – 40.0	36.1 – 40.1

The lower calorific value (H_i^i) is the main indicator of the efficiency of energy recovery by burning this poultry manure. It was determined by calculation based on the elementary analysis, using the Eq. (3.1):

$$H_i^i = 339\,C^i + 1029\,N^i + 109(O^i - S_c^i) - 25{,}1\,W_t^i \quad [kJ/kg] \tag{3.1}$$

The range of variation of the lower calorific value is shown in Table 3.5.

Table 3.5.

Lower calorific value limits (H_i^i)

Test Poultry manure	I - V
Pure	5910 – 3810
With solid biomass bed	5940 - 3840

There are low values for the lower calorific value, which implies for the direct combustion the presence of a thermal support fuel.

3.2. Energy characteristics of the solid biomass used

For the experimental test, the fuel used was the poultry manure taken directly from the poultry house, fed over a fixed layer of solid biomass (wood or agricultural), there was also the situation when vine ropes and branches were added on top. The energy characteristics of the solid biomass used for the experiment were analyzed according to standard methods and are presented in Table 3.6.

Table 3.6.

Energy characteristics of the types of solid biomass sorts used [17]

Biomass	C^i	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
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

3.3. Description of the experimental installation

The experiment was performed on a laboratory scale, with the help of a hot water oven / boiler installation, with fixed grill, represented in Fig. 3.1.

The experimental installation consists of:

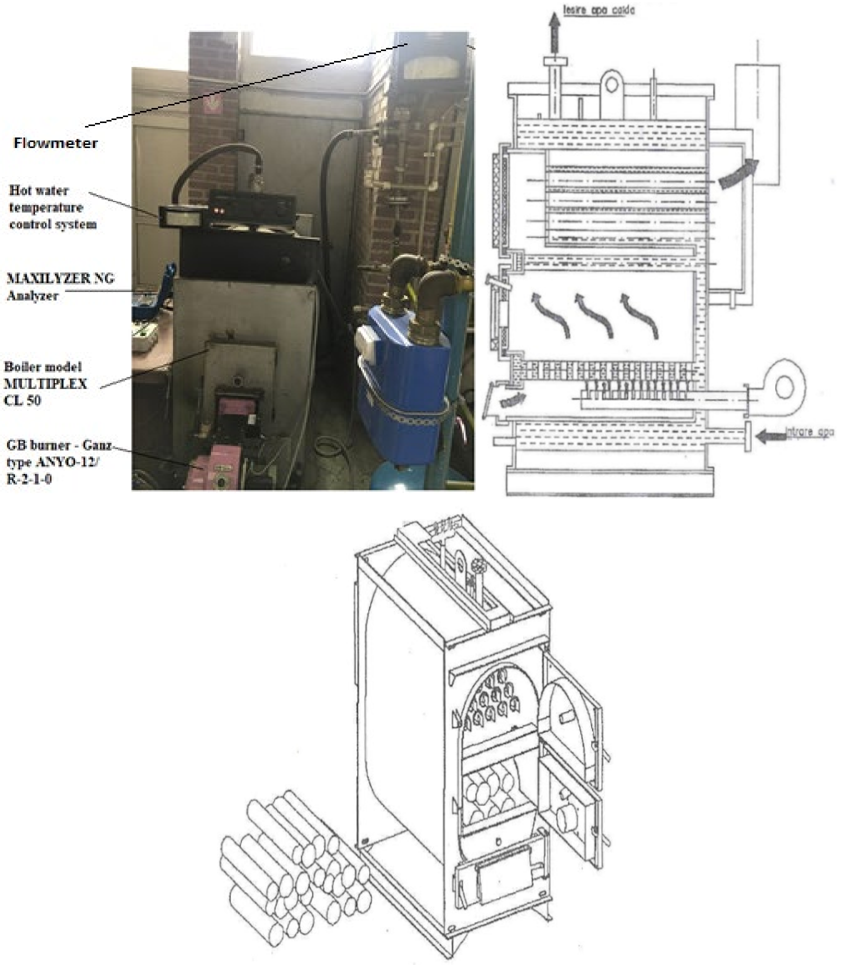
- Boiler Multiplex CL 50 was designed for a power of 50000 kcal/h, 58 kW and a maximum pressure of 3 bar [16].

The pilot boiler has a power of 55kW and has the following dimensions of the hearth [17]:

- length: L_f = 750 mm; width: l_f = 550 mm; height: h_f = 600 mm
- hearth volume: V_f = 0,25 m^3

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

- length: L_g = 520 mm; width: l_g = 550 mm
- bar width: l_b = 15 mm; space between bars: s = 15 mm;
- free space length between bars: l_{sl} = 360 mm;
- surface of the grill: S_g = 0,286 m^2;
- active surface of the grill: S_{g_a}= 0,19 m^2.



(a) (b) (c)

Fig. 3.1. (a) Pilot installation, 55 kW boiler from the Thermotechnical Laboratory of the Faculty of Mechanics and Mechatronics, UPB; (b) Diagram of the cross-section of the pilot boiler; (c) Diagram from the front of pilot boiler.

The Multiplex CL 50 pilot boiler, used in experimental research, is intended for the production of thermal energy and is intended for heating homes, office buildings or factory halls that do not exceed an area of 1500 m^3 (maximum thermal power being 55 kW) [16]. The boiler has a natural draft with a chimney mounted outside the building.

- Flue gas analyzer MAXILYZER NG

Flue gas analysis is necessary to determine the components of the flue gas, the excess air and the efficiency of the combustion process. In order to have a complete picture (depending on the additional objectives pursued), they can be measured along with CO_2 emissions and the proportion of oxygen and the percentages of CO, hydrocarbons, NO_x and SO_x.

Fig. 3.2. Positioning of the flue gas analyzer probe in the flue gas channel connecting the boiler to the chimney

The analyzer is equipped with electrochemical measuring cells for O_2, CO, CO_2, NO_x, and SO_2. It has automatic cleaning according to the measured concentrations, has an LCD screen with simultaneous display of 10 recorded values, the data memory contains 100 measurement blocks, includes an integrated thermal printer and is protected by a robust, dust and water tight housing. In the experiment, the analyzer probe was placed at the end of the pilot boiler, at the flue gas outlet to the chimney so that measurements could be made and to determine the efficiency of the heating installation, Fig. 3.2.

Flue gas analysis performed with MAXILYZER NG analyzer was compared with the pollution requirements of EN50379-2 and environmental directives 98/336 / EWG (EEC). [16]

3.4. Experimental research methodology

The massive shareholdings of the fuel mixture used for co-combustion were:

- 66.67% forest biomass, wood mixture of different species (beech, oak, hornbeam) in the form of planks of size (3,5 x 7 x 25) cm^3, maximum humidity of 25%, as seen in Fig. 3.3(a), mass of 5.0 kg and volume in a layer of (40 x 307 x 25) cm^3;
- 13.33% manure, 50% humidity, as seen in Fig. 3.3(b), 1kg mass and layer volume (20 x 20 x 3) cm^3;
- 20% agricultural biomass, mixture of vines and bark branches, in the form of furrows 25 cm long, and of different thicknesses (the rays), between (1 ÷ 2.5) cm, maximum humidity of 15%, as seen in Fig. 3.3(c), mass of 1.5 kg and volume in a layer of (40 x 30 x 20) cm^3.

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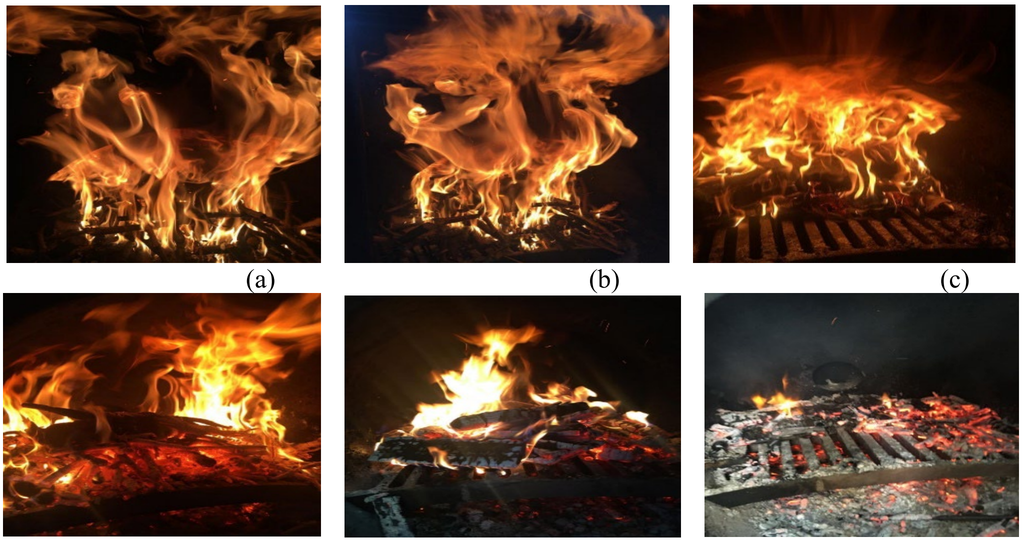
Fig. 3.3 Fuel mixture components
(a) Solid forest biomass in the form of plank; (b) Poultry manure;
(c) Agricultural biomass in the form of, bark branches and vines

In Fig. 3.4 images of the combustion process inside the 55kW pilot boiler at different times of the process are presented.

Initially, the fixed fuel layer was represented by wood biomass (40 x 7 x 30) cm^3. In this phase, the fuel layer was characterized by a low porosity (high density), over which the 3 cm thick layer of manure was added, and finally, on top of the manure, the vine ropes were placed in a volume of (40 x 15 x 30) cm^3, the fixed layer of fuel being at this stage characterized by a low density, which facilitated its rapid ignition and flickering of the fuel due to the increase in combustion rate, Fig. 3.4 (a), (b).



(a) (b) (c)

(d) (e) (f)

Fig. 3.4. Images of the burning process inside 55 kW pilot boiler at different times of the process

In Table 3.7. the experimental mixing parameters for the fuel mixture used for each of the experimental steps are specified.

Table 3.7.

Experimental parameters of the fixed layer fuel mixture

Parameters / Stage	Fixed layer fuel	H_{layer} [cm]	Burning time [min]	Fuel layer volume [m^3]
I	Wood	25	5	0.030
II	Wood + manure	25 + 3	12	0.001
III	Wood + manure + Branches of vines	25 + 3 + 20	4	0.024

In Table 3.8. the mass participations of the components of the experimentally used fuel mixture are specified.

Table 3.8.

Mass participation of experimentally used fuel mixture components

Fixed layer fuel / No.crt.	Layer components	Component quantity [kg]	Mass participation of the component [%]
1.	Wood	5	66,67
2.	Poultry manure	1	13,33
3.	Branches of vines	1,5	20,0

$H_{layer} = h_1 + h_2 + h_3 = (25 + 3 + 20)\ cm = 48\ cm$, $T_{burning} = 21\ minutes$, where,

H_{layer} - is the total height of the layer, [cm];

$T_{burning}$ - is the total burning time of the fixed layer fuel mixture, [min].

The combustion process is of maximum complexity, involving factors such as: time dependence, spatial dependence, the degree of mixing of the reactants, flow, reaction medium, combustion rate, convection conditions. In all three experimental tests the combustion was stationary, three-dimensional, without prior mixing, turbulent flow, in a heterogeneous environment.

The mass dosage presented is the result of multiple previous tests, thus achieving an optimization between the energy characteristics of the participations. Any change in energy characteristics, especially for avian manure, will require a dosage adjustment, in the sense that lowering the humidity of avian manure will increase their mass participation. The research undertaken is for a very high humidity of poultry manure, around 50% (see *Section 2*), the research aiming to give an answer to this unfavorable limit situation.

3.5. Experimental tests on wood burning speed compared to poultry manure

The burning rate of wood is an indicative physical quantity for industrial technology applications. Theoretically, the burning rate in m / s is the rate at which a layer of fuel decreases over time, according to Fig. 3.5. The combustion rate in the fuel layer was based on laboratory tests, in which wooden specimens of a certain size were used.

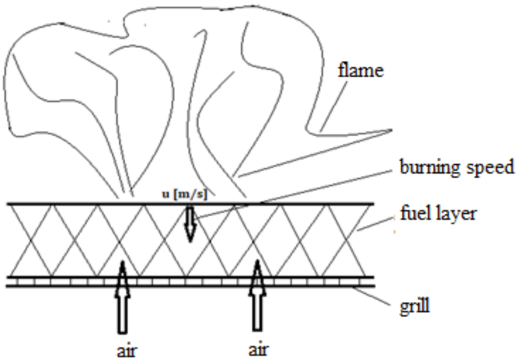


Fig. 3.5. Scheme of layered biomass combustion, with the definition of combustion rate

For experimental determinations, wooden specimens were made, with a length of 60 mm and a diameter of 6 mm, which were placed in an electrically heated oven, equipped with a thermostat.

Table 3.7.

Experimental parameters for wooden specimens

Parameters No. crt.	W [%]	*u* [m/s]
1	40	0,005
2	30	0,007
3	20	0,010
4	10	0,012

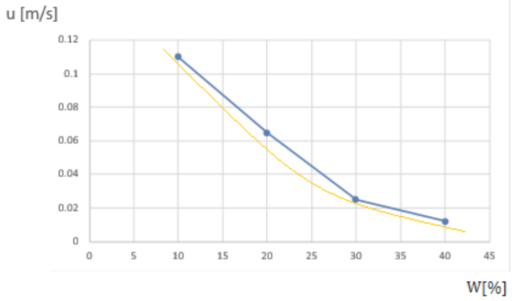


Fig. 3.6. Burning speed for wooden specimens

For poultry manure with a humidity of W = 40%, for a layer with a height of 10 mm, for similar conditions of determination as in the case of wood, the burning rate was *u* = 0,012 m/s, about 10 times lower than that of biomass woody.

The combustion of the fuel was carried out partly in the layer and partly in the volume of the furnace, as can be seen in Fig. 3.4 (a), (b). It is noteworthy that the burning rate increases with the decrease of the density of the fuel in the layer. [17]

The volume of the fuel mixture placed in a fixed layer on the oven grate was (40 x 30 x 48) cm^3, Fig. 3.7.

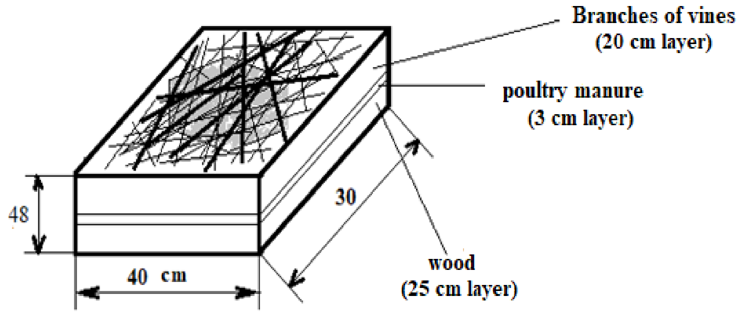


Fig. 3.7. Scheme of the fixed layer of fuel mixture (wood + poultry manure + branches of vines)

3.6. Results and discussions

Results of flue gas composition measurements using the MAXILYZER NG flue gas analyzer during the experiment are given in Table 3.8.

Table 3.8.

Experimental parameters measured by the MAXILYZER NG flue gas analyzer

Parameters / Stage	Hour	O_2 [%]	CO_+ [%]	CO_2 [%]	T_{gas} [^OC]	T_{air} [^OC]	Dif. t [^OC]	NO_X [ppm]	NO_2 [ppm]	SO_2 [ppm]	λ
I	11:06:29	9.6	0.48	11.1	387	22.9	363.1	81	0	0	1.84
	11:07:41	9.8	0.541	10.9	386	21.6	363.4	75	0	0	1.88
II	11:11:34	11.5	0.188	9.2	307	22.3	283.7	72	0	0	2.21
	11:14:16	13	0.136	7.8	279	22.3	256.7	61	0	0	2.63
	11:15:36	13.3	0.159	7.5	275	22.3	252.7	56	0	0	2.73
III	11:23:52	10.1	0.363	10.6	331	24.1	305.9	67	0	0	1.93
	11:24:15	9.2	0.632	11.5	365	23.9	341.1	74	0	0	1.78
	11:24:27	8.8	0.713	11.9	364	24.2	339.8	81	0	0	1.72
	11:25:12	9.8	0.403	10.9	383	24.1	357.9	100	0	0	1.88
	11:27:29	13.7	0.179	7.1	300	24.5	275.5	82	0	0	2.88

It is also worth noting that with the presence of manure in the fuel mixture, CO_+, CO_2, NO_X emissions decrease, as well as the temperature of the gases emitted in the chimney, Fig. 3.8.

Analyzing the results of the experimental tests, it turned out that the technology proposed by the combustion of solid manure avian manure is a viable solution. Thus, both combustion time and pollutant emissions recommend the technology for industrial application.

Regarding the performances of the boiler installation, Fig. 3.9., data were presented including: the temperature of the flue gases discharged to the chimney of the installation and the efficiency of the installation (values up to 82%).

Consequently, it is possible to use for that combustion, energy installations for the production of thermal energy equipped with a fixed grate for low and medium powers and with a fixed or mobile grate for medium powers.

The comparison of the technical-economic effect of the combustion of poultry manure with biomass was made by appealing to the results of the paper [3]. This paper shows an industrial poultry production hall of 1728 m^2, with a total energy consumption of 1438 kWh/day.

Considering the energy obtained by burning in combustion the poultry manure with biomass of 3.89 kWh/kg, results in a fuel consumption for the energy consumption of the same hall of 370 kg/day, of which the poultry manure has a mass share of 13.3% , exactly 49.21 kg/day.

This amount is a contribution to the protection of the environment from the situation of its storage over time.

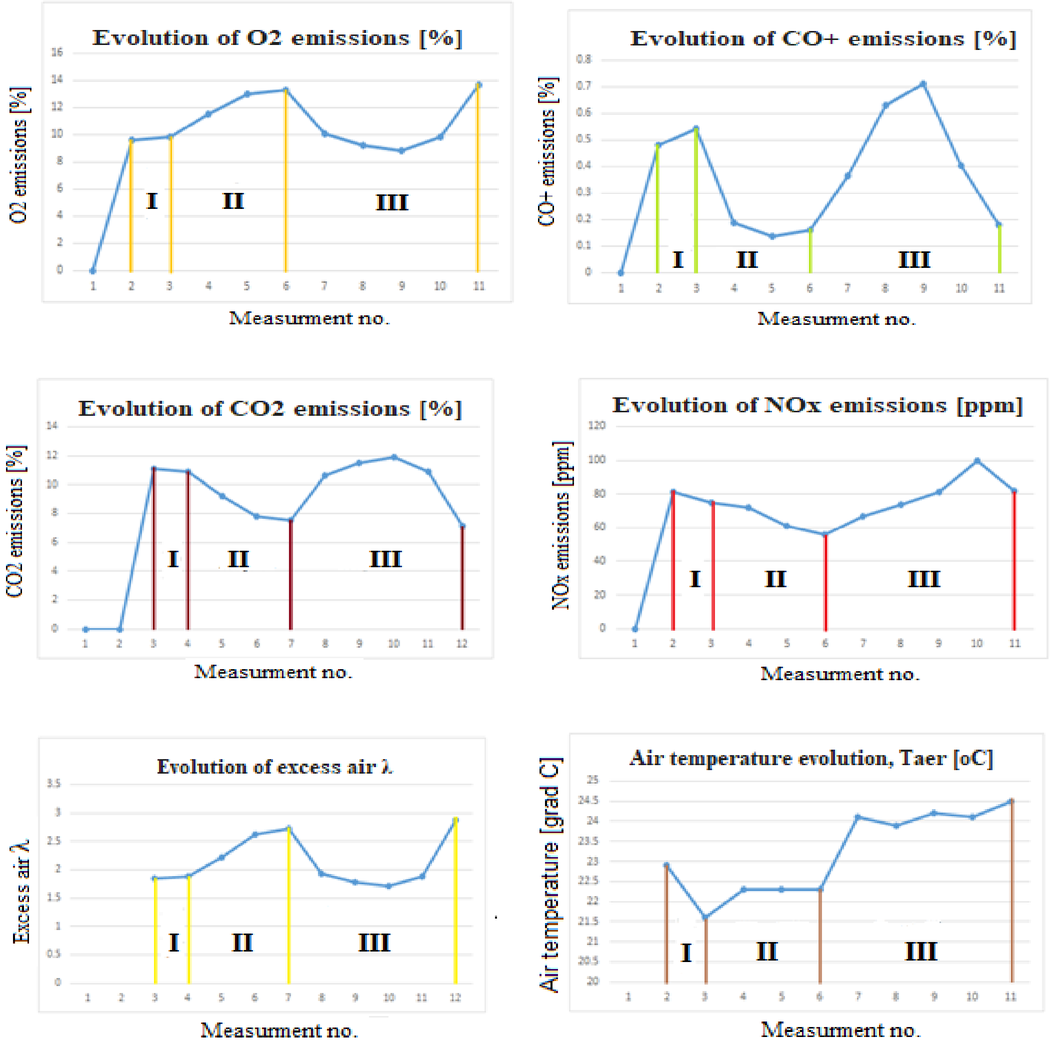


Fig. 3.8. Evolution of co-combustion parameters;
I, II, III - the three stages of co-combustion depending on the fuel mix

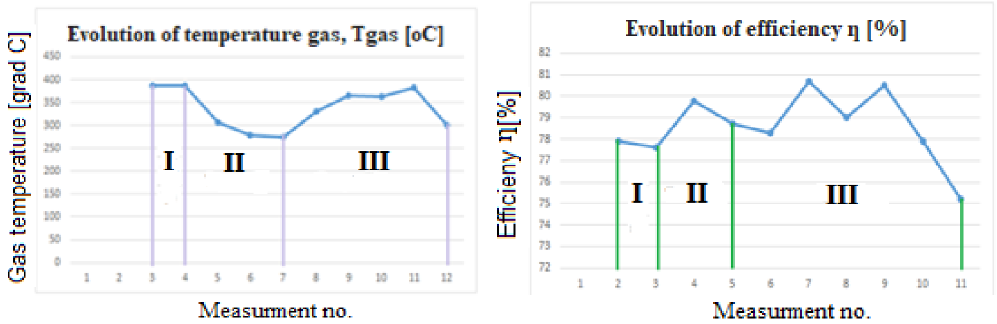


Fig. 3.9. Evolution of the efficiency parameters of the thermal energy production installation; I, II, III - the three stages of co-combustion depending on the fuel mix

4. Conclusions

The research highlighted the possibility of burning highly polluting poultry manure along with solid biomass. The developed co-combustion technology has responded positively both in terms of energy and environment. Solid biomass co-combustion was used based on the energy characteristics of the bird droppings, which have a high humidity and a low calorific value. The proposed combustion has solved the problems of high combustion speed, which is very low for wet bird droppings, while respecting the limits of environmental pollution. The performance of the co-combustion was also a consequence of a controlled mass dosing, in accordance with their energy characteristics, represented mainly by humidity and calorific value.

The paper also examines the possibility of co-combustion of wet poultry manure with biomass, which replaces the heat produced by hydrocarbons (the elimination of hydrocarbons reduces CO_2 emissions proportionally).

Poultry manure can be used as agricultural fertilizer, but also as an energy source. The combustion of poultry manure reduces the amount of waste stored and can interface between storage and distribution to agricultural users.

In addition, the combustion of poultry manure produces energy, which is necessary for the technological process in the poultry farm, which requires a certain heating. This heating is done today by burning hydrocarbons or with electric heaters.

As the poultry manure has an extremely high humidity, the solution of co-combustion of those with wood waste was chosen. Under the Kyoto agreement, the combustion of biomass-poultry manure leads to zero CO_2 emissions.

The research presents the situation of the combustion of poultry manure with a very high humidity (around 50%). Changing the quality of fuels will require a change in their mass proportions in the mix, so that at lower humidity, the share of poultry manure can be increased.

The flue gas analysis of this combustible waste mixed with biomass is meeting the efforts to find solutions for the eco-energy recovery of this livestock waste, in accordance with the EU rules in force.

The experimental results showed that the fixed-layer burning of manure in co-combustion with wood or agricultural biomass can comply with the environmental protection rules imposed by the legislation in force, provided that in order to increase the combustion efficiency the adiabatic burning temperature does not increase above the threshold. beyond which NOx formation becomes important. After the combustion, the presence of ammonia was not noticed.

The Commission's report to the European Parliament on the Second Prospective Assessment of Clean Air (Brussels, 8.1.2021 COM (2021)) [2] specifies that there is a trend towards a decrease in EU air supported by continuous efforts, especially for pollutants that have shown a lower reduction. The report cites ammonia emissions, which have been capped since 2005 and even increased in recent years in some Member States. Ammonia is one of the main pollutants found in poultry manure, a fuel that is the subject of study in the present research.

The pollutant NH_3 (ammonia) disappears through the combustion reaction, the flue gases, the high temperature biomass layer, as well as the excess air, allowing the combustion of ammonia.

Experimental data allow the conclusion that energy can be obtained by burning biomass – poultry manure, simultaneously with a reduction in environmental pollution.

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REFERENCES

[1]. *I. Custură*, Proiectul ADER 8.1.9. – Cercetări privind capacitatea de combinare generală şi specific a rasei Gât Golaş de Transilvania cu diferite rase şi linii de găini privind calitatea cărnii (Research on the ability to combine the general and specific combination of the Gât Golaş de Transilvania breed with different breeds and chicken lines regarding the quality of the meat). . (in Romanian)

[2]. http://www.cdep.ro/afaceri_europene/CE/2021/COM_2021_3_RO_ACTE_f.pdf

[3]. *G. Lazaroiu, D.A. Ciupageanu, R.-M. Grigoriu and I.Simion*, „Energy recovery from poultry manure: a viable solution to reduce poultry industry energy consumption” 18th International Conference on Renewable Energies and Power Quality (ICREPQ’20).

[4]. *L. Mihaiescu et al*., Cazane si turbine (Boilers and turbines), **Vol. I** - Boilers, 2nd edition", Ed. PERFECT, Bucureşti 2002,

[5]. *G. Lazaroiu et al.*, Biomasa solidă, o sursă de energie curată (Solid biomass, a source of clean energy), Ed. POLITEHNICA Press, Bucureşti, 2018. (in Romanian)

[6]. *O. Udrea and G. Lazaroiu*, „RES integration in ROMANIA," U.P.B. Sci. Bull., Ser. C, 2015.

[7]. *G. Lazaroiu, L. Mihaiescu, D.-A. Ciupageanu, R.-M. Grigoriu, and I. Simion*,"Efficient poultry industry waste management approach in the bioeconomy framework", ICAMS 2020 – 8th International Conference on Advanced Materials and System.

[8]. *L. Mihaescu, G. Lazaroiu, I. Pisa, D.-A. Ciupageanu, and V. Berbece*, "Energy valorization of poultry manure through products resulted in a pyrolysis process," in 18th International Multidisciplinary Scientific GeoConference SGEM2018, 2018.

[9]. *L. Mihaescu, G. Lazaroiu, I. Pisa, G.-P. Negreanu*, V. Berbece, and D.-A. Ciupageanu, "Thermal conditions required for poultry manure combustion in furnace boilers," in 19th International Multidisciplinary Scientific Geoconference SGEM2019, **Vol. 19**(4.1), 2019.

[10]. *C. Neaga and Al. Epure,* „Thermal calculation of steam generators, Guide", Ed. Tehnică, 1988, 315 pg.

[11]. https://eur-lex.europa.eu/legal-content/RO/TXT/HTML/?uri=CELEX:32008L0050

[12]. *I. Ioana,* Termoenergetica şi mediul (Thermal energy and the environment), Editura Tehnică, pg. 275 Bucureşti 1996

[13]. *L. Mihaiescu, et al.*, Cazane de abur şi apă fierbinte (Steam boilers and hot water), Editura PERFECT în colaborare cu Editura Printech, 2007. . (in Romanian)

[14]. *C.P. Fenimore*, Formation of Nitric Oxide in Premixed Hydrocarbon Flames. Thirteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 373–380, 1971.

[15]. *C.P. Fenimore,* Studies of fuel-nitrogen in. rich flame gases. 17th Int. Symp. On Combustion, The Combustion Institute, Pittsburgh, PA, 661–670, 1979.

[16]. *Gh. Lăzăroiu., L. Mihaiescu, și al.*, HORESEC – Holistica impactului surselor regenerabile de energie asupra mediului și climei - Spre o energetică circulară (Holistic impact of renewable energy sources on the environment and climate - Towards a circular energy), **Vol. 3**, Editura POLITEHNICA Press, Bucureşti, 2020. . (in Romanian)

[17]. *G. Lazaroiu et al*," Experimental researches on poultry manure combustion in co-combustion with biomass", 10th International Conference on Thermal Equipment, Renwable Energy and Rural Development, TERERD 2021.