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► **To cite this version:**

Rafail Isemin, Frederic Marias, Natalia Muratova, Sergey Kuzmin, Dmitry Klimov, et al.. Wet Torrefaction of Poultry Litter in a Pilot Unit: A Numerical Assessment of the Process Parameters. Processes, 2021, 9 (10), pp.1835. 10.3390/pr9101835 . hal-03695673

HAL Id: hal-03695673

<https://univ-pau.hal.science/hal-03695673v1>

Submitted on 6 Jan 2025

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Article

Wet Torrefaction of Poultry Litter in a Pilot Unit: A Numerical Assessment of the Process Parameters

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Abstract: A numerical model for the wet torrefaction of poultry litter in a pilot unit was developed in this study. The model accounted for the following process steps: preheating biomass in a feed hopper, feeding biomass into the reactor, fluidized-bed generation using superheated steam, and the supply of additional heat by the electric heating of the reactor walls. Following a “black box” approach, a major assumption of the model is that the behavior of the fluidized-bed reactor is similar to a completely stirred tank reactor (CSTR). Under this assumption, the properties of the particles and gases do not depend on their location inside the reactor. During wet torrefaction, poultry-litter biomass was heated to a predetermined temperature and decomposed, generating biochar along with a gas phase (torgas), whose amounts depended on the content of inert ash in the biomass particles. Variable optimization in the model was performed using MATLAB software. The model successfully estimated the optimal duration required for the completion of wet torrefaction under various conditions: temperature, batch weight, reactor dimensions, etc. The model was validated using experimental data obtained from a series of wet torrefaction experiments performed in a fluidized bed, and provided reliable estimations of the duration of the process depending on material properties, reactor size and feedstock characteristics.

Keywords: biofuel; poultry litter; wet torrefaction; fluidized bed; simulation



Citation: Isemin, R.; Marias, F.; Muratova, N.; Kuzmin, S.; Klimov, D.; Mikhalev, A.; Milovanov, O.; Brulé, M.; Tabet, F. Wet Torrefaction of Poultry Litter in a Pilot Unit: A Numerical Assessment of the Process Parameters. *Processes* **2021**, *9*, 1835. <https://doi.org/10.3390/pr9101835>

Academic Editors: Camino Fernández and Roberto Lopez

Received: 20 September 2021

Accepted: 11 October 2021

Published: 15 October 2021

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1. Introduction

The problems triggered by global warming and the accumulation of waste from human–economic activities have encouraged the search for alternative sources for the production of heat and electricity, sorbents, energy-storage devices and other products with high added value. One such promising source is biomass waste, of which approximately 181 billion tons are generated annually all over the world [1].

The focus of this study is on poultry litter, which is a heterogeneous feedstock consisting of bedding material, faeces, urine, feathers and waste feed [2]. Common poultry-litter treatments include composting, anaerobic digestion and direct combustion. However, these all have their drawbacks [3,4], and alternatives solutions are needed [5].

Several biological and thermochemical processing pathways have been applied to biowaste. The thermochemical conversion pathway, generating biochar, was used in this work. Biochar can be used for soil improvement [6], as a sorbent for CO₂ capture [7], as a sorbent for wastewater treatment from organic pollutants [8] and heavy metals [9].

Recent studies of carbon materials derived from biochar demonstrated its potential for application in the production of supercapacitors and fuel elements [10]. The supercapacitors

currently available on the market have high costs, which can be reduced by the use of cheap materials, including biochar [11].

Biochar can be obtained from biomass using gasification, pyrolysis and torrefaction processes. Within torrefaction processes, one can distinguish between dry and wet torrefaction, the latter being also labeled as hydrothermal carbonation, in particular when the wet torrefaction reaction is performed under high pressure [12].

Recently, wet torrefaction has attracted the attention of researchers, since this technology produces biochar with a higher concentration of oxygen functional groups and a low degree of aromatization, which makes the biochar more suitable for further chemical activation [13–22].

Nitrogen-containing biochar obtained by the wet torrefaction of bird droppings is a promising candidate for use as a sorption material for water purification from heavy metals (for example, Pb^{2+} , Cd^{2+} , Cu^{2+} , U^{6+}) or from organic pollutants (for example, dyes) due to its abundance of surface functional groups [22].

The process of wet torrefaction can be carried out in an aqueous environment at a temperature of 180–260 °C with a treatment duration ranging from 5 to 240 min [12], or in a water–steam environment at a temperature of 200–260 °C with a treatment duration of 5–10 min [23–28]. The use of water and steam complicates the reactor's design and increases its cost. A recent study demonstrated the possibility of applying superheated water–steam for wet torrefaction at a pressure slightly higher than the atmospheric pressure, and a temperature up to 350 °C. The quality (solid fuel characteristics and porosity) of the biochar obtained after 15 min of wet torrefaction in a fluidized bed powered by superheated steam was comparable to the biochar produced in slow pyrolysis, and superior to biochar from traditional torrefaction [29].

In this paper, the process of wet torrefaction in a fluidized bed, in an environment of superheated water–steam at an excess pressure of no more than 0.07 MPa is described numerically, and a model for estimating the processing time required for the completion of the wet torrefaction process is proposed.

2. Materials and Methods

2.1. Numerical Model Equations

A numerical model for the wet torrefaction of poultry litter in a pilot unit was developed in this study. The model accounted for the following process steps: preheating biomass in a feed hopper, feeding biomass into the reactor, fluidized-bed generation using superheated steam, and the addition of heat supplied by electric heating of the reactor walls. During the process, poultry-litter biomass was heated to a predetermined temperature and began to decompose, generating biochar, along with a gas phase (torgas), dependent on the content of inert ash in the biomass particles. A major assumption of the model was that the fluidized-bed reactor was assumed to behave like a completely stirred tank reactor (CSTR).

The model relied on the following assumptions: (1) the properties of the particles and the gas held did not depend on their location inside the reactor, (2) the temperature was homogenous in the entire surface of the reactor walls in contact with biomass, (3) the biomass was converted only into a solid fraction (biochar) and a gaseous fraction (non-condensable gases), so that the production of soluble and volatile organic compounds, which were present in the condensate after steam cooling, was neglected, and (4) the amount of superheated steam required from the process could be estimated from the total amount of condensate collected after the experiment.

The initial conditions for the wet torrefaction process were as follows: a portion of biochar was collected from previous batches amounting to half the volume of the reactor, which was considered inert, was loaded into the reactor at a temperature of 20 °C, while a portion of fresh particles were located in the loading hopper. It was found from preliminary experiments (results not shown) that the inclusion of biochar from previous batches provided inert particles as support materials, to sufficiently enhance heat and mass

transfer in the fluidized bed, without the requirement for additional inert material such as sand or glass.

The modeling process operated in two stages. In the first stage, the process of heating the reactor containing the pretreated poultry-litter particles to a desired temperature was calculated, taking into account the heat capacity of the poultry-litter particles, as well as the heat capacity of the material constituting the reactor walls. In the second stage, the wet torrefaction process of fresh particles gradually loaded into the reactor was simulated.

The list of parameters used in the model is presented in Table 1.

Table 1. Nomenclature.

Symbol	Parameter	Units
$N_{f,bunker}$	Number of fresh particles loaded into the hopper	—
$m_{f,bunker}$	Mass of fresh particles inside the hopper	kg
$m_{f,t,0}$	Mass of single fresh particle	kg
$\dot{N}_{dis,bunker}$	Number of particles per unit of time leaving the hopper	1/s
$t_{dis,bunker}$	Total time of discharging the hopper	s
m_r	Mass of particles processed in the reactor	kg
m_{OM}	Mass of organic material in the particles	kg
m_{char}	Mass of biochar in the particles	kg
m_{ash}	Mass of ash in the particles	kg
r_{reac}	Thermochemical reaction rate	kg/s
α_{Char}	Stoichiometric coefficient of biochar production by thermochemical reaction (mass basis)	kg _{char} /kg _{OM}
α_{Gas}	Stoichiometric coefficient of gas production by thermochemical reaction (mass basis)	kg _{gas} /kg _{OM}
A	Frequency factor of thermochemical reaction	s ⁻¹
T_a	Activation temperature of thermochemical reaction	K
$N_{g,i}$	Number of moles of chemical species i in gas	mol
$N_{g,t}$	Total number of moles of gas in reactor	mol
$F_{i,in}$	Molar flux of species in the reactor	mol/s
$F_{g,out}$	Molar flux of gas leaving the reactor	mol/s
$x_{gas,i}$	Molar composition of chemical species i released by the reaction	mol _i /mol _{gas}
U_r	Internal energy of the particles processed in the reactor	J
C_w	Heat capacity of liquid water	J/(kg·K)
C_{sol}	Heat capacity of solid material	J/(kg·K)
T_r	Temperature of the particles processed in the reactor	K
T_{ref}	Reference temperature	K
T_{gas}	Temperature of gas	K
$h_{i,in}$	Molar enthalpy of chemical species i at the temperature prevailing at the inlet of reactor	J/mol
$h_{i,out}$	Molar enthalpy of chemical species i at the temperature prevailing at the outlet of reactor	J/mol
$h_{r,i}$	Molar enthalpy of chemical species i at the temperature prevailing at the particle temperature	J/mol
$\dot{Q}_{r,gas}$	Heat exchange between a particle and the surrounding gas	W
$\dot{Q}_{reac,wall}$	Total heat of reaction	W
$\Delta_r H_{reac}$	Heat of reaction	J/kg

2.1.1. Mass Balance Equations

When dealing with the feedstock to be supplied to the reactor for thermochemical processing, it was first necessary to estimate the number of biomass particles initially loaded into the feedstock hopper:

$$N_{f,bunker} = \frac{m_{f,bunker}}{m_{f,t,0}} \quad (1)$$

This equation states that the number of particles loaded inside the hopper ($N_{f,bunker}$) is equal to the total mass of all particles contained in the hopper ($m_{f,bunker}$) divided by the initial mass of each fresh particle $m_{f,t,0}$.

Then, during the discharge of the feedstock hopper into the wet torrefaction reactor, the number of particles per unit of time that leave the hopper was calculated as follows:

$$\dot{N}_{dis,bunker} = \frac{N_{f,bunker}}{t_{dis,bunker}} \quad (2)$$

where $t_{dis,bunker}$ is the total time required for the feedstock hopper to be discharged into the wet torrefaction reactor.

Within the model, it was assumed that each feedstock particle consisted of three components: organic material, biochar and ash. Then, the mass of the particle was determined as follows:

$$m_r = m_{OM} + m_{char} + m_{ash} \quad (3)$$

Moreover, during wet torrefaction, organic matter decomposed into biochar and gas (torgas). The amounts of H_2O , CO_2 , CO , H_2 and CH_4 in the gas were calculated by the model. Scheme of decomposition of a biomass particle is shown in Figure 1.

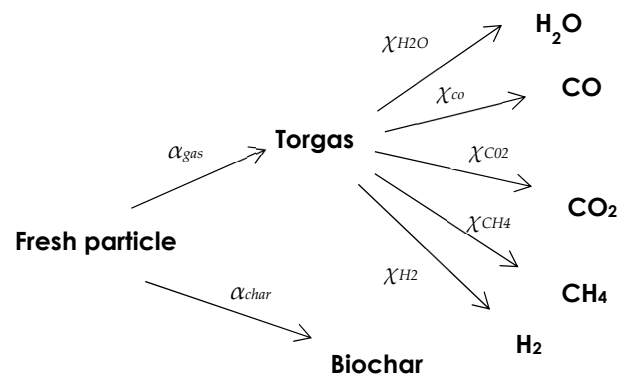


Figure 1. Scheme of decomposition of a biomass particle in the wet torrefaction process.

Changes in the masses of organic material and biochar are described by the following equations:

$$\frac{dm_{OM}}{dt} = -r_{r,react} \quad (4)$$

$$\frac{dm_{r,Char}}{dt} = \alpha_{Char} r_{r,react} \quad (5)$$

where α_{Char} represents the mass of biochar produced every time one kilogram of organic material has reacted.

The thermochemical reaction rate ($r_{r,react}$) was computed according to the work of [30]:

$$r_{r,react} = A \exp\left(\frac{-T_a}{T_r}\right) m_{r,OM} \quad (6)$$

where A and T_a are the frequency factor and activation temperature of the thermochemical reaction, respectively.

A separate mass balance equation was made up for each component of the gas phase:

$$\frac{dN_{g,i}}{dt} = F_{i,in} - F_{g,out} \frac{N_{g,i}}{N_{g,t}} + \sum_r N_r \left(\frac{\alpha_{gas}}{M_{gas}} x_{gas,i} r_{r,react} \right) \quad (7)$$

where $F_{i,in}$ represents the molar flux of species in the reactor. In the device depicted in Figure 2, only steam was supplied as a gaseous species to the reactor. Hence, only $F_{H_2O,in}$ has a meaning here.

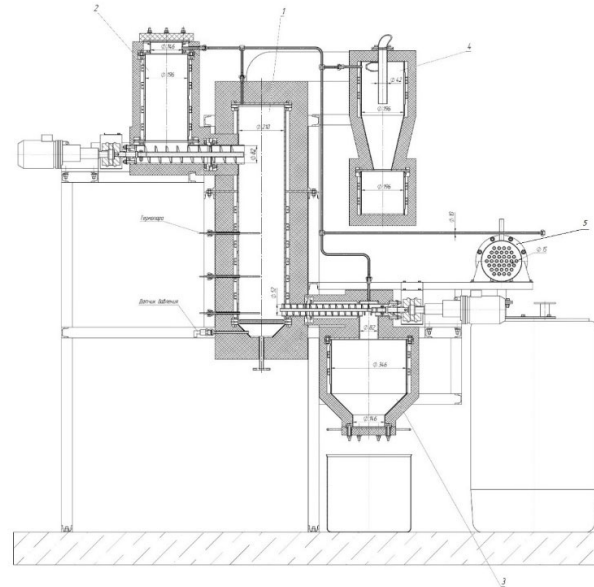


Figure 2. Scheme of the apparatus for experimental validation of the wet torrefaction model.

α_{gas} is the stoichiometric coefficient of gas production by thermochemical reaction on a mass basis, whereas $x_{gas,i}$ represents the molar composition of these gases generated by the wet torrefaction reaction.

The initial chemical composition of poultry-litter particles was determined based on the literature data [2].

2.1.2. Energy Balance Equations

The internal energy of a particle was computed as follows:

$$U_r = (m_{r,w}C_w + (m_{r,OM} + m_{r,Char} + m_{r,Ash})C_{sol})(T_r - T_{ref}) \quad (8)$$

where C_w and C_{sol} stand for the heat capacity of liquid water and the solid material held within the reactive particle, respectively, whereas T_{ref} stands for the reference temperature.

The energy balance allowed for the computation of the internal energy of the gas held in the reactor. It can be derived as follows:

$$\frac{dU_g}{dt} = \sum_i \left(F_{i,in} h_{i,in} - F_{g,out} \frac{N_{g,i}}{N_{g,t}} h_{i,out} \right) - \sum_r N_r \dot{Q}_{r,gas} - \dot{Q}_{reac,wall} + \sum_r \sum_i N_r \left(\frac{\alpha_{gas}}{M_{gas}} x_{gas,i} r_{r,react} h_{r,i} \right). \quad (9)$$

In the previous expression, $h_{i,in}$ and $h_{i,out}$ stand for the molar enthalpy of the chemical species at the temperature prevailing at the inlet and outlet of the reactor, respectively. Given the fact that the reactor was assumed to be a CSTR, the temperature at the outlet of the reactor was equal to the one inside the reactor.

$\dot{Q}_{r,gas}$ stands for the heat exchange between a particle and the surrounding gases, whereas $h_{r,i}$ represents the molar enthalpy of chemical species i evaluated at the particle temperature (fresh or already processed), since it corresponds to the temperature at which chemical species are released from the particles and enter the gas phase:

$$\dot{Q}_{r,gas} = \pi d_r^2 h_{r,gas} (T_g - T_r) \quad (10)$$

In this equation, d_r and T_r stand for particle diameter and temperature, respectively, for both fresh and already processed biomass particles, whereas T_g is the temperature of the gas held in the reactor.

The heat of reaction $\dot{Q}_{r,react}$ is computed according to:

$$\dot{Q}_{r,react} = r_{r,react} \Delta_r H_{r,react} \quad (11)$$

where $\Delta_r H_{r,react}$ is the thermochemical reaction heat.

2.2. Litter Characteristics

The characteristics of the fresh poultry litter are shown in Table 2.

Table 2. Characteristics of poultry litter.

Material	C, %	H, %	N, %	S, %	O ₂ , %	Ash, %	LHV, MJ/kg
Fresh poultry litter	41.4	5.7	4.8	0.8	30.7	16.6	16.7

The humidity of the initial biomass and the resulting biochar was determined using the Ohaus MB45 humidity analyzer (relative measurement error $\pm 0.1\%$). The ash contents (A) in the initial biomass and biochar were determined according to the norm ASTM E1755-01.

The contents of carbon (C), hydrogen (H), nitrogen (N) and sulfur (S) in the initial biomass, and in the produced biochar, were determined using the Elementar Vario Macro Cube element analyzer (relative error less than 0.2%). The oxygen content (O, weight. %) in the initial biomass and in the biochar was estimated according to the formula:

$$100 - (C + H + N + S + A)$$

In addition to the poultry litter being used as the sole feedstock, a feedstock mixture was also tested by mixing poultry litter together with sawdust in 1:1 ratio (w/w). The wet torrefaction tests were performed at temperatures of 300 and 350 °C.

2.3. Experimental Unit

The experimental validation of the kinetics for the wet torrefaction of poultry litter and its mixture with sawdust in the fluidized bed was performed in the apparatus described in Figure 2.

The installation consisted of a fluidized-bed reactor for torrefaction (1), a feedstock hopper for initial biomass (2), a hopper for biochar (3), a cyclone (4) for separating the steam-gas flow from the bio-coal particles removed from the reactor, and a condenser of the steam-gas mixture (5). The steam generation was performed in a boiler. It was then superheated in a superheater. The boiler and the superheater are not shown in the figure. The torrefaction reactor was equipped with a gas-distribution grid for introducing superheated steam under the boiling layer. Additionally, electric heaters were installed on the side walls of the reactor in order to maintain the required temperature inside the reactor. The feedstock hopper for the initial biomass was equipped with a lid for biomass loading and a screw feeder with a gear motor. The electric drive of the gear motor was operated with a frequency controller, which allowed the smooth regulation of biomass supply to the reactor. The feedstock hopper was designed as a heated device in order to avoid the condensation of steam in the hopper when it came into contact with cold biomass particles. The biochar-collection hopper was also heated and equipped with a screw with a gear motor with an adjustable speed for unloading the biochar from the reactor. The cyclone for separating the entrained biochar particles from the steam-gas flow was also heated to prevent the premature condensation of steam and subsequently the clogging of the cyclone with stuck pieces of biochar. The heat exchanger (5) for the cooling of the spent water-steam was made of shell-and-tube: spent superheated steam entered the pipe

space, while cooling water with a temperature of 10 °C entered the inter-pipe space. In order to collect the resulting condensate, a special container was used, which is not shown in the figure.

The preliminary experiments on wet torrefaction in a fluidized bed using quartz sand as an inert material were unsuccessful (data not shown). In these initial experiments, the separation of the generated biochar from the quartz sand was difficult and resulted in an increase in ash content in the obtained biochar. To overcome this issue, it was decided to apply biochar from previous batches as an inert material.

Before the start of the experiment approximately 6 kg of biochar, obtained from the biomass studied in this experiment, was placed into the reactor for hydrothermal carbonation. Then, 2 kg of biomass feedstock was filled into the hopper, and subsequently introduced into the wet torrefaction reactor.

With the help of electric heaters, the installation was initially brought to the following operating mode:

- Temperatures of hopper (2) and hopper (3), as well as cyclone (4): 110–120 °C;
- Temperature in the reactor 1: 225–350 °C.

During heating, the system was purged with nitrogen. During the operating mode, the nitrogen supply was switched off while the superheated steam was fed under the grid. The temperature under the grid was fixed at 225–350 °C. Then, the initial biomass feedstock was loaded into the reactor for wet torrefaction. The loading of the biomass was completed within 15 min. From the beginning of the biomass supply, the gas analyzer “Vario Plus Industrial Syngas” continuously measured non-condensable gases behind the condenser and determined the contents of carbon dioxide, carbon monoxide, hydrogen and methane. The data were used to evaluate the kinetics of the process of wet torrefaction. From the beginning of the biomass supply to the reactor, the concentrations of carbon dioxide, carbon monoxide, methane, and hydrogen in non-condensable gases began to increase, reaching a maximum at a specific time after loading the entire biomass feedstock into the wet torrefaction reactor. Then, the concentration of gaseous components started to decrease, eventually reaching the initial values that were measured prior to the biomass entry into the reactor. At this moment, the wet torrefaction process was considered to be complete, and biochar was discharged from the reactor.

The flowrate of the superheated steam supplied to the reactor (1) was regulated by special valves. The total amount of steam supplied to the reactor was determined by the amount of condensate collected during one experiment. This method of estimating the steam consumption of the wet torrefaction process was applicable since the poultry-litter moisture as a result of wet torrefaction decreased by no more than 5%.

3. Results and Discussion

3.1. Experimental Data on the Study of the Kinetics of the Process of Wet Torrefaction of Poultry Litter and Its Mixture with Sawdust

Figure 3 shows the changes in the composition of non-condensable gases during the wet torrefaction process for a mixture of poultry litter and sawdust at a ratio of 1:1, and at a temperature of 300 °C. The torrefaction process lasted for approximately 32 min. The maximum concentration of carbon dioxide reached 16%. The maximum concentrations of CO and CH₄ amounted to 33,000 and 2000 ppm, respectively. The biochar yield was 86.5%. The maximum generation rate of non-condensable gases was about 0.001 L/s.

Increasing the temperature of the torrefaction process up to 350 °C (Figure 4) did not significantly reduce the duration of the wet torrefaction process, which was 30 min, but the intensity of the release of non-condensing gases was enhanced. The maximum concentrations of the gases were as follows: CO₂ 31%, CO 87,500 ppm, CH₄ 14,000 ppm, and H₂ 0.18%. The biochar yield was 74.4%. The maximum generation rate of non-condensable gases was about 0.005 L/s.

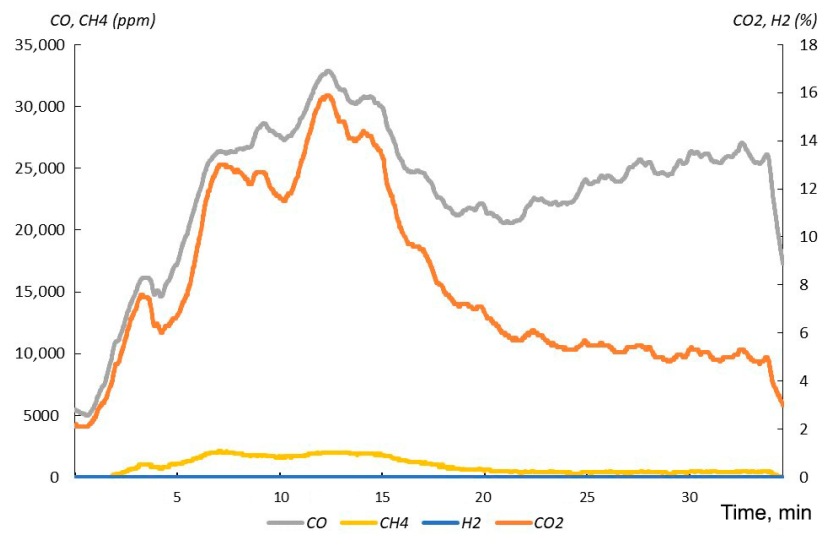


Figure 3. Evolution of the content of non-condensable gaseous carbonation products during wet torrefaction of a mixture of poultry litter and sawdust at a reaction temperature of 300 °C.

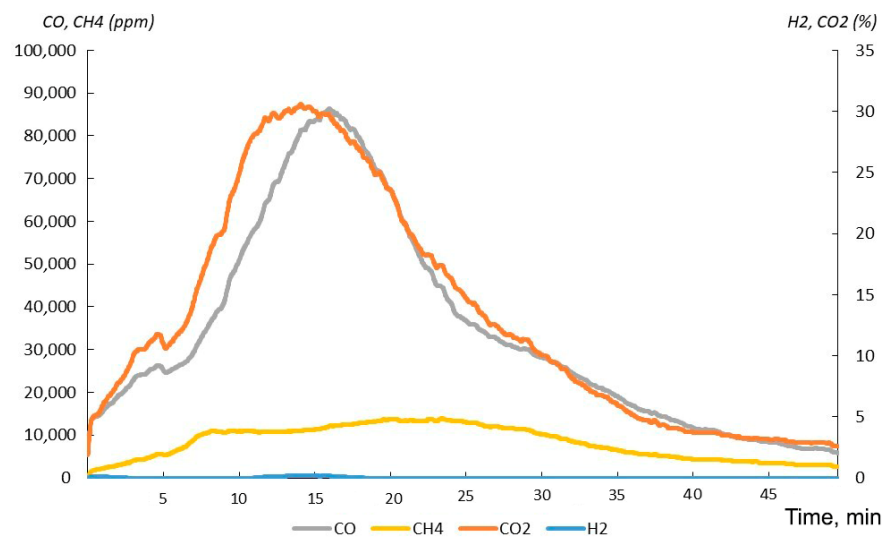


Figure 4. Evolution of the composition of non-condensable gaseous products during the wet torrefaction of poultry litter and sawdust (1:1 *w/w*) at a reaction temperature of 350 °C.

As for the hydrothermal carbonation of poultry litter, as can be seen from Figure 5, at a temperature of 350 °C this process took about 40 min, and the intensity of the release of non-condensable gases was close to that observed during the carbonation of a mixture of poultry litter and sawdust at 300 °C. The concentrations of the non-condensable gases were as follows: CO₂ 22%, CO 40,000 ppm, CH₄ 4000 ppm. Thus, the carbonation of poultry litter was much less intense than that of the 1:1 mixture of poultry litter together with sawdust. The biochar yield was 72.1%, and the maximum generation rate of the non-condensable gases was 0.003 L/s.

It can be seen from the figures that at a temperature of 350 °C, when replacing 50% of the poultry litter with sawdust, the duration of the wet torrefaction process was reduced by 10 min, and reached significantly higher values of CO, CO₂ and CH₄. Hence, one may assume that at the same temperature, the process of the wet torrefaction of sawdust was much more intensive than the process of the wet torrefaction of poultry litter, resulting in the accelerated reaction rates for the feedstock mixture of poultry litter together with sawdust (1:1 *w/w*).

The characteristics of biochar obtained from the wet torrefaction of poultry litter, and mixture of poultry litter together with sawdust (ratio 1:1 *w/w*), are shown in Table 3.

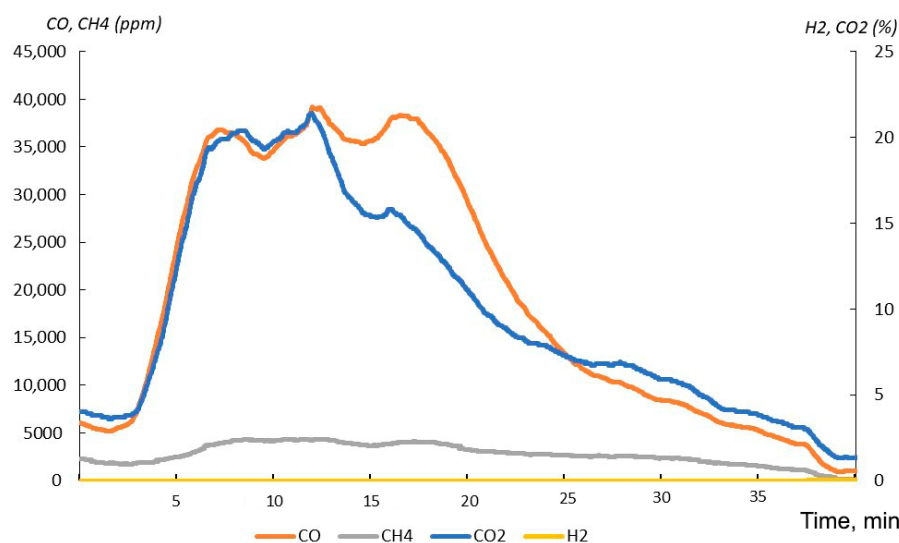


Figure 5. Evolution in the content of non-condensable gaseous products during the wet torrefaction of poultry litter at a temperature of 350 °C.

Table 3. Characteristics of biochar obtained as a result of wet torrefaction.

Material	C, %	H, %	N, %	S, %	O ₂ , %	Ash, %	LHV, MJ/kg
Mixture (1:1). Torrefaction at 300 °C	49.5	3.7	6.3	0.96	10.9	28.64	19.3
Mixture (1:1). Torrefaction at 350 °C	52.1	2.9	7.8	1.01	5.8	30.39	20.7
Poultry litter. Torrefaction at 350 °C	48.2	3.63	4.65	0.9	12.48	30.1	18.8

The wet torrefaction of poultry litter increased the carbon content by 17% and reduced the oxygen content 2.46-fold, while raising the heat of combustion by 12.5%. It is also noted that wet torrefaction may completely disinfect poultry litter and its mixture with sawdust by removing pathogenic microflora [31].

The characteristics of biochar derived from the wet torrefaction of droppings and its mixture with sawdust were close to the characteristics of the biochar obtained from the same material by classical hydrothermal carbonation [2]. This confirmed the effectiveness of the investigated method of the wet torrefaction of biomass in a fluidized bed in an environment of superheated steam.

Furthermore, in the developed technology of wet torrefaction in a fluidized bed in an environment of superheated water vapor, it is possible to control the process by changing the yield of non-condensable gaseous torrefaction products. The process ends when the yield of non-condensable gaseous products is the same as it was prior to the initial biomass loading into the reactor. Under this assumption, the model developed in this article can determine the processing period after which the generation rate of non-condensable gaseous products will become minimal.

3.2. Model Validation

The developed model was tested for the process of wet torrefaction of a mixture of poultry litter and sawdust (component ratio 1:1) at temperatures of 300 and 350 °C, as well as in the case of poultry litter as sole feedstock at a temperature of 350 °C. Figure 5 shows the results of the calculations based on the model according to the input parameters specified in Table 4. These parameters correspond to the conditions of the experiment described above.

Table 4. List of parameters used in the model.

Symbol	Parameter	Value	Units
$m_{f,bunker}$	Mass of fresh particles in the feedstock hopper	2	kg
$t_{dis,bunker}$	Total discharging time of the feedstock hopper	1020	s
α_{Char}	Stoichiometric coefficient of biochar production by thermochemical reaction (mass basis)	0.47	kg _{char} /kg _{OM}
α_{Gas}	Stoichiometric coefficient of gas production by thermochemical reaction (mass basis)	0.53	kg _{gas} /kg _{OM}
A	Frequency factor of thermochemical reaction	7.6×10^{-4}	s ⁻¹
T_a	Activation temperature of thermochemical reaction	573	K
x_{gas,H_2O}	Molar composition of H ₂ O released by reaction	0.07	mol _{H₂O} ·mol _{gas} ⁻¹
x_{gas,CO_2}	Molar composition of CO ₂ released by reaction	0.76	mol _{CO₂} ·mol _{gas} ⁻¹
$x_{gas,CO}$	Molar composition of CO released by reaction	0.14	mol _{CO} ·mol _{gas} ⁻¹
x_{gas,H_2}	Molar composition of H ₂ released by reaction	0.1	mol _{H₂} ·mol _{gas} ⁻¹
x_{gas,CH_4}	Molar composition of CH ₄ released by reaction	0.03	mol _{CH₄} ·mol _{gas} ⁻¹
C_w	Heat capacity of liquid water	4180	J/(kg·K)
C_{sol}	Heat capacity of solid material	2000	J/(kg·K)
T_{ref}	Reference temperature	273.15	K
$\Delta_r H_{reac}$	Heat of reaction	500	J/kg

Figure 6 shows the estimation of the total amount of non-condensable gases leaving the reactor with time (i.e., CO₂, CO, H₂ and CH₄) if the model predictions did not estimate accurately the amount of gas leaving the reactor. The discrepancies between experimental and modeling results for non-condensable gases might be related to the fact that the model does not account for soluble as well as volatile organic compounds, which are also produced during the wet torrefaction process; the model was able to estimate the duration of the process based on the changes in the gas output. Accordingly, the curve displays a similar pattern to the obtained experimental data. From the modeling results, the process duration was approximately 43 min, which is very close to the experiment.

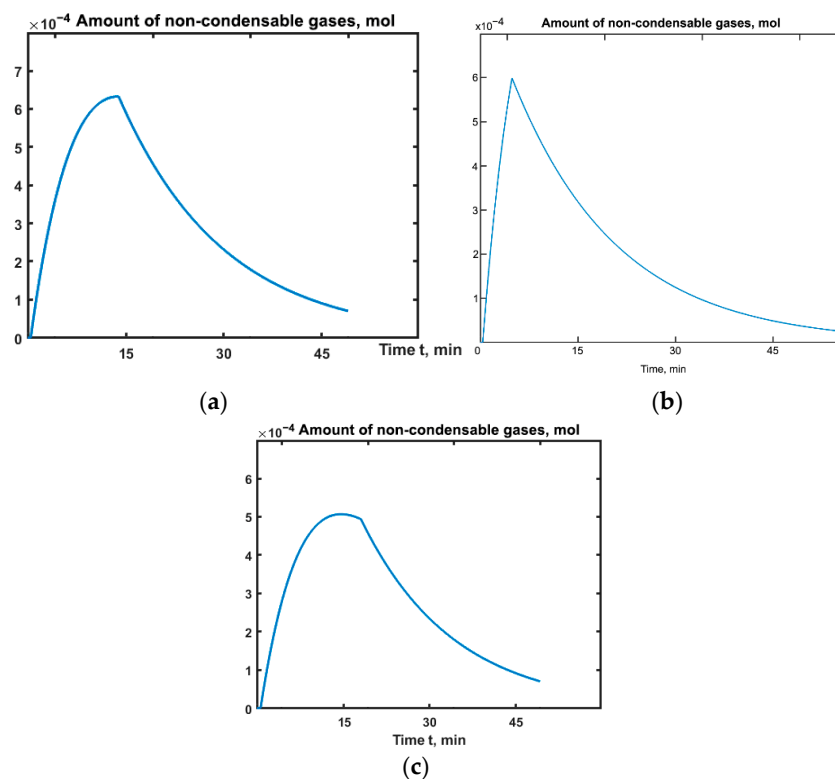


Figure 6. Results of the calculations for the amount of non-condensable gaseous carbonization products during heat treatment of a mixture of poultry litter and sawdust with a content of (1:1) at a temperature of 300 (a) and 350 °C (b) and poultry litter at a temperature of 350 °C (c).

4. Conclusions

A non-stationary model of wet torrefaction was developed, for the prediction of the fluidized-bed wet torrefaction process duration in an environment of superheated steam. The model accounts for feedstock properties, reactor size, temperature and the amount of supplied superheated steam. The model was implemented in a MATLAB environment. The predictions showed sufficient agreement with the experimental data from the pilot plant, in particular the time required for biomass processing in the reactor. In this regard, the model can be useful in the calculation and design of industrial reactors for wet torrefaction in a fluidized bed. However, the model should be enhanced to accurately calculate non-condensable gases generated during the wet torrefaction process. This can be achieved by including a biomass roots conversion to soluble, as well as volatile, organic compounds. Considering the advantages of wet torrefaction in an environment of superheated steam, this process can be considered as an alternative method of processing biomass waste.

Author Contributions: Conceptualization, R.I.; methodology, R.I. and F.M.; software, F.M., N.M.; validation, N.M. and D.K.; formal analysis, A.M.; investigation, R.I., A.M. and O.M.; resources, O.M.; data curation, S.K.; writing—original draft preparation, R.I. and F.M.; writing—review and editing, M.B., F.T. and D.K.; visualization, D.K.; supervision, S.K., project administration, R.I.; funding acquisition, R.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ministry of Science and Higher Education of the Russia, grant number 075-11-2020-035 IGK 000000S207520RNV0002. The APC was funded by Ministry of Science and Higher Education of the Russia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The work was carried out with financial support of the Ministry of Science and Higher Education of the Russia (Agreement No. 075-11-2020-035 of 15 December 2020 IGK 000000S207520RNV0002. Project name: “Development of technology and equipment for accelerated hydrothermal carbonization of poultry waste in order to obtain an intermediate product (biochar) suitable for the production of a highly effective sorbent or soil improver”. Lead contractor—Tambov State Technical University).

Conflicts of Interest: The authors declare no conflict of interest.

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