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Simulation and Analysis of Poultry Litter Drying Process Using Residual Heat from Combustion System

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Abstract: The moisture content of the biomass fuels has been identified as one of the critical fuel properties to achieve high combustion efficiency with lower gaseous emissions during combustion process. Drying of biomass with thermal energy during the waste-to-energy conversion process may help in the reduction of moisture content of the biomass fuels resulting in a high flame and fuel gas temperature, steady combustion process and improved overall combustion performance. The objective of this study is to design and improve the drying process of poultry litter by using residual heat recovered from the flue gas of the poultry litter and natural gas co-combustion process. Several operating factors of the biomass drying process were reviewed and significant factors were determined using the design of experiment (DOE) method. The effects of factors on poultry litter drying process were simulated and evaluated in the Simprosys software. In addition, energy flow analysis was performed to identify the amounts of waste heat that can be used to reduce moisture content of poultry litter after useful energy (e.g. electricity, and hot water generation. Based on statistical analysis, it was observed that the flue gas temperature had a significant effect on the moisture reduction rate at a significant level of $p<0.05$. In addition, simulation results found that an increase in flue gas temperature led to a moisture content reduction from 0.22 kg/kg w.b to 0.10 kg/kg w.b. Experimental results showed that the flue gas temperature after energy production during the poultry litter co-combustion ranged from 130 to 181 °C with a heat load of 11.92 to 21.30 MJ/h. This study suggests that the flue gas from waste-to-energy process can be used to remove moisture content of poultry litter while future investigation between the flue gas temperature and moisture content reduction should be performed in the experimental test of poultry litter and natural gas co-combustion process.

Keywords: Biomass Drying, Poultry Litter, Moisture, Flue Gas, Simprosys, Energy Flow, Simulation, Statistical Analysis

1. Introduction

Poultry litter is one type of biomass and agriculture waste from poultry farming. Poultry litter includes a mixture of poultry manure (excreta), bedding materials (e.g., wood shavings, sawdust, straw, pine or rice husk), waste feed, dead birds, broken eggs, and feathers removed from poultry houses (Kelleher et al., 2002; Abelha et al., 2003). The U. S. is one the largest broiler production with an annual production approximately between 8.3 billion in 2012 and 8.9 billion in 2017 (Lynch et al., 2013; 3, Qian et al., 2019). Using the assumption of poultry litter production between 1.1 to 1.4 tons/1,000 birds, the annual production in U. S. around 9.24 - 12.46 million tons of poultry litter (Qian et al., 2019). In most cases, poultry litter is applied to the croplands as an organic fertilizer due its rich nutrients, such as nitrogen, phosphorus, calcium, and potassium. However, excess land application of poultry litter caused several issues, such as pathogen contamination, nuisances (e.g., flies and odors), eutrophication, fish and aquatic death, and other negative effects on human and animal health. Incremental production of poultry litter and raised challenges of poultry litter stimulated the development of alternative disposal methods and technologies, pyrolysis, gasification, anaerobic digestion, and combustion. Among them, combustion is one of the simplest, cost-effective, and environmentally benign thermal-chemical processes.

The design and operation of more efficient biomass combustion systems rely substantially on several important fuel characteristics, namely heating value, moisture, ash content, and elemental compositions (Sheng and Azevedo, 2005). Moisture content of the biomass has been identified as one of the critical fuel properties to influence the combustion process and gaseous emissions. Based on the available fuel analysis results of poultry litter samples, it was found that moisture content of poultry litter ranged from 5.00 % to 43.01% with an average of 17.99% (Qian et al., 2018). It was found that poultry litter from US poultry farms in Maryland Eastern Shore had an average value 21.20% and slightly higher than the other regions (e.g., Europe). Different farming practices, clearing periods, and beading material in the US result in low fixed carbon, low heating value, high ash content, and high moisture content. Several studies have shown that high moisture content of biomass fuels lead to reduction of flame temperature, combustion efficiency as well as calorific value. In addition, the low flame temperature could result in incomplete combustion with high gas emissions and/or other operational problems.

In order to reduce the moisture content of fuel wood source its pre-drying in kilns of various types was used. However, drying of biomass leads to additional costs and, in some cases, increases the cost of energy production (Anisimov et al., 2016). Drying of biomass with thermal energy during the waste-to-energy conversion process may help in the reduction of additional drying cost and moisture content of the biomass fuels. Many studies have proven that moisture content reduction of biomass results in a steady combustion process and improved overall combustion performance with reduced gas emissions. It is of no doubt that the drying process is a particularly energy-consuming unit operation, thus, a user-friendly software is needed by industry and academia to improve the energy efficiency of drying and reduce the carbon footprint of drying products. Some of the commercially available software are Simprosys, dryPAK, and DrySel (Gong and Mujumdar, 2008). Simprosys has the features needed to perform simple yet reliable drying simulations with easy to navigate graphical user interface.

There are few studies that have been conducted to investigate the factors affecting the moisture content of biomass. Zabski et al. (2018) carried out experimental and numerical investigations of the wood drying process. Some of the factors, such as temperature, air velocity, initial moisture content, pressure drop in the dryer, mass flow rate, and drying time were evaluated. In studying energy efficiency of the pulp and paper drying process, Vieira et al. (2007) examined and investigated the effect of drying air velocity and temperature on the moisture content and drying rate of fuels. However, the effect of factors on the poultry litter drying process have been barely studied. This paper focuses on designing and improving the drying process of poultry litter by using residual heat recovered from the flue gas of the combustion process.

2. Methodology

2.1 Drying Simulation Using Simprosys

Simprosys software vs 3.0 has been used to simulate the poultry litter drying process in this research paper. Simprosys is a windows-based software package developed by Simprotek Corporation, provides an integrated, powerful, yet highly user-friendly, contemporary tool for the design and simulation of a dryer flow sheet as well as drying systems not only for aqueous but for the commonly encountered nonaqueous drying systems (Gong and Mujumdar, 2009). The software package is specifically designed for the heat and mass balance calculations of the drying process and combined evaporation and drying process. It is also a very efficient tool for the design, evaluation and troubleshooting of drying systems as well as dryers and burners. The material balance equation is expressed as shown in equation 1 in which W_g is the gas mass flowrate, W_s is the solid mass flowrate, Y_o and Y_i are the outlet and inlet absolute humidity for the gas (hot air) while X_i and X_o are the inlet and outlet moisture content respectively. The heat transfer rate (dQ) from the hot gas to the poultry solid waste can be obtained using equation 2.

$$Wg(Yo - Yi) = Ws(Xi - Xo) \quad (1)$$

$$dQ = \frac{dm\_hot\_gas}{dt} * (hi - ho) \quad (2)$$

which can be further expressed in terms of drying gas temperature as shown in equation 3

$$dQ = \frac{dm\_hot\_gas}{dt} * Cp\_hot\ gas * (Ti - To) \quad (3)$$

The drying factors such as the wet poultry litter flowrate (kg/hr), the inlet and outlet temperature of both hot air and poultry litter (^oC), the inlet air pressure (kPa), initial moisture content (kg/kg) served as input to the Simprosys software for the drying simulation. The drying process efficiency was measured using the Thermal Efficiency and the Specific Heat consumption of the simulated dryer with governing equations as shown in equations 4, 5, and 6 respectively.

$$Drying\ efficiency = \frac{moisture\ evaporation}{total\ input\ energy} (\%) \quad (4)$$

$$Thermal\ Efficiency\ = \frac{mass\ of\ moisture\ evaporated}{amount\ of\ heat\ supplied}\ (kg/kJ) \tag{5}$$

$$Specific\ Heat\ Consumption\ = \frac{amount\ of\ heat\ supplied}{mass\ of\ moisture\ evaporated}\ \ (kJ/kg) \tag{6}$$

The simulation for the lab-scale drying process was carried out with factors specifications as shown in Table 1. The drying objective was to reduce the initial moisture content in the feed to less than 0.15 kg/kg wb

Table 1. Simulation Factors

Poultry Litter	**Hot Air**
Feed moisture content = 0.22 kg/kg wb	Inlet Temperature (Dry Bulb) =60 - 90ºC
Feed Temperature = 20ºC	Inlet Pressure = 101.3 kPa
Product Temperature = 50ºC	Initial absolute humidity = 0.009 kg/kg
Mass Flow Rate = 10kg/h	Air Velocity = 0.5-1.0 m/s

2.2 Statistical Analysis Using Design of Experiment (DOE)

A 2-level factorial design analysis was conducted using Minitab software to study the effect of gas temperature, initial moisture content and air velocity on the drying rate of poultry using the simulated results. Table 2 summarizes the factors and its individual levels. Response for this DOE is moisture reduction rate which was calculated by dividing the final moisture content after drying process with initial moisture content.

Table 2. Design of Factors and Its Individual Level

Factors	**Low Level**	**High Level**
Temperature	80ºC	90ºC
Initial Moisture	20 kg/kg	25 kg/kg
Air Velocity	0.5 m/s	1.0 m/s

2.3 Residual Heat Recovery from Waste-to-Energy Combustion Process

As shown in Figure 1, poultry litter and natural gas co-combustion was performed in the combustion chamber to generate thermal energy. This thermal energy was to produce electricity from a Stirling engine and hot water from the lab-scale shell and tube heat exchanger (Qian et al., 2020). After the energy production, the residual heat was recovered to remove the moisture in the poultry litter and improve the combustion performance. Under various feeding rates (e.g., 5.76 kg/h and 7.08 kg/h) of poultry litter with constant feeding of natural gas at 0.57 kg/h during the co-combustion process, the flue gas temperature range was measured to estimate the residual heat after waste-to-energy generation. Data was collected after the stable combustion process was observed. The specific heat of flue gas was assumed to be the same as specific air at different temperatures. Specific heat of flue gas ranged from 1.012 kJ/kgK to 1.019 kJ/kgK. The heating value of poultry litter was 11.30 MJ/kg (as received) for the collected poultry litter sample from Maryland Eastern shore (Qian et al., 2018).

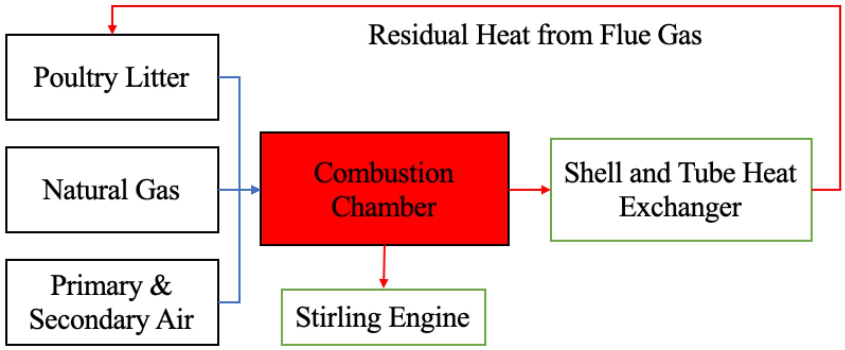
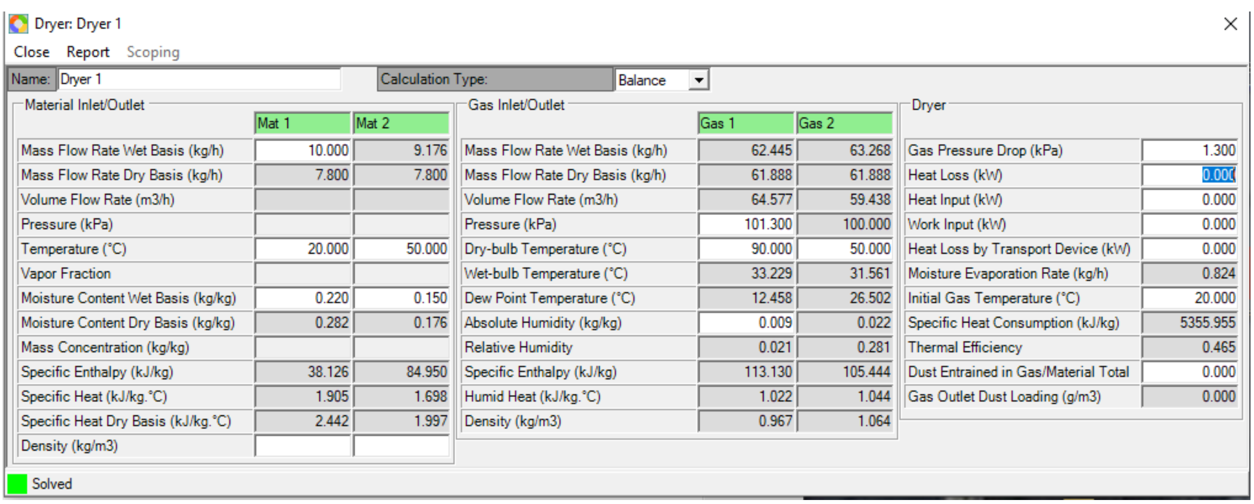


Figure 1. Schematic Diagram of Recovery Heat from Waste-to-Energy Process

3. Results and Discussion

The simulation was conducted as specified using the factors in Table 1. As shown in Figure 2, the moisture content of the poultry litter was reduced from 0.22 kg/kg wb to 0.10 kg/kg wb. The biomass was fed in at a temperature of 20 °C and brought out at 50 °C. The result indicates that the thermal efficiency increases with increasing the drying temperature while the specific heat consumption decreases as shown in Figure 3. Similarly, the moisture evaporation rate increases with reduction in initial moisture content. At 0.15 kg/kg wb, the evaporation rate was observed to be 0.824 kg/hr, at 0.12 kg/kg wb, the evaporation rate was 1.136 kg/hr and at final moisture of 0.10 kg/kg wb, the evaporation rate was observed to be 1.333 kg/hr. Table 3 summarizes the Analysis of Variance (ANOVA) for moisture reduction of poultry litter under various conditions of initial moisture content, flue gas temperature, and air velocity. Results showed that flue gas temperature had a P-value of 0.001 and a significant effect on the moisture reduction during the drying process at a significant level of P<0.05. These results indicate that flue gas temperature plays a critical role in the general biomass drying process and agreed with findings obtained by Zabski et al. (2018) and Vieira et al. (2007) in wood drying and paper pulp drying processes.



Dryer: Dryer 1

Close Report Scoping

Name: Dryer 1 Calculation Type: Balance

Material Inlet/Outlet

	Mat 1	Mat 2
Mass Flow Rate Wet Basis (kg/h)	10.000	9.176
Mass Flow Rate Dry Basis (kg/h)	7.800	7.800
Volume Flow Rate (m3/h)		
Pressure (kPa)		
Temperature (°C)	20.000	50.000
Vapor Fraction		
Moisture Content Wet Basis (kg/kg)	0.220	0.150
Moisture Content Dry Basis (kg/kg)	0.282	0.176
Mass Concentration (kg/kg)		
Specific Enthalpy (kJ/kg)	38.126	84.950
Specific Heat (kJ/kg.°C)	1.905	1.698
Specific Heat Dry Basis (kJ/kg.°C)	2.442	1.997
Density (kg/m3)		

Gas Inlet/Outlet

	Gas 1	Gas 2
Mass Flow Rate Wet Basis (kg/h)	62.445	63.268
Mass Flow Rate Dry Basis (kg/h)	61.888	61.888
Volume Flow Rate (m3/h)	64.577	59.438
Pressure (kPa)	101.300	100.000
Dry-bulb Temperature (°C)	90.000	50.000
Wet-bulb Temperature (°C)	33.229	31.561
Dew Point Temperature (°C)	12.458	26.502
Absolute Humidity (kg/kg)	0.009	0.022
Relative Humidity	0.021	0.281
Specific Enthalpy (kJ/kg)	113.130	105.444
Humid Heat (kJ/kg.°C)	1.022	1.044
Density (kg/m3)	0.967	1.064

Dryer

Gas Pressure Drop (kPa)	1.300
Heat Loss (kW)	0.000
Heat Input (kW)	0.000
Work Input (kW)	0.000
Heat Loss by Transport Device (kW)	0.000
Moisture Evaporation Rate (kg/h)	0.824
Initial Gas Temperature (°C)	20.000
Specific Heat Consumption (kJ/kg)	5355.955
Thermal Efficiency	0.465
Dust Entrained in Gas/Material Total	0.000
Gas Outlet Dust Loading (g/m3)	0.000

Solved

Figure 2. Simulation results of the Lab-scale poultry litter drying process

Table 3. Summary of Analysis of Variance (ANOVA) for Moisture Reduction

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.006177	0.002059	26.02	0.004
Linear	3	0.006177	0.002059	26.02	0.004
Initial Moisture	1	0.000378	0.000378	4.78	0.094
Temperature	1	0.005778	0.005778	73.03	0.001
Air Velocity	1	0.000021	0.000021	0.27	0.633
Error	4	0.000317	0.000079		
Total	7	0.006494			

The effect of hot gas temperature on the drying rate is related to the internal transport of moisture in the poultry litter through a diffusion mechanism. As the gas temperature increases from 60-90 °C, the moisture evaporation rate increases as well as the SHC and thermal efficiency of the dryer as shown in Figure 3. Results indicated that moisture content of poultry litter was reduced from 0.22 kg/kg w.b to 0.15 kg/kg w.b, 0.13kg/kg w.b, 0.12kg/kg w.b, and 0.10kg/kg w.b at flue gas temperature of 60- 90°C, respectively. From the ANOVA result, the gas temperature was observed to have the highest significant effect on the moisture reduction.

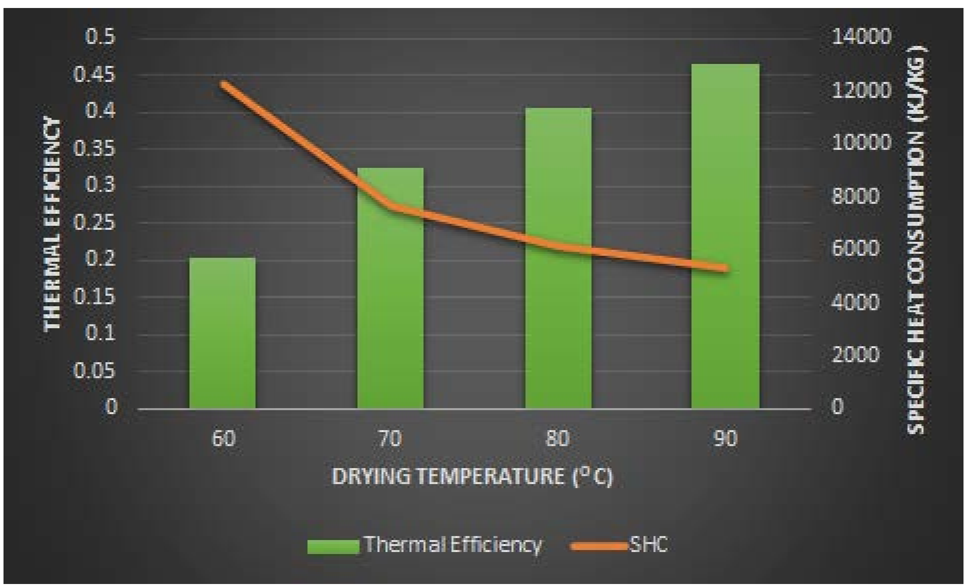


Figure 3. Effect of Drying Temperature on Thermal Efficiency and Heat Specific Consumption

Table 4 summarizes the flue gas temperature and heat load of flue gas after energy production. Experimental results indicated that the flue gas temperature of residual heat after energy production during poultry litter and natural gas co-combustion ranged from 130 to 181 °C with a heat load of 11.92 to 21.30 MJ/h. It shows the energy inputs from poultry litter was mainly transferred to energy production at the Stirling engine and shell and tube heat exchanger system. On the other hand, there is still approximately 18.3% to 26.6% thermal energy in flue gas that can be recovered to reduce the moisture content of poultry litter. It is expected to utilize partial waste-to-energy from poultry litter and natural gas co-combustion process on the drying process of poultry litter to reduce moisture content of poultry litter, increase flame temperature, improve combustion efficiency and reduce emissions.

Table 4. Summary of Flue Gas Temperature and Heat Load

Poultry Litter Feeding Rate (kg/h)	Energy Input from Poultry Litter (MJ/h)	Flue Gas Temperature (°C)	Heat Load of Flue Gas (MJ/h)
5.76 kg/h	65.09	130-151	11.92-15.69
7.08 kg/h	80.00	151-181	15.69-21.30

4. Conclusions

In this study, several factors of the drying process were selected and further analyzed to investigate the effect of factors on the drying process using simulation and available data from the literature reviews. Statistical analysis found that the flue gas temperature is one of the most significant factors for the drying process of biomass fuels (e.g. wood, paper pulp, poultry litter). In addition, the effect of gas temperature on the drying process of poultry litter were modelled and simulated using the Simprosys software. Results indicated that moisture decreased from 0.22kg/kg w.b to 0.10 kg/kg w.b when the flue gas temperature was increased from 60 to 90 °C. In addition, energy flow analysis showed poultry litter co-combustion processes had a flue gas temperature of 120-181°C can be used to reduce moisture content of poultry litter after electricity and hot water generation. This study showed a possibility of recovering heat from the poultry litter combustion process to reduce original moisture level of poultry litter. It is also expected to increase energy utilization, improve combustion temperature, and reduce the emission by reducing moisture content of poultry litter. In the future study, the effect of several other factors on the poultry litter drying process will be studied using a specially designed drying system.

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