AIR-STEAM GASIFICATION OF POULTRY LITTER IN A BUBBLING FLUIDISED BED REACTOR

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ABSTRACT: This study focuses primarily on poultry waste valorisation process to produce bioenergy and nutrients. The research aims to identify the most promising route to create a new agricultural and farm-based bio-industry while mitigating the carbon footprint originating from landfilling of animal waste. This study investigates experimentally the technical feasibility of an air-steam gasification of poultry litter in a bubbling fluidised reactor and evaluates its performance. The maximum carbon conversion efficiency of 98% was reported at 750 °C and remaining unreacted carbon was found in the bottom ash. The reported permanent gas compositions (vol%, db) at the temperature of 750 ºC and an equivalence ratio (ER) of 0.30 were H_2: 19.2%, CH_4: 2.2%, CO: 13.6%, CO_2: 15.7%, C_2H_4: 1.0% and C_2H_6: 0.2%. Agglomeration issue was not encountered however, ash sintering had occurred at 750 ºC on the grate (air inlet pores) but they were not blocked. The amount of total tar was 24.2 gr/$kg_{feedstock,daf}$ at the tested temperature 750 ºC whereas, the moisture content was 13.2 vol.% in the wet gas. The mass balance calculations were performed to ascertain the accuracy of the experimental measurements.
Keywords: gasification, bioenergy, fluidised bed, product gas, tar, animal residue

1 INTRODUCTION

A rapidly growing world population has triggered a substantial rise in food consumption and energy demand. Increase in household income due to industrial revolution, urbanisation and industrialisation of agriculture sector has led to the increasing demand for animal protein. According to the Organisation for Economic Co-operation and Development (OECD) report, poultry meat is expected to account for half of the increase in global meat production as it surges past pork as the most consumed meat by 2020 [1]. The demand of animal protein forced farmers to switch to more efficient and intensive farming practises resulting in more waste. Primarily, animal waste has been used as a source of nutrient for nearby agriculture crop land. However, the amount of manure based nutrient generated is much more than that actually can be taken up by crops on nearby crop lands [2]. Over application of animal feedlot can cause several environmental issues including water contamination, odour problem, heavy metal contamination, pathogens, air pollution and climate change through emissions of greenhouse gases (GHG) [3]. The European Union's sustainable waste management hierarchy system (prevention, re-use, recycling, recovery and disposal of waste to be landfilled) is paving the path of waste processing to reduce its environmental impact and recover bioenergy (heat and electricity) [4].

Refused derived fuel, municipal solid waste, agricultural waste (harvested crops), animal waste *etc.* has shown great potential to be used as a carbon neutral source of energy because of its geographical diversification and it can contribute towards achieving the challenges of climate change. Manure processing technologies including anaerobic digestion, biological treatment, composting, incineration, pyrolysis, gasification and combustion, have been developed to reduce the processing cost and environmental impact while recovering nutrient and bioenergy [5–7]. It has been demonstrated that low moisture waste such as poultry litter can be subject to thermal treatment, such as hydrothermal carbonisation, combustion, pyrolysis and gasification [8–11]

Poultry litter has been subjected to gasification process mainly in small scale fix bed gasifiers [12,13]. In contrast, relatively a few studies have been conducted in a fluidised bed reactor. Fluidised bed systems are not extensively exploited yet because the operability of these system can be curtailed by the risk of sintering and agglomeration from ash constituents (mainly K and Na). Poultry litter was gasified in a pre-pilot scale air blown gasifier to investigate behaviour of ash composition whilst using silica sand as a bed material. The authors have stressed that considering the heterogeneous nature of the feedstock, characterisation of fuel is essential prior to gasification [14]. Air and air-steam blown fluidised bed rectors with silica sand as a bed material have been used to gasify poultry litter [15,16]. To encounter ash sintering and bed agglomeration issues, authors have blended poultry litter with limestone [16]. Recently, as a counter measure of agglomeration issue, a low temperature and co-gasification approaches were tested to gasify poultry litter [17,18]. Additionally, gasification process provides flexibility to produce fuels, heat and power based on a clean biomass/waste derived product gas while complying with emission standards [16,19].

Despite gasification is regarded as a cleaner conversion technology, the greatest challenges that prevents this technology from further development and commercialisation is the presence of tar in the produced gas. Tar is classified as a mixture of complex hydrocarbons that may condense in the colder sections of the gasification unit causing corrosion and fouling. There is no official definition of the tar but one of the most common definitions that can be found in the open literature belongs to the IEA task force describing tar as "the organics produced under thermal or partial oxidation regimes of any organic material, are called tar and are generally assumed to be largely aromatic".

This study aims at to investigate the technical feasibility of an air-steam gasification process of poultry litter in a bubbling fluidised bed reactor using dolomite (*Myanit B*) as a bed material. Furthermore, the influence of the reactor temperature on the product gases and their

composition, gas yield, carbon conversion efficiency (CCE), lower heating value of product gas and the evolution of tar were experimentally investigated.

2 MATERIALS AND METHODS

2.1 Materials

Poultry litter of was supplied by Biolan, Finland in a pelletised form with particle size in the range of 0.50-0.98 mm. The proximate and ultimate analyses of feedstock are presented in Table I. The moisture content and lower heating value of the feedstock was 9.71 wt.% (as received basis) and 16.78 MJ/kg. The empirical formula of poultry litter ($CH_{1.54}O_{0.57}N_{0.08}$) was calculated using the ultimate analysis on a dry basis. Dolomite (*Myanit B*) with particle size of 0.28-0.55 mm was used as a bed material.

Table I: Proximate and ultimate analyses of poultry litter

Proximate analysis (wt.%)	
Moisture (a.r.)	9.71
Ash content (d.b.)	14.30
Volatile matter (d.b.)	69.60
Fixed carbon* (d.b.)	16.10
Ultimate analysis (wt.%, d.b.)	
Carbon	42.72
Hydrogen	5.51
Nitrogen	3.93
Sulphur	0.64
Chlorine	0.29
Oxygen*	32.59
HHV (in MJ/kg)	17.99
LHV (in MJ/kg)	16.78

*Calculated by difference, a.r. – As received, d.b. – dry basis

The elemental composition of poultry litter ash was also analysed by inductively coupled plasma (refer Table II).

Table II: Inorganic trace elements in poultry litter ash

Major elements	Amount (mg/kg, dry)	Minor elements	Amount (mg/kg, dry)
Al	1200	As	<0.5
Ca	15,500	Ba	29
Fe	1600	Cd	0.14
Mg	8200	Co	1.9
Mn	600	Cr	16
P	10,200	Cu	84
K	27,700	Hg	<0.02
Si	7300	Mo	4.8
Na	4200	Ni	16
S	6100	Pb	1.5
Zn	450	Sb	<0.5
		Tl	<0.5
		Ti	95
		V	4.2

2.2 Experimental facility

The experiments were carried out in a bubbling fluidised bed reactor operating at an atmospheric pressure with continuous feeding of poultry litter and provision of ash removal from the bed. Figure 1 shows a schematic diagram of the test facility. The total height of the reactor is 2560 mm with the bed section's inner diameter of 100 mm and freeboard section of 150 mm. Fuel feeding rate was 1805 g/hr and 1720 g/hr (as received basis) at 700 and 750 ºC, respectively. The experiments were conducted at two different temperatures (700 and 750 °C) while keeping the fluidisation velocity in the bed (0.31 m/s) and the ER constant. The gas velocity in the freeboard section was 0.25 m/s. ER is defined as the ratio of mixture of air and steam to fuel feed on a dry and ash free basis.

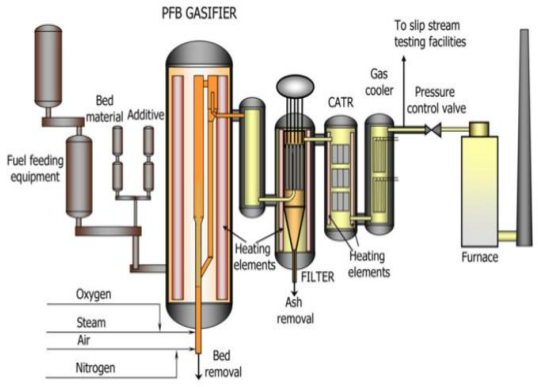

Figure 1: Experimental facility at VTT Finland

Poultry litter was fed into the reactor using a mechanical screw feeder as well as by the means of gravitational force. The fuel feeding point was situated 101 mm above the grate. The fluidising medium (air and steam) was preheated to 320 ºC before being fed into the reactor. Nitrogen flow rate of 0.20 g/s is used to avoid backflow of gases.

Two ceramic filters (*Dia-Schumalith 10-KK)* supplied by Pall Corporation with an outer diameter of 60 mm and heights of 1000 mm were used to collect elutriated char and dust particles. To avoid the condensation of tar, the temperature of the filtration unit was maintained at 450 ºC. Filter dust were collected every 60 minutes. Flow rate of filter dust was calculated based on the collected filter dust (elutriated char, ash and dust) over the hours of operation. Each experiment ran at steady-state condition for 3 hrs. Tar, ammonia (NH_3), moisture (H_2O) and hydrogen sulphide (H_2S) samples were collected from the sampling port for the analysis. The product gases were measured continuously using an online micro gas chromatograph with an interval of 7 minute. The data reported here are on averaged basis along with the standard deviation.

2.3 Moisture and tar sampling methods

Tar sampling was performed based on the standard method proposed in the European Tar Protocol [20]. Isopropanol was used as absorbent. Samples were analysed for benzene and tar compounds up to coronene ($C_{24}H_{12}$, 300.35 g/mol) by a gas chromatograph (Agilent 6890A, column: Agilent 19091B-112 Ultra 2) equipped with FID detector. Water content in the gas was determined from tar samples by using a gas chromatograph (HP 5890 series II, column: PoraPLOT U) equipped with a TC detector. Detailed description of measurement methods can be found elsewhere [21].

Tar are classified into two categories depending either on the temperature regime [22] or the dew point, water solubility, and aromatic ring number of the tar compounds [23]. Considering the first classification, Milne et al. categorised tar into primary, secondary, alkyl-tertiary and PAH-tertiary (polyaromatic hydrocarbons) [22]. Primary tar consists of oxygenated compounds developing as products of pyrolysis reactions in the temperature range between 200-500 °C. As the temperature rises primary tar is converted into non-condensable gases and heavier hydrocarbons (phenols and olefins) which remain stable until the temperature of 750 °C. At even higher temperatures, tertiary tar is formed, comprising of complex PAH being very stable and with high dew point.

It is worth to mention that the CCE was calculated by dividing the carbon in the dry product gas and tar minus the unconverted carbon (bed and cyclone filter) by the amount of carbon fed into the gasifier. In addition, benzene and toluene are reported as tar compounds.

3 RESULTS AND DISCUSSION

Figure 2 shows the bed and freeboard temperature profiles during the gasification of poultry litter at 700 °C and an ER 0.30 (steady state operation for 3 hrs). Once the gasifier temperature attained a steady state condition, the experiment run for 3 hrs and during this time the product gas, tar, NH_3, H_2S and H_2O samples were taken for further analysis. Gas composition measurements were performed continuously at 7 min intervals for around 180 min and four samples of tar, NH_3 and 2 samples of H_2S and H_2O were taken during the same time. Since poultry litter has considerable high ash content which is accumulated during the experiment and in order to maintain the same fluidisation condition in the bed, bed ash was removed resulting in a sudden drop in reactor temperature up to 20 °C (refer Figure 2).

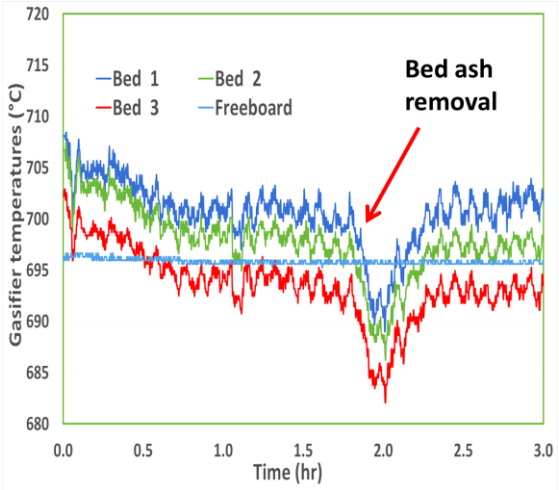

Figure 2: Bed and freeboard temperature profile in a poultry litter gasification test at 700 °C and ER = 0.30

3.1 Effect of temperature on gas composition, yield, and calorific value

Figure 3 shows the composition of the major and light hydrocarbon species in the product gas as a function of temperature at the ER (0.30). The concentrations of H_2, CO and CH_4 increased with temperature, whereas the CO_2 content decreased. Since higher temperature favours the char gasification, Boudouard reaction and also the cracking of higher hydrocarbons and tars, the concentrations of H_2 and CO are increasing. A slight increase in CH_4 yield is linked to the tar decomposition into lighter molecules such as CH_4 at higher temperature. The results of this study are in a good agreement with the relevant literature on poultry litter gasification from a fluidised bed reactor [15,16]. Furthermore, the concentration of C_2H_4 increase with temperature and could be linked to tar cracking into lighter hydrocarbons. A decrease in ethane (C_2H_6) concentration explains that the thermal cracking and steam reforming reactions are favoured at an elevated temperature [16]. In addition, C_2H_2 and C_3H_6 also decrease with rising temperatures.

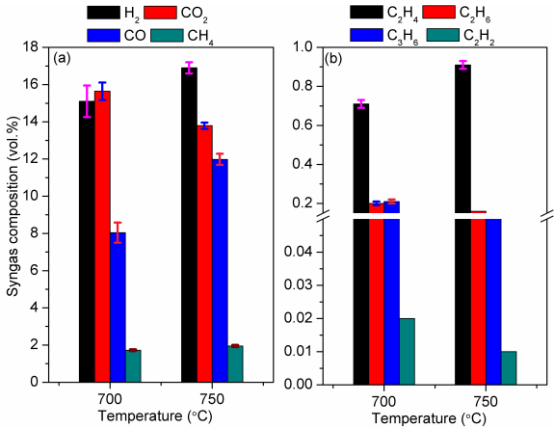

Figure 3: Effect of temperature on the composition of the product gas at ER = 0.30 (a) yield of major gas species (b) yield of light hydrocarbon gas species in the product gas.

Table III presents gas yield, LHV, CCE, NH_3, H_2S and moisture content in the product gas. The product gas yield is reported on a dry basis. The product gas yield increased from 2.39 to 2.64 Nm^3/kg_{db}, due to favourable thermal cracking of molecules at higher temperature. CCE is reported to be over 91% and increased with temperature (reported an increase of 6.7%).

Table III: Gasification experiment results

Attributes	700 °C	750 °C
Gas yield (Nm^3/kg_{db})	2.39	2.64
LHV (MJ/Nm^3, dry gas)	4.05	4.81
CCE (%)	91.1	97.6
NH_3 (g/ Nm^3, dry gas)	19.55	18.65
H_2O (g/ Nm^3, dry gas)	166	122
H_2S (ppmv, dry gas)	180	60

An increase in temperature shows the improvement of calorific value of the product gas. It is imperative to mention that the LHV of the product gas exceeded the limit of 4.71 MJ/Nm^3 making it suitable to be used internal combustion engines [24]. Moreover, the total tar content is higher than the allowable limit therefore, the produced gas needs to be cleaned before it can be used in power generation devices (internal combustion engines, turbines, fuel cells *etc.*). The amount of NH_3, H_2O and H_2S decreased with temperature. Sulphur in the gas phase is reported in the form of H_2S. It is highly likely that

other sulphur containing compounds could have been formed during the gasification test however, they are not measured. Two samples were collected to measure the moisture content in the gas phase. The moisture content decreased with reactor temperature.

3.2 Effect of temperature on tar yield and composition

Table IV presents the identified tar compounds in the product gas while in Figure 4 total GC-detectable tar along with the different tar groups are illustrated. It can be observed from the Table IV that the toluene and indene decreased with an increase in the reactor temperature. A similar trend was observed during the gasification of poultry litter blended with limestone in a fluidised bed gasifier at temperatures of 700, 750 and 800 °C [25].

Table IV: Identified tar compounds and their classification

Tar (mg/Nm^3)	700 °C	750 °C	Tar groups
Benzene	2465.25	2610.18	Secondary
Pyridine	398.83	391.54	Secondary
Toluene	1685.2	1393.4	PAH-tertiary
Ethylbenzene	146.71	52.26	Secondary
m-Xylene	230.75	162.74	Secondary
Styrene	437.11	297.29	Secondary
o-Xylene	58.13	6.1	Secondary
Phenol	270.48	109.44	Secondary
Benzonitrile	63.47	36.17	Secondary
4-Methylstyrene	103.95	49.54	Alkyl-tertiary
Indene	280.15	272.56	Alkyl-tertiary
o-Cresol	28.55	0	PAH-tertiary
m+p-Cresol	82.84	0	PAH-tertiary
Naphthalene	379.77	455.19	Secondary
Quinoline	50.61	58.64	Secondary
1H-Indole	110.94	105.86	Secondary
2-Methylnaphthalene	110.88	99.49	PAH-tertiary
1-Methylnaphthalene	130.94	76.89	Secondary
Biphenyl	40.82	28.2	Alkyl-tertiary
2-Ethylnaphthalene	11.33	0	PAH-tertiary
1,6 Dimethylnaphtalene	18.77	11.07	Alkyl-tertiary
Acenaphtylene	52.67	66.23	PAH-tertiary
Acenaphthene	25.35	21.74	PAH-tertiary
Dibenzofuran	13.98	9.59	PAH-tertiary
2-Methyl-1-Naphthol	19.78	0	Secondary
Fluorene	32.04	45.99	Secondary
Phenanthrene	53.59	72.71	PAH-tertiary
Anthracene	14.82	20.26	Secondary
Fluoranthene	3.89	10.47	Secondary
Pyrene	3.14	5.31	Alkyl-tertiary
Chrysene	15.25	11.24	Alkyl-tertiary

It is evident from Figure 4 that the total GC-detectable tar decreases from 7340 mg/Nm^3 of dry gas to 6480 mg/Nm^3 of dry gas (~12% decrease) as the temperature rises from 700 °C to 750 °C. As expected, due to tested temperature range secondary tar is the predominant among the tar groups. On the other hand, the alkyl-tertiary tar depicts the lowest yield. Generally, alkyl-tertiary tar act as intermediate between secondary and PAH-tertiary tar at the temperature range between 750-850 °C [23], however since the temperature was limited to 750 °C it is not possible to draw conclusions regarding the evolution of both alkyl-tertiary and PAH-tertiary compounds.

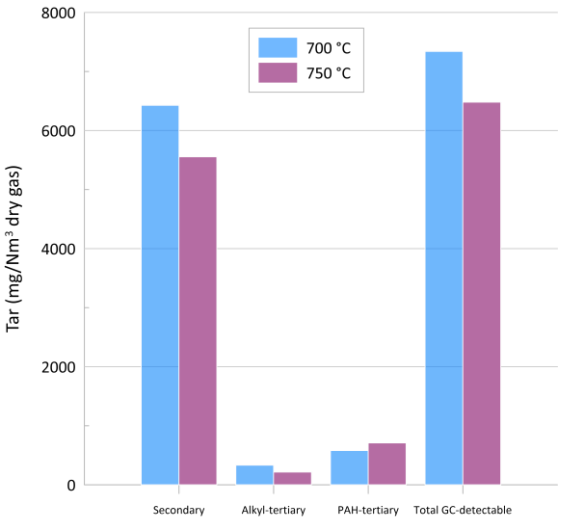

Figure 4: Tar groups and total GC-detectable tar as a function of temperature

Figure 5 denotes eight identified compounds with the highest concentration at the two tested temperatures. Benzene and toluene belonging in the secondary group show the highest concentrations amongst all the GC-detectable tar compounds, followed by styrene and pyridine. On the other hand, naphthalene is the most representative compound of the PAH group. In general naphthalene is considered a very stable compound, even at temperatures of 900 °C or higher [26,27].

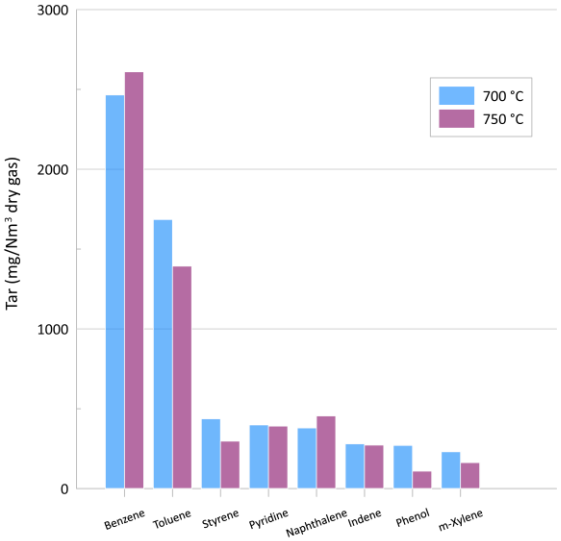

Figure 5: Yield of individual tar compounds as a function of temperatur

3.3 Mass balance analysis

Table V presents the mass balance calculation for the main elemental species. The input streams comprise of poultry litter on a received basis, air, steam, nitrogen, whereas the output consists of dry gas including NH_3, H_2S, unconverted material collected from the bed and cyclone (elutriated char and fly ash), along with the moisture present in the product gas. It can be observed from Table V that the mass balance ratios for carbon, hydrogen, nitrogen, and oxygen are in the range of 0.96 – 1.03. Moreover, the ash mass balance (output/input) ratio at 700 °C is reported to be 0.34. It is imperative to mention that the authors do not know exactly what caused this discrepancy. Moreover, the reported mass balance clearly demonstrates the accuracy of the experimental measurements.

Table V: Mass balance closure (output/input)

Elements	700 °C	750 °C
Carbon	0.96	1.03
Hydrogen	1.0	1.0
Nitrogen	1.0	1.0
Oxygen	1.0	0.96
Ash	0.34	0.97

4 CONCLUSIONS

Technical feasibility of poultry litter gasification was experimentally studied at an air-blown bubbling fluidised bed reactor. As expected, lower carbon conversion was observed at 700 °C and unreacted fuel was found in the bottom ash. By increasing the temperature at 750 °C, both CCE and LCV were enhanced. Ash sintering was observed at 750 ºC around air inlets however, they were not blocked until the end of the test run. Total GC-detectable tar decreased with temperature, whereas secondary tar was the predominant tar group at the tested temperature range.

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6 ACKNOWLEDGEMENTS

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