



2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF
2018, 17-19 October 2019, Paphos, Cyprus

Low temperature gasification of poultry litter in a lab-scale fluidized reactor

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Abstract

Low temperature gasification of poultry litter (PL) was experimentally studied in a lab scale fluidized bed reactor. The experiments were carried out at three different equivalence ratios (ER) of 0.17; 0.21; 0.25 and temperature 700 °C, to investigate its impact on cold gas efficiency (CGE), carbon conversion efficiency (CCE), gas yield, lower calorific value (LCV), and tar evolution. Maximum CGE and LCV of the produced gas was 43.4% and 3.34 MJ/m³ respectively at an ER of 0.25. The maximum CCE of 72% was attained at the highest value of ER (0.25). The gas yield showed an increasing trend with ER reaching its highest value of ~1 m³/kg_{daf} N₂ free. Highest amount of total tar was 2.41 g/Nm³ in the dry gas at the lowest tested ER. Styrene- xylene, phenol, and naphthalene, were the components with the highest concentrations of up to 30%, whilst the tar compounds detected but couldn't be identified ranged between 25-30% with respect to the total tar yield. The average compositions of the main components in permanent gases (vol %, dry basis) at the indicative value of the lowest ER were as follows: H₂:7.87%, CH₄:2.04%, CO: 6.37%, CO₂:11.47%, C₂H₄:1%, and C₂H₆:0.22.

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Selection and peer-review under responsibility of the 2nd International Conference on Sustainable Energy and Resource Use in Food Chains, ICSEF2018

Keywords: Poultry litter; gasification; fluidized bed; tars;

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1. Introduction

In the past decades, meat production has increased significantly, reaching globally 315 million tons in 2014 [1]. Population increment, rising income, along with the growing need for high value proteins are the main factors explaining this trend. Among the different meat segments, poultry is predicted to have the highest development in the near future, accounting for nearly half (45%) of the projected increase in meat production over the next decade [2]. Key drivers for the growth of poultry meat production are shorter production cycles, cheaper prices, and better nutritional image compared to pork and beef meat. On the other hand intensive livestock farming, although more efficient and cost effective than traditional farming, poses significant environmental challenges due to the large accumulation of waste in concentrated areas [3]. Foged *et al.* reported that EU member states generate 1.4 billion tons of manure to be processed or landfilled [4]. The over application of manure leads to excessive fertilization of agricultural land, giving rise to environmental concerns such as eutrophication, nitrate leaching, crop toxicity and emission of greenhouse gases [5,6]. Therefore, there is an urgent need to develop and adopt sustainable waste management practices, such as thermochemical conversion processes, which are able to reduce the mass and volume of waste significantly, whilst offering the possibility to produce energy in the forms of electricity and heat. Among the different technologies of thermochemical conversion, combustion is the most prevalent, whereas gasification and pyrolysis are still on the early stages of development.

In gasification process, carbon based feedstock is dissociated by an oxidant (air, oxygen, steam) into a gas known as syngas in a reducing environment at high temperature. Equivalent ratio is defined as the ratio between the amount of oxidant supplied in the process to the one required for stoichiometric combustion. In gasification the equivalent ratio is lower than the stoichiometric and usually ranges between 0.2-0.4. In comparison to combustion, gasification shows a number of advantages. Firstly, it is regarded as a cleaner technology, since combustion environment favors the formation of nitrogen and sulfur oxides which are considered major air pollutants. Furthermore syngas can be valorized as a fuel in different power production technologies, i.e. internal combustion engines, gas turbines and fuel cells. Moreover, it can be the base for the production of valuable chemicals, biofuels and fertilizer products. However, syngas contains different kind of impurities such as fine particles, tars, and alkali metals whose presence require extensive cleaning of the syngas before it can be utilized in the applications mentioned above.

Gasification can be categorized by different types of reactors, namely fixed bed, fluidized bed, and entrained flow. The former display the simplest design among the different types of reactor available and are suitable for small to medium scale applications due to physical limitations stemming from the geometry of the reactor. Fluidized bed gasifiers exhibit fuel flexibility, high heat exchange rates due to effective mixing, and are capable of handling feedstock with high ash content and operate in all range of applications. Entrained flow are mostly applied when syngas is needed at elevated pressures (e.g. direct injection in the gas grid) and at much larger scale compared to the other two types [7].

Experiments on gasification of PL have been conducted by numerous researchers in the recent past [5, 8, 9]. The authors have concluded that due to high ash content of PL which consists of elements with low melting points (e.g. potassium) the risk of agglomeration and further sintering of the bed is higher compared to other fuels. The objective of the present study is to investigate the low temperature gasification process of PL in a lab-scale fluidized bed reactor and assess the performance parameters.

2. Methodology

2.1. Materials

PL is considered as a heterogeneous fuel (excreta, bedding material such as straw or sand, and feathers) with low calorific value and high ash and moisture content. In the present study PL was supplied by Biolan, Finland in a pelletized form with moisture content of 9.71% w/w and a particle size of 0.5-0.98 mm. Table 1 represents ultimate, and proximate analysis along with the LCV of PL. The value of fixed carbon was calculated by subtracting the percentages of moisture, volatile matter, and ash from 100%. Similarly oxygen content was determined by the difference from the elements presented in ultimate analysis.

Table 1: Chemical composition of PL.

Type of feedstock	PL
<i>Proximate analysis (% w/w, as received)</i>	
Moisture	9.71
Volatile matter	69.6
Fixed carbon	20.7
Ash	14.3
<i>Ultimate analysis (% w/w, dry basis)</i>	
C	42.82
H	5.49
N	3.9
Cl	0.25
S	0.6
O	32.69
<i>LCV (MJ/kg db)</i>	16.78

2.2. Experimental facility and measurement methods

Gasification tests of PL were performed in a 5 kW_{th} input fluidized bed gasifier (bed section: 500 mm high and 74 mm internal diameter (ID) and a freeboard section: 600 mm high and an ID of 108 mm). Sieved silica sand with particle size of 0.25-0.5 mm (averaged 0.31 mm) was used as bed material during the experiments. It was estimated that under the operating conditions (air gasification, 700 °C, sand), the minimum fluidization velocity was 0.036 m/s. The fuel feeding rate was ~0.55 kg/h fuel (as received basis). Three different ER, 0.17-0.21-0.25, were tested by adjusting the flow rate of air and nitrogen entering the reactor. Neon (10 mL/min) was added as tracer gas to measure the flowrate of the evolved gases. On-line micro-gas chromatograph (GC) was used for the measurement of the syngas compositions (O₂, CO, CO₂, CH₄, C₂H₂, C₂H₄, C₂H₆, C₆H₆, C₇H₈, H₂S, and COS). Once the process parameters reached steady state, Solid Phase Absorption (SPA) samples were taken to determine the content and compositions of tar. A detailed description of SPA tar sampling method can be found elsewhere [10]. The experimental facility is presented in Fig. 1.

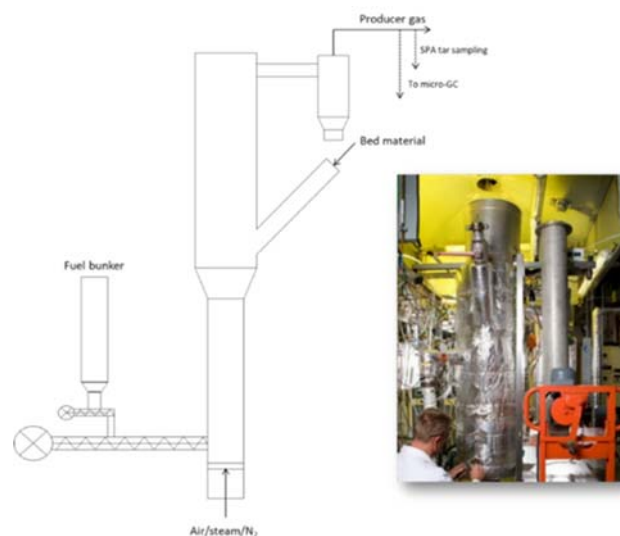


Fig. 1. Experimental facility at ECN, Netherlands.

2.3. Tar

One of the major challenges that impedes the development and commercialization of gasification technology is the amount of tar present in the syngas. Tar is a mixture of complex hydrocarbons which cause fouling and clogging of the downstream equipment when temperature falls below tar's dew point [11]. There is no official definition for gasification tar but one of the most common found in literature describes tar as the organic components having a higher molecular weight than the benzene excluding soot and char [12]. Once the biomass is fed into the gasifier, it undergoes pyrolysis process at the temperature between 200 °C and 500 °C. At this temperature range the biomass polymeric structures (i.e. cellulose, hemicellulose, and lignin) break down and form primary tar which consists of oxygen-rich hydrocarbons such as sugars, acids, alcohols, ketones, etc. At temperature above 500 °C primary tar reforms into secondary tars by partially losing functional groups and increasing the aromatic molecular structures. At temperatures above 800 °C the secondary tar molecules undergo rearrangement into tertiary tars by completing the condensation pathway resulting in purely aromatic species. A more detailed description and classification of tars can be found in [13].

Depending on the final utilization of syngas, tar concentration limits apply. Indicatively if syngas is destined to internal combustion engines or gas turbines for the generation of electricity and heat the maximum limits are 50-100 $\text{mg}_{\text{total tar}}/\text{Nm}^3_{\text{dry gas}}$ and 0.05-5 $\text{mg}_{\text{total tar}}/\text{Nm}^3_{\text{dry gas}}$ respectively. In case the amount of tar exceeds the aforementioned limits gas cleaning is imperative, a fact that increases process complexity and costs [13]. Apart from the total amount of tar present in the gas, the composition also plays a significant role in predicting the tar condensation in downstream applications. In general, the presence of tar compounds with higher molecular weight tends to increase tar dew point and vice versa. The calculation of tar dew point was performed by an online tool developed by the Energy Research Center of The Netherland (ECN).

3. Results

3.1. Gas composition

Fig.2 illustrates the evolution of gaseous species as a function of increasing ER at constant temperature 700 °C. Fig. 2(a), shows that CO₂ yield is rising due to increasing availability of oxygen which promotes oxidation reactions ($\text{C}+\text{O}_2\rightarrow\text{CO}_2$ and $\text{CO}+0.5\text{O}_2\rightarrow\text{CO}_2$). In contrast to the previous findings [14, 15], the compositions of H₂ and CO increase with ER. The possible reason could be attributed to water-gas reaction ($\text{C}+\text{H}_2\text{O}\rightarrow\text{CO}+\text{H}_2$) and steam-methane reforming reaction ($\text{CH}_4+\text{H}_2\text{O}\rightarrow\text{CO}+3\text{H}_2$). This hypothesis is supported by the small decrease in methane concentration. However, the composition of methane produced during pyrolysis zone is hardly affected from an increase in ER since it is kinetically controlled at temperature below 1000 °C [16, 17]. Similarly ethylene shows a stable trend acquiring values around 1% volume basis. Fig.2 (b) presents the trends of the minor gas components. Among these components, ethane depicts the highest concentration without a constant trend with increasing ER. Furthermore, sulfur is present in the form of COS and H₂S. COS seems to be unaffected by the changes of ER, whereas H₂S shows a slight increase. It is worth to mention that sulfur fed in the gasifier mainly remains in the bed or is collected in the cyclone as particulates, with a small amount detected in the gas phase, as evident from the mass balance described in section 3.5.

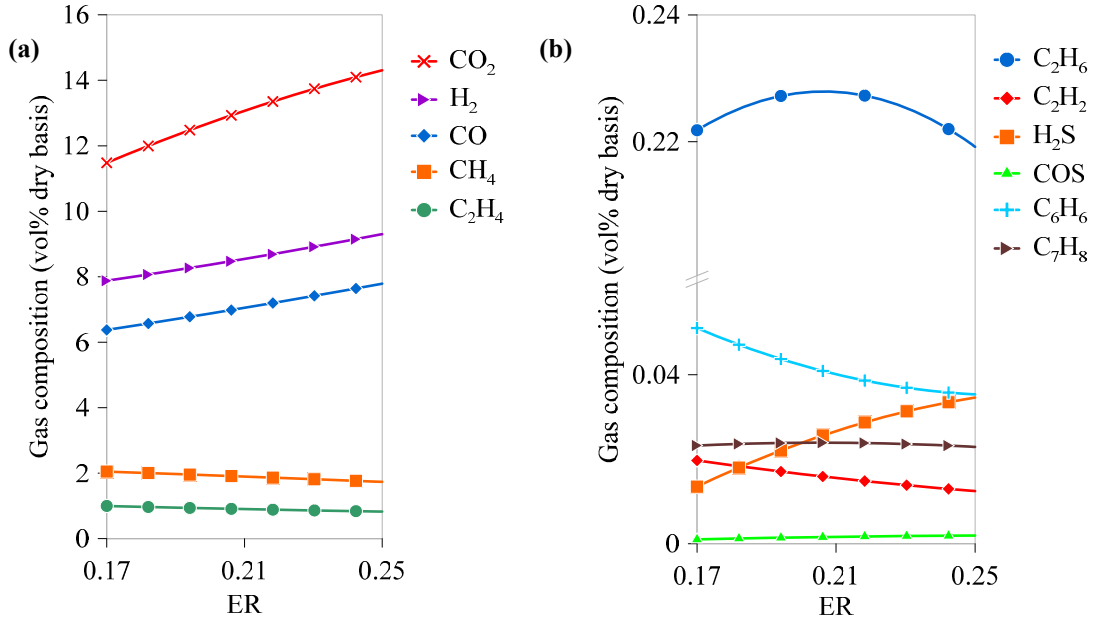


Fig 2. Effect of ER on (a) Main gas components; (b) Minor gas components.

3.2. Gas yield and lower calorific value (LCV)

Fig.3 shows the effect of ER on both the gas yield and LCV (excluding tar compounds). Gas yield rises as the ER increases due to the higher amount of oxygen available in the reactor allowing higher carbon conversion and consequent release of volatiles. The gas yield is reported on a nitrogen free basis to avoid the dilution effects.

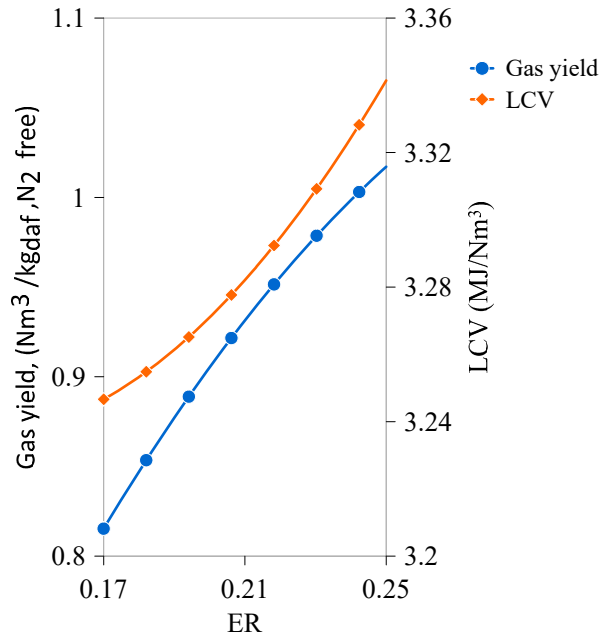


Fig.3. Effect of ER on gas yield and LCV

In general, the LCV of the gas evolved during the gasification process decrease with increase in ER [18–20]. The explanation stems from the fact that the increased amount of oxygen favors the products of oxidation reactions ($\text{CO} + 0.5\text{O}_2 \rightarrow \text{CO}_2$ and $\text{H}_2 + 0.5\text{O}_2 \rightarrow \text{H}_2\text{O}$). However in this study the LCV of the syngas increased by 3% with ER, due to the increase in H_2 and CO content explained in the previous section.

3.3. Carbon conversion efficiency (CCE) and cold gas efficiency (CGE)

Process performance parameters CCE and CGE are presented in Fig.4. CCE is defined as the ratio between the carbon which is converted into gas (dry basis) and the carbon contained initially in the fuel, both on the mass basis. The CCE shows an increase of 20% with ER. The increase in CCE is linked to the higher amount of oxygen available to react with volatiles and char, a fact that reduces the amount of unburnt carbon in the bed. Similarly, the CGE is defined as the ratio of chemical energy contained in the syngas to the chemical energy of the fuel input, both on a dry basis. Fig. 4 shows that the CGE rises slightly from 40.5% to 43.4%, mainly due to an increase of both the LCV and the gas yield.

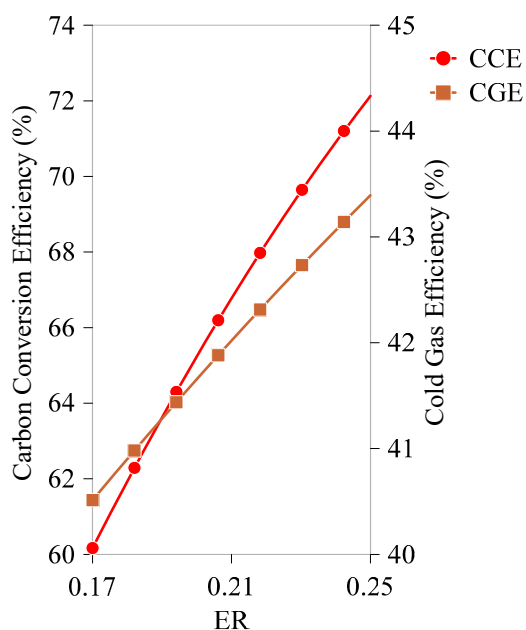


Fig. 4. Effect of ER on CCE and CGE.

3.4. Tar development

Fig. 5 depicts the total gas chromatography (GC) detectable tar yield and its composition in the dry gas as a function of ER. It is evident that the total tar content decreased by ~24% with the increase in ER. The results are in line with the previous finding [16] but in contradiction with [8, 21]. Overall it is difficult to draw definite conclusions regarding the trend of total GC detectable tar as a function of ER. The elemental composition of tar as a function of ER is shown in Fig.5 (b). It is evident that the concentrations of the different tar compounds haven't shown any major change with ER. In all the tests the most abundant tar components are styrene-xylene followed by phenol and naphthalene. Styrene-xylene and phenol are classified as secondary tar while naphthalene belongs to tertiary tar group. Other compounds (e.g. ethylbenzene, indole, biphenyl, etc.) are present in concentrations less than 4% with respect to the total GC detectable tar. The yield of tar that was detected but not identified is in the range of 25-30% with respect to total GC detectable tar. Calculated tar dew point at the indicative value of ER 0.17 is 100 °C. However, considering the fact

that the SPA method is not capable of measuring tars with higher molecular weight than the coronene, this can lead to an underestimation of the actual tar dew point, which may ultimately be higher [22].

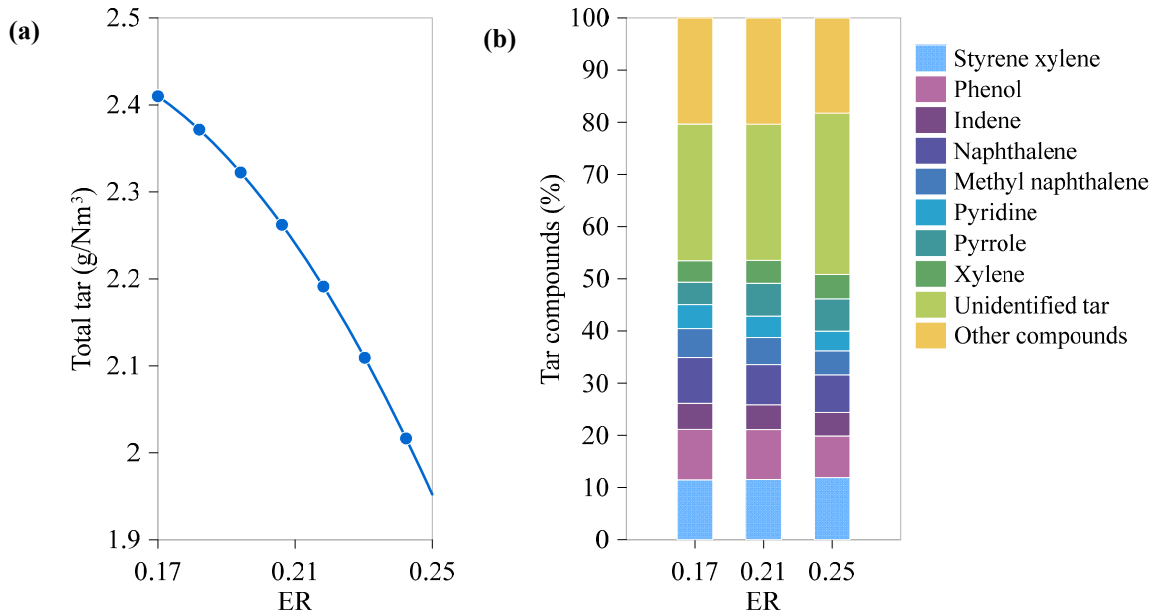


Fig. 5. Effect of ER on (a) Total GC detectable tar; (b) Tar composition.

3.5. Mass balance

Mass balance calculations were performed in order to estimate the accuracy of the experimental measurements. The input streams comprises of PL fuel, air, nitrogen, and moisture content whilst the output consists of gas and unconverted material collected from the bed and cyclone. It can be observed from Table 2 that the relative errors are within the acceptable limits of 15%. Carbon mass balance displays the highest deviation, which is expected since the carbon from tar was not taken into account. Furthermore deviations in hydrogen and oxygen balance can be attributed to the lack of information regarding elements such as ammonia but also to any errors occurred during moisture determination using P_2O_5 moisture analyzers.

Table 2: Mass balance for all gasification tests.

Elements	ER=0.17			ER=0.21			ER=0.25		
	Input	Output	Relative error (%)	Input	Output	Relative error (%)	Input	Output	Relative error (%)
C (kg/h)	0.212	0.15	29.2	0.212	0.166	21.3	0.212	0.174	17.6
H (kg/h)	0.033	0.027	16.9	0.033	0.027	15.9	0.033	0.028	14
N (kg/h)	0.854	0.863	-1.1	0.831	0.850	-2.3	0.81	0.83	-2.4
S (kg/h)	0.0029	0.003	-0.9	0.0029	0.0036	-21.7	0.0029	0.0026	11.7
O (kg/h)	0.311	0.343	-10.2	0.337	0.374	-10.8	0.362	0.405	-12

Relative error: $[(Input-Output)/Input]*100\%$

4. Conclusions

Gasification of PL was experimentally studied in a bubbling fluidized bed reactor. Low operating temperature did not give rise to any problems related to agglomeration and all the experiments were conducted successfully. The LCV was low acquiring values around 3.3 MJ/Nm³. It is worth to note that in contrast to the findings of other studies, the LCV of the evolved gases showed an increase with ER. The CCE and CGE as well showed an upward trend with increasing ER with the maximum attained values at 72% and 43.4% respectively. Total GC detectable tar yield is considerably low possibly due to the low content of lignin in poultry litter ranging around 2 g/Nm³, and furthermore it decreased with ER. Performed mass balance calculation indicated the highest inaccuracies in the case of carbon, whereas for most of the other elements it was found to be within the acceptable limits.

Acknowledgements

The work presented in this paper is supported by the Research Councils UK Centre for Sustainable Energy Use in Food Chains, grant no. EP/K011820/1 and EPSRC project 'Optimising Energy Management in Industry - OPTEMIN', grant No. EP/P004636/1. The Authors would like to acknowledge the financial support received by the project funders and the industry partners. The data used in the analysis are given in the paper but if more data or information is required they can be obtained by contacting the corresponding author.

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