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Simulation of gasification of livestock manure with Aspen Plus

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Abstract

Gasification is a flexible technology where all types of organic waste including biomass from manure can be used as feed to the reactor. The recovery of energy from solid waste offers several benefits including substantial reduction in the total quantity of waste and reduction in environmental pollution. The most suitable application of the product gas from the reactor is dependent on the quality and composition of the gas.

In this study, gasification of manure and wood chips is simulated. In the gasification process, the carbonaceous feedstock is fluidized with steam at 850°C. The simulations are performed using Aspen Plus. The focus has been to study the heating values and the fractions of the different components in the product gas. The results are discussed and different modifications of the process parameters in the simulations are considered. Sensitivity analyses with respect to the steam to biomass ratio have been performed.

Keywords: Gasification, livestock manure, biomass, Aspen Plus

1 Introduction

Biomass is a renewable energy resource. Depletion of fossil fuels reserves and environmental issues requires optimal utilization of biomass to replace use of fossil fuels (Wang et al, 2010). Production of renewable energy from livestock manure gives reduction in emissions of greenhouse gases as methane and nitrogen monoxide. In addition, more energy from renewable resources are produced (Triolo et al, 2013).

Intensified livestock industry and increased consumption of meat and animal products gives surplus of animal manure. This surplus can be used an energy resource. The main part in animal manure is animal slurry (feces and urine). In addition the manure can content sand, cleaning water, bedding materials (straw and branches). The quality of the manure depends also on how it is handled, diets and type of livestock (Triolo et al, 2013).

The conventional way to handle animal slurry for energy purposes is wet fermentation. Direct combustion is not so appropriate for most animal manures since the dry matter content in the sample is too low. To enrich the dry matter content, the liquid fraction needs to be separated from the solids. This manure can be separated into solid and liquid in the farmhouse by different practical solutions. Mechanical separation is a common separation technique. Dry matter, phosphorous and nitrogen are separated from the slurry fractions (Hjorth et al, 2011).

The main aim of this study is to use Aspen Plus for simulation of biomass gasification (Doherty et al, 2013). Combustion, pyrolysis and gasification can be used to convert biomass into energy product (Wang et al, 2010).

The gasification process is simulated as a steam blown dual fluidized bed reactor at atmospheric pressure. The application of the product is determined based on composition of the product gas.

2 Biomass gasification

Gasification of biomass is a thermochemical process that gives gaseous products. Carbonaceous materials in the biomass are converted into gaseous products with acceptable heating values. The produced gas can be used in gas engines or turbines to produce electricity or in production of liquid fuel for transport. (Ptasinski et al, 2007).

Energy is stored in biomass, since plants absorb energy from the sun through the photosynthesis process. Biomass sources can be woody plants, agriculture plants, sludge and manure. The different types of biomass have different heating values, chemical compositions, moisture content and ash content. Organic matter in the biomass shows small variations. The difference in moisture content and ash content are normally large. Manure can contain an essential part of water. To avoid a low gasification efficiency, the moisture content in the biomass needs to be reduced before gasification. (Ptasinski et al, 2007).

3 Biomass feed

Biomass values used for studying the gasification are proximate analysis and ultimate analysis of pig manure and poultry manure (Xiao et al. 2008), (Font-Palma, 2012). Data from gasification of wood chips are used for model validation (Doherty et al, 2013).

Xiao et al. have carried out experimental studies using pig manure. The raw pig manure was mechanically pretreated to separate feces and urine and then composted for two weeks. Samples used for

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gasification was dried, crushed and assorted in different sizes. The size fraction used for gasification was 0.5 – 1.0 mm. Characteristics of pig manure samples are presented in Table 1.

Poultry manure consists of manure and litter from chicken production. The organic matter in the manure is high and makes is suitable for gasification. The concentrations of potassium (K), calcium (Ca) and phosphorous (P) in the ash is also high and are therefore suitable as fertilizer in the agriculture production (Font-Palma, 2012). Values used in the simulation are presented in Table 1. Doherty et al present proximate and ultimate analysis for wood chips.

Table 1. Characteristics of pig manure, poultry litter and wood chips.

Components	*Pig manure* (Xiao et al. 2008)	*Poultry manure* (Font-Palma, 2012)	*Wood chips* (Doherty et al, 2013)
Proximate analyses (wt %)			
Volatile matter	65.78	64.97	80
Fixed carbon	16.07	13.46	18.84
Ash	18.15	21.57	1.16
Moisture	21.61	27.4	20
Ultimate analyses (wt %)			
Carbon, C	36.45	37.05	51.19
Hydrogen, H	4.89	5.06	6.08
Oxygen, O	37.89	31.44	41.3
Nitrogen, N	4.52	3.66	0.2
Sulphur, S	0.88	0.45	0.02
Chlorine, Cl	-	0.97	0.05
Ash	15.36	21.37	1.16
Lower Heating Value, LHV [MJ/kg]	14.46	14.79	19.09

3.1 Gasification process

Gasification of biomass results in a mixture of combustible gases (Wang et al, 2010). Gasification converts the internal chemical energy of the carbon in the biomass into combustible gases (Puig-Arnavat et al). Biomass is heated in a gasifier at a high temperature with a controlled volume flow of oxidant (air, oxygen or steam). The produced gas includes hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), water vapor (H_2O), nitrogen (N_2), higher hydrocarbons and impurities such as tars, ammonia (NH_3), hydrogen sulphide (H_2S) and hydrogen chloride (HCl) (Doherty et al, 2013). Gasification is in general a very complex process due to combination of different mechanisms like mass transfer, chemical reactions and heat transfer. Input values used for gasification simulation are literature values from proximate and ultimate analyses.

The produced gas can reach different compositions and yields. Important factors are type of biomass, composition, type of oxidation agent, reaction temperature and pressure. (Wang et al, 2010). The chemistry in biomass gasification involves both biochemical and thermochemical reactions (McKendry, 2002). Simulations with Aspen Plus are based on the FICFB (Fast Internally Circulation Fluidized Bed) gasification process (Doherty et al, 2013). This model uses Gibbs free energy minimization method. It means that thermochemical processes for conversion of biomass is used to predict the composition of the producer gas (Doherty et al, 2013), (McKendry et al, 2002). If steam is used as gasification agent, the five chemical reactions showed in Table 2 can be considered.

Table 2. Chemical reactions in steam gasification of biomass, adapted from (Dorthey et al, 2013), (Thapa 2015)

Reactions	*Chemical equations*	*Reaction type*	$\Delta H_{R,850}$ [*kJ/mol*]
Steam gasification	$C + H_2O \leftrightarrow CO + H_2$	Heterogeneous reaction	+118.5
Boundard	$C + CO_2 \leftrightarrow 2CO$	Heterogeneous reaction	+159.5
Methanation	$C + 2H_2 \leftrightarrow CH_4$	Heterogeneous reaction	-87.5
Water-gas shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	Homogeneous reaction	-33.6
Methane reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	Homogeneous reaction	+ 225.5

The four main processes in the gasifier is drying, pyrolysis, combustion (oxidation) and gasification (reduction) (Doherty et al, 2013), (Kaushal, Priyanka et al., 2011). Figure 1 shows a schematic gasifier setup of a circulating fluidized bed gasifier.

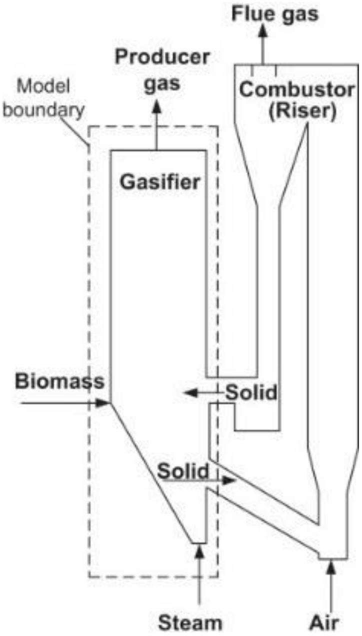

Figure 1 Schematic gasifier setup (Kaushal, Priyanka et al., 2011).

The typically moisture content in the biomass ranges from 5 – 35%. Drying happens at a temperature of 100-200 °C and reduces the moisture content to < 5% (Dorthey et al, 2013). The moisture content changes phase from liquid to gas. In addition to the added steam, the moisture contributes to the reactions in the gasifier. Pyrolysis happens at a temperature of (200-500 °C). Here the biomass is devolatilized to char and volatile gases. Gasification and combustion reactions are physically separated, to produce a producer gas with a low content of nitrogen (Dorthey et al, 2013). Typically, temperatures in the gasifier is 800-900 °C. The gasification takes place in a fluidized bed and the main reactions taking place are described in table 2. The bed material is circulated to the combustor where carbon attached to the bed material surface is burned off. Flue gas is removed. Hot bed material is recirculated back to the gasifier. The hot bed material supply the gasifier with necessary heat to the endothermic reactions.

4 Aspen plus simulation

The Aspen Plus model used in the simulation is based on the work of Doherty and described in more details by Doherty et al, 2013. In the simulation performed, pig and poultry manure are used as feed, but simulation with wood chips has also been performed to compare our model with the model of Dorethy et al 2013. Deviations is observed in the results with wood chips from the two models. The difference is due to the definition of the conversion of non-conventional components to conventional components in the first unit operation.

The stream class used in Aspen Plus is MIXCISLD, implying streams of gas mixture and solid carbon. The property method used is Redlich-Kwong-Soave (RKS) cubic equation of state with Boston-Mathias alpha function (RKS-BM).

The following assumptions were made for the Aspen simulation (Dorthey et al, 2013):

- The system is isothermal and operates under steady state conditions.
- Operation at atmospheric pressure, pressure drops are neglected.
- Tar formation is not considered.
- Char is 100% carbon.
- Heat loss from the gasifier is neglected.

4.1 Flow Sheet

The Aspen Plus flow sheet used in the simulation is presented in Figure 2 and is based on the model described by Doherty et al, 2013. The 'MANURE' is defined as a non-conventional stream and the ultimate and proximate analyse is given in Table 1. The thermodynamic condition for the manure stream was specified to 25 °C and 1 bar.

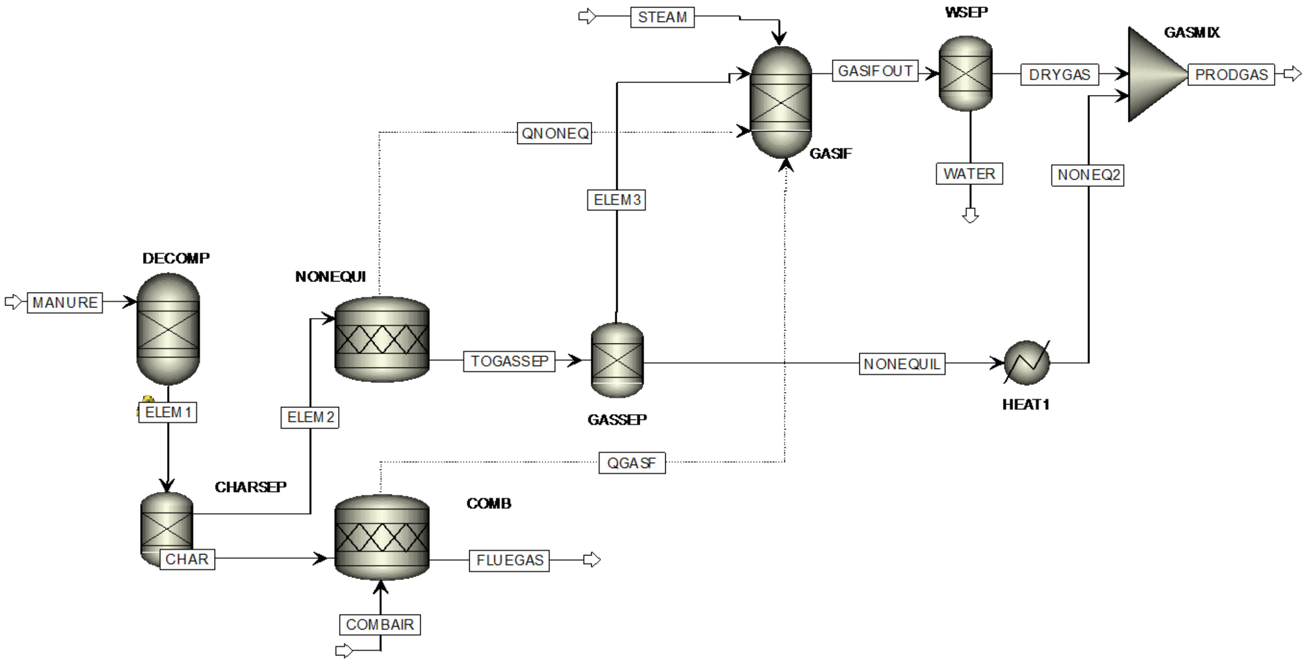

Figure 2. The Aspen Plus flow sheet.

In the RYield reactor 'BRKDOWN' the non-conventional components converts to conventional components. It is assumed that all hydrogen in the non-conventional component are converted to H_2, all oxygen are converted to O_2, all nitrogen are converted to N_2, all chlorine are converted to Cl_2, sulphur to elementary S and carbon to elementary C. The conversion are set using a calculator block (Doherty et al, 2013, Aspen tech, 2010). The outlet stream 'ELEM1' are fed to 'CHARSEP' where a portion of the char and all ash are separated out. The char and ash are directed to a combustion reactor RStoic titled 'COMB'. The air stream 'COMBAIR' is also fed to the same block. The air and char react, and the heat produced in this reactor is available for the gasification reactor by the heat stream 'QGASIF'. The char split fraction is set using a design specification, and varied until the temperature in the gasification reactor 'GASIF' is 850°C. The 'FLUEGAS'is the exhaust gas from the combustion process.

The material stream 'ELEM2' is directed to an RStoic reactor 'NONEQUIL' where all the nitrogen gas, chlorine gas and sulphur are converted to ammonia (NH_3), hydrogen chloride (HCl) and di hydrogen sulfide (H_2S) by the reaction with hydrogen. The stoichiometric reactions are defined in Table 3.

The heat produced in these reactions is made available for the gasification reactor by connecting the two blocks with the heat stream 'QNONEQ'. NH_3, HCl and H_2S are removed from the main fuel stream by the separator 'GASSEP'.

'ELEM3' is the main flow stream that is fed to the gasifier 'GASIF' which is a RGibb reactor. This stream contains mainly carbon, H2, O2 and water. Steam is also added to the 'GASIF' to gasify the manure and fluidise the bed. Reactions described in Table 2 is added in the RGibb reactor. After the RGibb reactor, water is removed in a separator 'WSEP' to determine the gas composition on a dry basis.

Table 3 Reactions for nitrogen, sulphur and chlorine (Doherty et al, 2013)

Chemical element	*Formation reactions*
Nitrogen, N_2	$0.5N_2 + 1.5H_2 \leftrightarrow NH_3$
Sulphur, S_2	$S + H_2 \leftrightarrow H_2S$
Chlorine, Cl_2	$Cl_2 + H_2 \leftrightarrow 2HCl$

Information of the process parameters are given in Table 4. The steam flow is given with a steam to biomass (e.g. manure) ratio (STBR) of 0.4. The STBR is defined as the mass flow rate of biomass moisture plus injected steam divided by the dry biomass flow rate (Doherthy, 2013). The steam temperature is set to 450°C and the pressure is 1 bar.

The stream 'NONEQUIL' is heated in a heater 'HEAT1' to make it possible to mix the 'DRYGAS' with NH_3, HCl and H_2S in 'GASMIX' to 'PRODGAS'.

Table 4. Process parameters used in Aspen Plus simulation.

	Pig	*Poultry*	*Wood chips*
Manure in pr. reactor [kg/h]	1000	1000	1000
STBR	0.4	0.4	0.4
Steam in reactor [kg/h]	97.46	16.40	120
Reactor temperature [°C]	850	850	850
Reactor pressure [bar]	1	1	1

5 Results and Discussion

The feed compositions of the pig and poultry manures are presented in Table 1. The proximate analysis shows that the poultry manure has a higher moisture and ash content and lower content of fixed carbon compared to pig manure. Wood chips has higher concentration of volatile components, more fixed carbon and significantly lower content of ash. The ultimate analyses show that the concentration of carbon in pig manure and poultry manure is approximately the same. The main difference between the two types of manure is that the pig manure has higher oxygen concentration and the poultry manure has higher ash content. Wood chips have significantly higher concentration of carbon compared to the manures. The content of nitrogen, sulphur, chlorine and ash are low in wood chips. The measured LHV of pig manure, poultry manure and wood chips are 14.46, 14.79 and 19.09 MJ/kg respectively.

Table 5 presents the results from simulations using pig manure, poultry manure and wood chips on dry and ash free basis as feed to the gasification process.

Table 5. Results of the main components after gasification

Components	*Pig (sim[1])*	*Poultry (sim[1])*	*Wood Chips (sim[1])*
CH4 (vol % dry basis)	0	0.04	0.14
CO (vol % dry basis)	42.86	32.40	39.72
CO_2 (vol % dry basis)	5.36	9.42	5.18
H_2 (vol % dry basis)	45.75	53.20	54.77
NH_3 (*ppm dry*)	55605	42527	1721
H_2S (*ppm dry*)	4729	2284	75
HCl (*ppm dry*)	na[2]	4453	170
LHV [MJ/m^3]	10,34	9.83	10,97
Gasification temperature [°C]	850	850	850

[1]sim = simulated, [2]na = not available.

Result from simulations shows that gasification of pig manure and poultry manure, and wood chips gives about the same lower heating values. The product gas from gasification of pig manure has higher CO and lower H_2 content compared to the product gas from the poultry manure. The concentration of CH_4 are insignificant for all cases, which is favourable for downstream processing to bio fuel. The gas composition from woodchips is comparable with the gas composition of the manures, but have higher H_2 concentration than pig manure and higher CO concentration than poultry manure.

Comparison of the product gas from manures shows that the pig manure gives higher concentration of NH_3 and H_2S than the poultry manure. Since the poultry manure has a certain content of Cl, the product gas also includes HCl. It is necessary to remove HCl, NH_3 and H_2S from the product gas if further processing to other specified products.

Table 6 shows typical dry composition of producer gas from the Guessing steam gasification process, which is based on wood chips (Pröll, T *et al,* 2004*)*

Table 6. Typical dry composition of producer gas from the Guessing steam gasification process (Pröll, T *et al,* 2004*).*

Components	*Experimental values*
CH4 (vol % dry basis)	10…11
CO (vol % dry basis)	24…26
CO_2 (vol % dry basis)	20…22
H_2 (vol % dry basis)	38…40
Others (vol % dry basis)	1…8
LHV [MJ/m^3]	12.9-13.6
Gasification temperature [°C]	850

Significant variations in the gas composition are observed when comparing the steam gasification process in Güssing with the simulations. Especially in the real plant, a significant amount of CH_4 obtained. In the simulation, the concentration of H_2 and CO reaches higher values than in a real plant, whereas the CO_2 content is lower. The simulation of the gasifier uses Gibbs reactor, which applies Gibbs free energy minimization to calculate equilibrium. The reactions in the gasification process are complex and by using the Gibbs reactor, it is not necessary to specify the stoichiometry or the reaction rates. However, this will also imply that considerations due to reactions kinetics are not evaluated.

Sensitivity analysis for pig and poultry manure and wood chips are performed using Aspen Plus. The reactor temperature is 850 °C. Figures 3 to 5 shows the steam to biomass ratio (STBR) as function of volume fraction of CH_4, CO, CO_2 and H_2 in the produced gas.

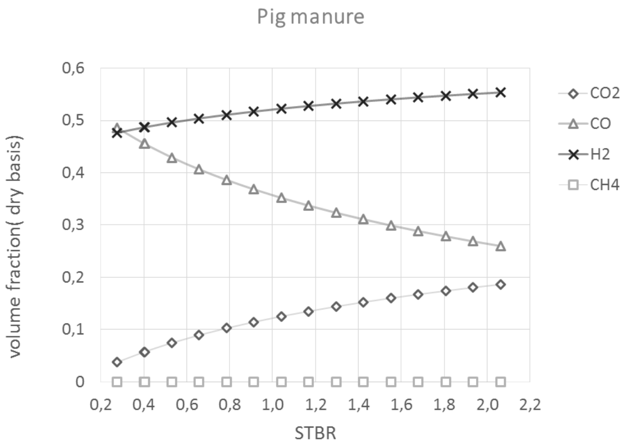

Figure 3. STBR as as function of volume fraction (dry basis) of CH_4, CO, CO_2 and H_2 for pig manure.

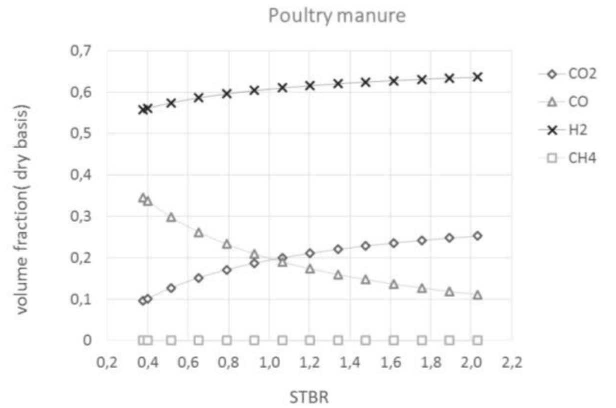

Figure 4. STBR as a function of volume fraction (dry basis) of CH_4, CO, CO_2 and H_2 for poultry manure.

Figure 5. STBR as as function of volume fraction (dry basis) of CH_4, CO, CO_2 and H_2 for wood chips.

All types of biomass show the same trend regarding the gas composition. H_2 and CO_2 concentrations increase with increased STBR. CO and CH_4 decrease with increased STBR. Poultry manure gives the highest H_2 production, and the lowest CO content, while pig manure gives highest CO content, and lowest H2 production. The CO_2 content is highest for the poultry manure.

From the reaction equations given in Table 2, an increase in the steam will give a reduction in CO concentration and an increase in the CO_2 concentration due to the water gas shift reaction. The figures show that a ratio of CO/CO_2 equal to 1 will take place at different STBR. For pig manure, this will be at a STBR at 2.8, for poultry manure at 1.0 and for wood chips at 1.6. This ratio is for all cases at a CO concentration of approximately 20 vol %.

Depending of the application of the produced gas the composition of the product is crucial. For production of chemicals for instant methanol, a ratio of H_2/CO of 1 is preferable, for other products the ratio differ. For production of heat and power, a high concentration of combustible gases is desirable. Related to the simulation given here, a low STBR is preferred.

6 Conclusion

Pig and poultry manures, together with woodchips, have been simulated in Aspen Plus based on the FICFB (Fast Internally Circulation Fluidized Bed) gasification process (Doherty et al, 2013). A model is developed using the Gibbs free energy minimization method to consider the possibility of using different types of biomass in a gasification process. Pig and poultry manures, together with woodchips, have been simulated in Aspen Plus to consider the possibilities to use different types of biomass in a gasification process.

The simulations of the gasification process with the three types of biomasses give comparable results regarding gas composition. Pig manure gives the highest CO concentration, while wood chips give the highest H_2 concentration. The lower heating value of the product gas is also comparable for the biomasses. Manure has relatively high concentration of NH_3 and H_2S and needs further cleaning processes compared to wood chips. This will give higher production costs.

Sensitivity analyses to study the composition of the produced gas as a function of steam to biomass ratio (STBR) show all an increase in H_2 and CO_2 concentrations and a decrease in CO concentration, with increasing STBR as expected.

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