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Fluidized-bed gasification of dairy manure by Box–Behnken design

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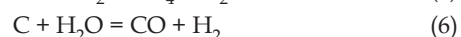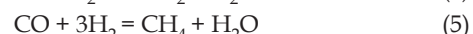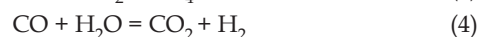211 L.W. Chase Hall, Lincoln, NE-68583, USA; email mhanna@unl.edu

Abstract

Application of excessive animal manure to the land may cause some environmental problems such as eutrophication of surface waters, degradation of ground water quality, and threats to human health. This paper reports an experimental study on the technology of biomass gasification to treat animal waste by analyzing the effects of key operating parameters on gasification. In this research, dairy manure from the University of Nebraska dairy farm was first collected and dried, and then gasified in a fluidized-bed, laboratory-scale gasifier to generate syngas. The effects of three parameters, namely temperature, steam to biomass ratio (SBR) and the equivalence ratio (ER), on the gasification were described by a Box–Behnken design (BBD). Results showed that increasing the temperature favored the formation of all three combustible gases, but the composition of each gas behaved differently according to the changing parameters. The lower heating value of the syngas varied from 2.0 to 4.7 MJ m^{-3}, indicating gasification could be used as a waste management option to produce bioenergy, and potentially reduce problems associated with the disposal of animal waste.

Keywords: Dairy manure, fluidized bed gasification, manure management, syngas production, Box–Behnken design

Introduction

Animal manure is a carbon-rich substance commonly applied to crop fields as a source of organic fertilizer, and according to a United States Department of Agriculture (USDA) estimation, more than 335 million tons of manure waste is produced annually on farms in the United States (USDA Agricultural Research Service, 2006). However, manure may be transported to surface water and groundwater through runoff and infiltration, when applied in amounts greater than can be used by the soil (Campagnolo et al., 2002). Consequently, some new technologies have been proposed to treat animal waste, and one of them is gasification. With the purpose of converting the manure waste into clean fuel gas, gasification technology has been taken into account by some researchers as an alternative way to treat animal waste in nutrient and energy recovery strategies (Prapaspongsa et al., 2009).

The principle of biomass gasification is to produce syngas through the thermo-chemical conversion of biomass, usually involving partial oxidation of the feedstock in a reducing atmosphere in the presence of air, oxygen and/or steam (Li et al., 2004). The composition of the syngas is the result of a combination of a series of chemical reactions. The main reactions are (Ciferno and Marano, 2002; Franco et al., 2003):

$$2C + O_2 = 2CO \tag{1}$$
$$C + O_2 = CO_2 \tag{2}$$
$$C + 2H_2 = CH_4 \tag{3}$$
$$CO + H_2O = CO_2 + H_2 \tag{4}$$
$$CO + 3H_2 = CH_4 + H_2O \tag{5}$$
$$C + H_2O = CO + H_2 \tag{6}$$
$$C + CO_2 = 2CO \tag{7}$$

Previous studies have investigated the application of gasification to treat animal waste. For example, Gordillo and Annamalai (2010) studied adiabatic fixed bed gasification of dairy biomass with steam and air. Young and Pian (2003) investigated the feasibility of integrating an advanced gasifier into the operation of a dairy farm for converting biomass wastes into fuel gas that can be used for power production. Research into fixed-bed gasification of feedlot manure and poultry litter biomass was conducted by Priyadarsan et al. (2004). However, less detailed information has been provided about the effects of operating conditions on syngas generated by animal manure. In the present study, dairy manure was gasified, and three key parameters were selected as the dependent variables: temperature, equivalence ratio (ER) and steam to biomass
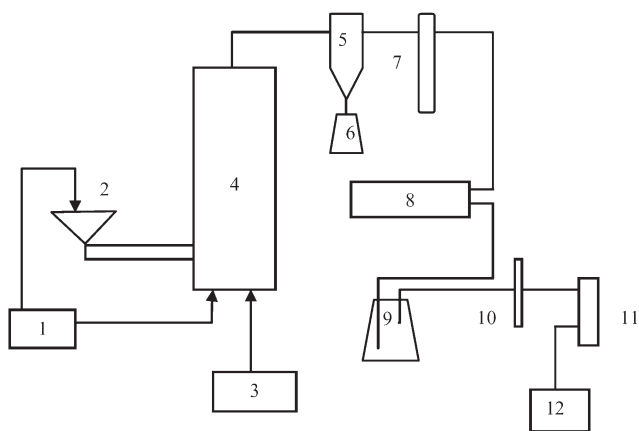
Figure 1. Schematic diagram of the fluidized-bed gasification system: 1, air supply system; 2, biomass feeder; 3, steam generator; 4, fluidized-bed gasifier; 5, cyclone separator; 6, char collection vessel; 7, high temperature filter; 8, heat exchanger; 9, condensation collection vessel; 10, syngas filter; 11, desiccator; 12, gas collection bag.

Figure 2. Geometry of a three factor BBD design.

ratio (SBR). Although the effects of some other parameters were analyzed in the previous gasification experiment, including the particle size of the biomass and secondary air injection (Li et al., 2004; Lv et al., 2004; Narvaez et al., 1996), these three parameters were considered as the most important variables that influenced chemical reactions in the gasifier. Box–Behnken Design (BBD) is a type of factional factorial designs, which is very efficient because of its smaller sample sizes (Haaland, 1989). Based on the principle of response surface methodology (RSM), BBD was applied to evaluate the effects of the above three factors on the syngas composition and energy efficiency of the gasification processes in this paper.
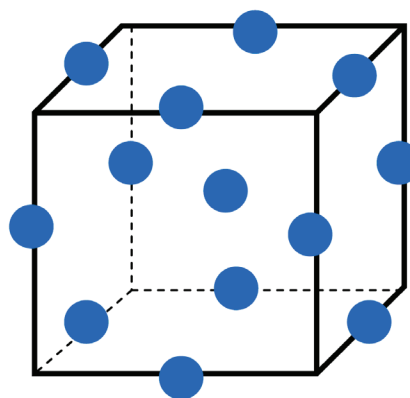
Material and methods

Materials

Fresh dairy manure collected from the University of Nebraska dairy farm was dried in the oven (60 °C) for 2 weeks, and then ground. After that, the moisture content, heating value, particle size distribution and ultimate analysis were conducted on the dried manure.

Equipment

The fluidized-bed gasification system is shown in Figure 1. The gasifier had two parts. The length of the lower part (bed) was 700 mm with an inside diameter of 3.81 cm, and the length of the upper part (freeboard) was 500 mm with an inside diameter of 6.35 cm. A data acquisition system (Model: NI SCXI-1102 with 32-channel thermocouple terminal block) and LabView 2009 (National Instruments Corporation, Austin, TX, USA) were applied to monitor the temperature at several locations throughout the gasification system.

Operation

At the beginning of the experiment, the fluidized bed was charged with 80 g of silica sand as the fluidized bed material, with the purpose of stabilizing fluidization and better heat transfer (Lv et al., 2003). The gasifier was heated by a tube furnace made of black iron, and the saturated steam was superheated. After both of the gasifier temperature and steam temperature reached their predetermined set points, air was fed into the gasifier first, and then the manure samples were fed at a constant rate of 1.67 kg h^{-1}. After 2 to 3 min, when syngas was observed downstream, superheated steam was fed from the bottom of the gasifier. After another 5 min, the syngas generated was collected in gas sample bags, and char was collected at the bottom of the cyclone separator (Kumar et al., 2009).

Gas sampling and analysis

For every experimental run, four sample bags were used. The composition of the syngas collected was analyzed by a gas chromatography system (Model: AutoSystem GC, PerkinElmer Inc., Waltham, MA, USA). As the syngas contained a very small amount of NH_3 and H_2S, the lower heating value (LHV) only took into account the CH_4, CO and H_2. This value was calculated by equation (8) (Kumar et al., 2009):

$$\text{LHV of syngas (MJ m}^{-3}) = (35.81 \times CH_4 + 12.62 \times CO + 10.71 \times H_2) \quad (8)$$

where CH_4, CO and H_2 were the volume fraction of each gas.

Experimental design

Box–Behnken designs (BBD) are experimental designs for response surface methodology, which explore the relationships between several explanatory variables and one or more response variables (Zhu et al., 2010). BBD consists of a central point and the middle points of the edges of the cube circumscribed on the sphere (Kumar et al., 2008). These designs are rotatable (or near rotatable) and require three levels of each factor, and the geometry of a three-factor BBD is shown in Figure 2 (Eriksson et al., 2008). In this experiment, a three-

Table 1. Levels of three variables.

Variables	Levels		
Coded level	−1	0	1
Temperature (°C)	650	750	850
ER	0.08	0.14	0.20
SBR	0	0.88	1.76

Table 2. The three-level three-factorial Box–Behnken design.

Exp no.	Temperature	ER	SBR
1	−1	−1	0
2	−1	1	0
3	1	−1	0
4	1	1	0
5	−1	0	−1
6	−1	0	1
7	1	0	−1
8	1	0	1
9	0	−1	−1
10	0	−1	1
11	0	1	−1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

Table 3. Properties of dried dairy manure sample.

Moisture content (% wet basis)	7.78
Ultimate analysis (% wet basis)	
C	35.21
H	4.07
O	27.35
N	1.48
S	
0.234	
Ash	23.89
Higher heating value (MJ kg^{-1})	11.6
Mean particle size (mm)	1.02

Statistical analysis

The statistical software SAS 9.2 (SAS Institute Inc., Cary, NC, USA) was used to establish the quadratic model, and the statistical software MINITAB 14.1 (Minitab Inc., State College, PA, USA) was applied to define the response surface plots.

Results and discussion

Characteristics of dairy manure

Characteristics of dairy manure, including moisture content, ultimate analysis, heating value and mean particle size are shown in Table 3.

LHV of syngas

The LHV of the syngas generated by air and steam gasification of dairy manure ranged from 2.0 to 4.7 MJ m^{-3}, which was lower than that of the syngas produced through oxygen gasification (oxygen as the gasification medium), which is usually more than 10 MJ m^{-3}, due to nitrogen dilution (Ciferno and Marano, 2002). In addition, the value was lower than that of the syngas from pine sawdust (6.7 to 9.1 MJ m^{-3}) (Lv et al., 2004) and olive particles (10.9 to 13.1 MJ m^{-3}) (Rapagnà et al., 2000), due to the relatively lower calorific value of dairy manure. However, this syngas can still be combusted to generate heat for steam or power generation (Priyadarsan et al., 2004), and Wang et al. (2009) pointed out that low heat-value syngas can be used in a combustor.

Char content

Amount of char separated by the cyclone varied 5 to 35 g in all experimental runs. As a byproduct of gasification, char was manufactured from biomass. Therefore char was high in carbon content and also contained a range of macro- and micro-nutrients (Lehmann and Joseph, 2009).

Statistical model

The four statistics models developed are listed in Table 4, where the coefficients of determination (R^2) indicate the overall fit of the model, and the square root of the variance of the residuals (RMSE) measure the difference between the predicted and the observed value.

level, three-factor BBD was applied to investigate the gasification parameters affecting the syngas composition and energy efficiency during the whole process. The three variables were temperature, ER and SBR, and the latter two were defined as follows (Lv et al., 2004).

$$ER = \frac{\text{weight air / weight dry biomass}}{\text{stoichiometric air / biomass ratio}} \quad (9)$$

$$SBR = \frac{\text{weight of steam}}{\text{weight of biomass}} \quad (10)$$

The response values were CH$_4$, CO, H$_2$, and energy efficiency, respectively; therefore, four models were established. Energy efficiency is defined by equation (11) (Rajvanshi, 1986).

$$\text{Energy efficiency} = \frac{LVH_{gas} \times F}{D \times E} \quad (11)$$

where F is the flow rate of the syngas (m^3 min^{-1}), LHV_{gas} is the lower heating value of the syngas (MJ m^{-3}), D is the flow rate of dairy manure (kg min^{-1}), E is the LHV of dairy manure (MJ kg^{-1}).

Three variables were equally spaced, and the low, middle, and high levels of each variable were coded as −1, 0, and 1, respectively, as given in Table 1. The experimental design is given in Table 2 (Annadurai and Sheeja, 1998; Kumar et al., 2007). For each experimental run, there were three replications.

Table 4. Statistic model for each response value.

Response value	Model	R^2	RMSE
CH$_4$	$y = 3.39 + 1.10x_1 - 0.60x_2 - 1.55x_3 - 0.51x_1{}^2 - 0.028x_1x_2 + 0.51x_2{}^2 - 0.33x_1x_3 + 0.30x_2x_3 + 1.65x_3{}^2$	86.0%	1.21
CO	$y = 1.86 + 0.55x_1 - 0.49x_2 - 0.56x_3 + 0.025x_1{}^2 - 0.14x_1x_2 - 0.025x_2{}^2 - 0.060x_1x_3 + 0.12x_1x_2 - 0.083x_3{}^2$	97.0%	0.21
H$_2$	$y = 12.03 + 1.11x_1 - 0.90x_2 - 0.90x_3 + 0.54x_1{}^2 - 0.26x_1x_2 - 0.47x_2{}^2 + 0.91x_1x_3 - 0.095x_2x_3 - 2.05x_3{}^2$	79.1%	1.53
Energy efficiency	$y = 20.67 + 4.63x_1 + 2.13x_2 - 5.72x_3 - 0.97x_1{}^2 - 0.27x_1x_2 + 1.68x_2{}^2 - 2.075x_2x_3 - 0.37x_3{}^2$	94.1%	2.52

x_1, x_2, and x_3 are the coded value for temperature, ER and SBR, respectively (from Table 1). All of x_1, x_2, and x_3 are in the range of $[-1, 1]$.
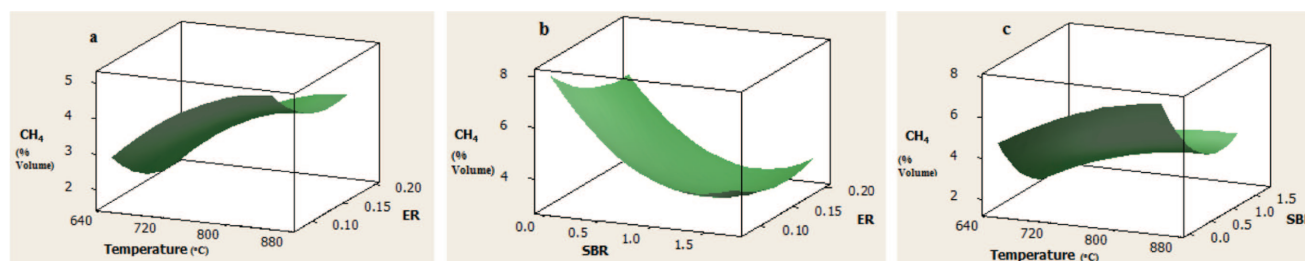
Figure 3. Influences of two parameters on CH$_4$ yield, where in (a) SBR = 0.88, in (b) T = 750 °C, and in (c) ER = 0.14.
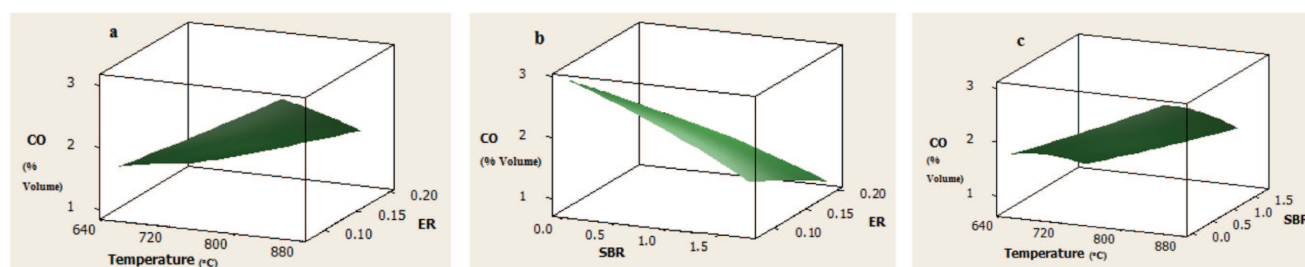
Figure 4. Influences of two parameters on CO yield, where in (a) SBR = 0.88, in (b) T = 750 °C, and in (c) ER = 0.14.

CH4 production

The influences of two parameters on methane yield, while holding the third parameter at the middle value, are shown in Figure 3(a)–(c). From the plot, it can be seen that the range of methane generated by dairy manure gasification varied from 2 to 8%. In Figure 3(b) and (c), with increasing SBR, the methane yield decreased first until the value of SBR reached around 1.4, after which the methane yield became stable. On the other hand, temperature and ER did not significantly influence the methane yield. Similar results were reported by Narvaez et al. (1996), who pointed out that the CH$_4$ amount did not vary a lot when the gasification temperature increased from 700 to 850 °C.

CO production

The influences of two parameters on the CO yield, while holding the third parameter at the middle value, are shown in Figure 4(a)–(c). During gasification of dairy manure, not much CO was produced, which may have been due to the relatively low energy density of dairy manure. The CO concentration

decreased significantly with the decreasing SBR shown in Figure 4(b) and (c), the same trend was observed by Franco et al. (2003). Furthermore, the declining ER resulted in a increasing concentration of CO; this was explained by Turn et al. (1998) that as ER decreased, less fuel was converted into CO$_2$ and H$_2$O, and steam gasification (reaction (6)) became more important, producing more CO.

H2 production

The influences of two parameters on the H$_2$ yield, while holding the third parameter at the middle value, are shown in Figure 5(a) to (c). From the plots in Figure 5(a) (c), an increasing trend of H$_2$ concentration was observed when the gasification temperature was increased from 650 to 850 °C. In another aspect, with the SBR rising from 0 to 0.8, the H$_2$ concentration increased from 10 to 14%, after which, increasing SBR did not increase the H$_2$ predication. The explanation may be that for a SBR lower than 0.8, not enough steam reacted with all the biomass and reactions (4) (water–gas shift) and (6) (steam–carbon reaction) did not seem to reach a state of completion. Consequently, the concentration of CO decreased, and the
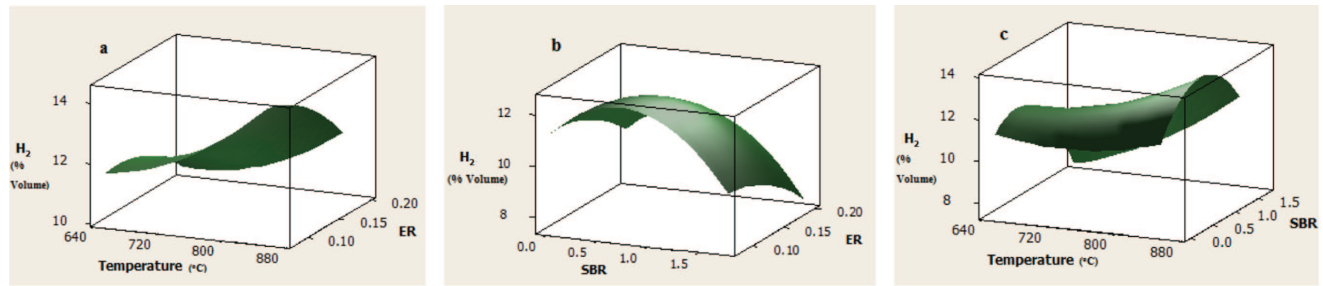
Figure 5. Influences of two parameters on H_2 yield, where in (a) SBR = 0.88, in (b) T=750 °C, and in (c) ER = 0.14.
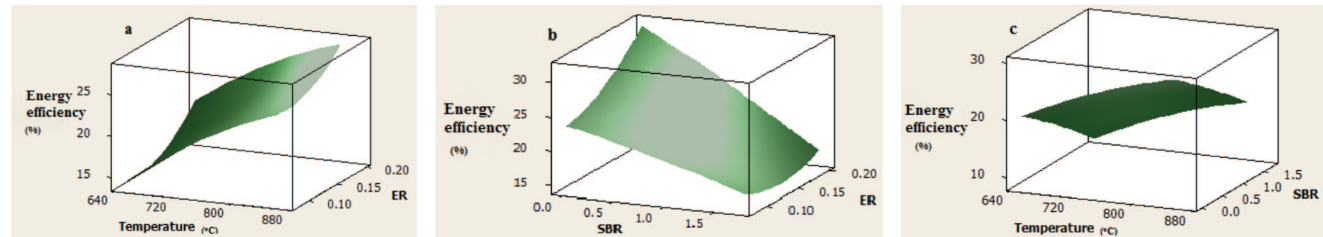

Figure 6. Influences of two parameters on energy efficiency, where in (a) SBR=0.88, in (b) T=750°C, and in (c) ER=0.14.

H_2 concentration increased simultaneously. With the increasing steam input, the influencing reactions could reach a state of equilibrium, leading to the maximum value of H_2 yield (Franco et al., 2003).

Energy efficiency

The influences of two parameters on the energy efficiency, while holding the third parameter at the middle value, are shown in Figure 6(a)–(c). Energy conversion efficiency of gasification of dairy manure (15 to 30%) was lower than that of wood, which was about 60 to 70% (Ciferno & Marano, 2002). It was interpreted that dairy manure had a relatively lower heating value than wood, and more ash content. It also showed that the temperature was the most influential factor with respect to the energy efficiency. Higher temperature favored the higher energy efficiency.

Conclusions

1. Dairy manure was successfully gasified in a laboratory-scale fluidized-bed gasifier, and the syngas was sampled and analyzed. In addition, a three-factorial BBD design was applied to evaluate the effects of three operating conditions (temperature, ER and SBR) on the syngas composition and energy efficiency of the gasification process.
2. As the temperature increased the combustible gas and energy efficiency also increased on the whole; however, the composition of each gas was also determined by the comprehensive effect of all operating parameters. In general, an increasing SBR (0 to 0.8) led to a decreasing CH_4 concentration and an increasing H_2 concentration, whereas the declining ER (2.0 to 0) resulted in a rising concentration of CO.

3. Depending on the operating parameters, the LHV of the syngas varied from 2.0 to 4.7 MJ m^{-3}. Although it is a low-heating value gas, some end-use applications can be taken into account. Experimental results suggest gasification could be used as a waste management option to reduce animal waste disposal problems in the USA.

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