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Steam plasmatron gasification of distillers grains residue from ethanol production

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ABSTRACT

In this study, a plasmatron reactor was used for gasifying the waste of distillers grains at different temperatures (773, 873, 973 K) and water flow rates (1, 2, 3 mL min^{-1}), which were heated to produce steam. Among all the gas products, syngas was the major component (88.5 wt.% or 94.66 vol.%) with temperatures yielding maximum concentrations at 873 K with a relatively high reaction rate. The maximum concentrations regarding gaseous production occurring times are all below 1 min. With the increase of steam, the recovery mass yield of syngas also increases from 34.14 to 45.47 ~ 54.66 wt.% at 873 K. Water–gas reactions and steam-methane reforming reactions advance the production of syngas with the increase of steam. Furthermore, the water-shift reaction also increases in the context of steam gasification which leads to the decrease of CO_2 at the same time.

1. Introduction

The use of biomass as an alternative feedstock to fossil fuels is intensifying due to its role in reducing CO_2 emissions and the rising cost of petroleum. Wood, crops, agricultural, and forestry residues comprise the main renewable energy resources available. In addition to these, the biodegradable components of municipal solid waste (MSW) and commercial and industrial wastes are also significant bioenergy resources (Bridgwater, 2003). Transformation of waste into energy can be efficiently achieved by applying thermochemical techniques such as combustion, pyrolysis, partial oxidation, and gasification (Shie et al., 2001, 2002, 2004a,b, 2008; Wu et al., 2003; Tu et al., 2008, 2009). Numerous innovative gasification processes have been developed during the previous decades; one of the most promising gasification technologies is catalytic or non-catalytic, high temperature, steam or steam/O_2 gasification (Panagna et al., 2000). The gasification of biomass to produce syngas offers an alternative supply of energy to fossil fuels. Because the syngas essentially contains molecular hydrogen and carbon monoxide, it has the potential for use as a high-quality fuel. Moreover, after purification, it becomes an important source of hydrogen which is important in the context of fuel cell technology (Tendler et al., 2005).

The processes of gasification and pyrolysis are old, but the commercialization of the process has been limited and recent (Stiegel and Maxwell, 2001). More research is needed to capture the full potential of the process by making it economically viable. The difficulties in cleaning the produced gas from tar and other contaminants, capturing the heat loss associated with high temperatures, and lack of extensive information about the gasification operation are the main obstacles facing large-scale commercialization of the gasification process. Furthermore, there are still several problems related to conventional gasification processes, such as low gas productivity associated with low heating value, high CO_2 production, corrosion of gas collection equipment from SO_x emissions, and the need for further treatment of the gas produced (Bridgwater, 2003; Mérida et al., 2004; Yaman 2004; Kumar et al., 2009). Limitation of excess quantities of CO_2 emissions released into the atmosphere is also a necessity due to the climatologic changes that are imposed by such atmospheric pollution (Skoulou and Zabaniotou, 2007). Notably, these disadvantages and problems described above can be overcome via the use of steam plasmatron gasification which offers unique advantages for biomass conversion, such as providing high temperatures and heating rates and low emissions of CO_2 in comparison to conventional pyrolysis and gasification methods. The high energy densities and temperatures associated with thermal plasmas and the corresponding fast reactions provide a potential solution for the problems generated by conventional processes (Zhao et al., 2001; Shie et al., 2008; Tang and Huang, 2005). The organic compounds are thermally decomposed into simple compounds, such as syngas (CO and H_2), or their constituent elements through a plasmatron reactor. The inorganic materials are melted and converted into a dense, inert, and non-leachable vitrified slag that does not require controlled disposal (Moustakas et al., 2005). The main advantages are: more effective control of the composition of the produced gas, higher heat capacity of the gas, reduction of unwanted contaminants such as tar and CO_2, and higher hydrocarbons (Van Oost et al., 2006).

In our previous study, a plasma torch was used to examine the feasibility and operational performance of the pyrolysis of biomass wastes, taking rice straw as the target material; the yield of H_2

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increased with the increase of input power or temperature. With the increase of moisture (5–55 wt.%), the mass yields of H_2 and CO_2 also increased with the H_2O decomposition. However, due to the CO_2 production, the accumulated volume fraction of syngas decreases with the increase of moisture (Shie et al., 2010).

In this study, the treatment of distillers grains using a thermal plasmatron reactor as the heat source was further examined. Distillers grains, a non-fermentable byproduct of ethanol production, was used as the biomass feedstock for the gasification. Gasification experiments were performed using a carrier gas (N_2) injected with temperatures ranging from 800 to 1000 K (2.87–3.89 kW). Distillers grains are the residue from the fermentation of grain for ethanol production. Thus, the main objective of this article is to assess the plasmatron steam gasification of the waste biomass of distillers grains with different water flow rates, which are heated to produce steam, and to examine the effects of operation parameters on the performance. It is the aim of this work to examine the steam gasification of distillers grains with the notion of providing product distribution at different steam contents. The steam gasification was performed using a plasmatron system in a nitrogen atmosphere with a 10 kW power capacity. The residual materials and non-condensable gases were collected and analyzed using an elemental analyzer, gas analytical instruments, and gas chromatography analyzers with thermal conductivity detectors (GC-TCD).

2. Methodology

2.1. Materials

The biomass used in this study was distillers grains. The distillers grains were taken from the fermentation process of ethanol production from the Yilan Distillery of the Taiwan Tobacco and Liquor Corporation. The sample was dried in a recycling ventilation drier for 24 h at 378 K before use and then cut into 10 mm cubes. For comparison, the effect of steam content and the water flow rates (circulated by a 378 K heating tape for steam production) were adjusted to 1, 2, and 3 mL min^{-1} and injected into the plasmatron reactor. The results of the proximate analysis were 50.84 ± 2.68, 0.81 and 48.36 ± 2.70 wt.% for combustible value, ash and moisture, respectively. After the removal of moisture, the combustible value is almost 98.43 wt.%. The contents of C, H, N, and S of dry distillers grains were 55.56, 6.41, 6.45, and 1.86 wt.%, respectively (Table 1). The BET surface area analysis of distillers grains residue is shown in Table 2. The BET surface area of dry distillers grains is very low and the value is 0.19 $m^2 g^{-1}$.

2.2. Plasmatron operational procedure

The pilot-scale apparatus used and the experimental procedures for the plasmatron steam gasification of distillers grains are shown in Fig. 1. A 10 kW plasmatron was used for the gasification procedure. For batch feeding, a cubed sample of known mass (10 g) was placed on the sample input apparatus for feeding the sample material. The flow rate of carrier gas N_2 (99.99%) (Q_N) was adjusted to the desired value, i.e., 10–12 L min^{-1} at 101.3 kPa (1 atm) and 293 K, and was controlled by a rotameter. The power supply control unit (chopper) (Taiwan Plasma Corp.) for the plasmatron reactor was set at 2–4 kW (P_L) for the temperatures (T) from 700 to 1000 K, respectively (Table 3). The operation process was similar to the previous study (Shie et al., 2010). For easy delivery and feeding, the distillers grains were cut to a 10 mm cube. For the analysis of gas products, a Thermo Scientific FOCUS GC gas chromatograph GC-TCD with a Supelco packing column (60/80 carbonxen-1000, 15 ft long, 2.1 mm i.d.) was used. The operation conditions were the same as the previous study (Shie et al., 2010) and set as follows: injector temperature 453 K, detector temperature 513 K, column temperature (following the sampling injection) was held at 513 K for 10 min, helium carrier gas flow rate was 30 mL min^{-1} for A and B columns, and sample volume was 2 mL. Several duplicate experimental runs were performed in order to verify the values.

Table 1
Elemental analysis of distillers grains and solid residues from steam plasmatron gasification at various temperatures and steam flow rates.

	Target temperature ± 20 (K)	773 K		873 K		873 K		873 K		873 K		973 K	
	Water flow rate (mL min^{-1})	0		0		1		2		3		0	
Element	Dry raw distillers grains[a]	[b]	[c]	[b]	[c]	[b]	[c]	[b]	[c]	[b]	[c]	[b]	[c]
C	55.56 (0.01)[d]	77.82 (1.25)	4.44	79.47 (1.54)	4.79	79.23 (1.75)	2.33	71.63 (0.72)	2.16	75.76 (1.85)	3.55	76.27 (0.17)	3.99
H	6.41 (0.80)	1.13 (0.18)	0.06	0.95 (0.00)	0.06	0.95 (0.01)	0.03	1.31 (0.06)	0.04	0.97 (0.05)	0.05	0.96 (0.00)	0.05
N	6.45 (0.04)	3.22 (0.07)	0.18	3.79 (0.79)	0.23	2.54 (0.21)	0.07	2.73 (0.02)	0.08	2.78 (0.01)	0.13	3.26 (0.05)	0.17
S	1.86 (0.77)	0.07 (0.01)	0	0.05 (0.00)	0	0.07 (0.03)	0	0.08 (0.02)	0	0.06 (0.03)	0	0.07 (0.01)	0
C/H ratio (wt/wt)	8.67	69.08	5.71[e]	83.74	6.03[e]	83.85	2.94[e]	54.64	3.01[e]	77.86	4.69[e]	79.62	5.23[e]

[a] Dry basis of distillers grains residue = 10 g.
[b] Based on mass of residue.
[c] Based on original mass of raw distillers grains residue.
[d] Numbers in parentheses are standard deviations (σ_{n-1}).
[e] Mass ratio of residue to raw distillers grains residue.

Table 2
BET surface area analysis of distillers grains and solid residues from steam plasmatron gasification at various temperatures and steam flow rates.

Target temperature ± 20 (K)	Dry raw sample	773 K	873 K	873 K	873 K	873 K	973 K
Water flow rate (mL min^{-1})	–	0	0	1	2	3	0
BET surface area ($m^2 g^{-1}$)	0.19	101.10	65.34	205.87	227.54	174.61	99.23