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ABSTRACT

Seeking appropriate approaches to utilize the crude glycerol produced in biodiesel production is very important for the economic viability and environmental impacts of biodiesel industry. Gasification may be one of options for addressing this issue. Co-gasificati of hardwood chips blending with crude glycerol in various loading levels was undertaken in the study involving a pilot scale fixed-bed downdraft gasifier. The results indicated that cr glycerol loading levels affected the gasifier's performance and the quality of syngas produced. When crude glycerol loading level increased, the CO, CH_4, and tar concentrations of the syngas also increased but par concentration decreased. Though further testing is suggested, downdraf ifiers could be run well with hardwood chips blending with liquid crude glycerol up to 20 (wt%). The syngas produced had relatively good quality for fueling internal combustion engines. This study provides a considerable way to utilize crude glycerol.

1. Introduction

Biodiesel production is continually growing in renewable energy market in recent years because of the concerns of national energy security and environmental impact. There is about 10% of liquid crude glycerol byproduct produced in biodiesel production (Dasari et al., 2005). The continually increasing biodiesel production results in abundant of crude glycerol flooding into the market and/or causing environmental impact. There were about 2.65 billion liters biodiesel produced in the US in 2008. This translated to about 0.23 billion kg of crude glycerol generated in a year (NBB, 11 9). Crude glycerol has high salt and pH values and contains methanol, soaps, and various elements including calcium, phosphorus, potassium, si n, sodium, zinc, etc. (Thompson and He, 2006). Although high pure glycerol is a very important industrial feedstock widely applied in food, drug, cosmetic and tobacco industries, crude glycerol derived from biodiesel produ n has very low value because of the impuriti contains (Pachauri and He, 2006; Johnson and Taconi, 2007). It is generally too costly to refine crude glycerol to a high purity, especially, for small to medium sized biodiesel plants. The numerous and continually increasing untreated crude glycerol has been big issues to biodiesel plants. Seeking appropriate approaches to utilize crude glycerol is very important for the economic viability and enviro ntal impact of biodiesel industry. Various methods, such as combustion, composting, animal-feeding, thermo-chemical processing, and biochemical conversion, for crude glycerol usage and disposal have been proposed, however, most of them are er developing at bench scale level in laboratory (Adhikari et al., 2007; Dasari et al., 2005; Mu et al., 2006; Cerrate et al., 2006; Dharmadi et al., 2006; Haryanto et al., 2007; Gan and Yuan, 2008). Although there were some potential shown in those research, the details of the effects of crude glycerol on the type and scale of conversion and the technical and economic feasibility of crude glycerol conversion are not well known yet. There is little information about gasification of crude glycerol at pilot or commercial scale reported in literature.

The presenting study is to explore a co-gasification approach for converting liquid crude glycerol into a gas phase mix e (called syngas), which mainly consists of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), steam (H_2O), and nitrogen (N_2). Though contaminants like tars, small char and ash particulates and/or other traces of impurities may be found in syngas, depending on the technologies and feedstock used in gasification, syngas can be further upgraded and used for generating electric power or producing liquid biofuels (Devi et al., 2003; Ma is, 2001; Wei et al., 2009a).

Gasification is one of the most promising technologies for utilizing renewable resources to producing fossil fuel alternatives. This technology is already developed. It has high thermal efficiency

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and neutral CO_2 emission. Among various biomass gasification technologies, fixed-bed downdraft gasifiers are attracted because of its long development history, reliable structure, stable and simple operation, and producing relatively high quality syngas with low tar content. Using fixed-bed downdraft gasifiers for wood chips' gasification is a proven technology, but this type of gasifiers was limited to solid feedstock (Chopra and Jain, 2007; Kalisz et al., 2004; Warnecke, 2000; Wei et al., 2009a,b). If wood chips such as hardwood chips and liquid crude glycerol are blended together, the crude glycerol will be absorbed by the hardwood chips and become a solid feedstock that can be gasified within downdraft gasifiers, then that would be a simple additional method of utilizing abundant crude glycerol which in this case is to produce syngas. The method of mixing hardwood chips and liquid crude glycerol together could be a means of changing the gas composition of syngas produced, or would be a means of minimizing the use of hardwood chips in gasification. Therefore, the aim of this study focused on examining the feasibility of gasifying the mixture of hardwood chips laden with crude glycerol in a pilot scale downdraft gasifier and evaluating the effects of crude glycerol loading levels on the gasifier's performance and the yield and quality of syngas.

2. Methods

To examine the possibility of crude glycerol co-gasification with hardwood chips and the effects of crude glycerol loading levels, a comparison was done against the results of gasifying regular hardwood chips. A series of test runs was undertaken gasifying mixtures of hardwood chips blending with of different levels of crude glycerol. A L_4^1 (one factor, four-level experiment) factorial experimental design was employed in the test. Four crude glycerol loading levels were selected as 0%, 5%, 10%, and 20% crude glycerol in weight. A total of 12 test runs were needed for a tri-replication test. The experimental test runs were carried out by following a completely randomized sequence (Petersen, 1985).

2.1. Test material preparation

The hardwood chips used in the study contained red oak more than 90% with balance of barks or other wood chips, which were obtained from Domtar Paper Co., LLC (Columbus, Miss.) The three dimensions of hardwood chips were not greater than 75 mm. The hardwood chips were originally delivered with 20–25% moisture content (MC, wet based) and thus dried by forced ambient air to approximately 12% MC prior to being blended with crude glycerol. The crude glycerol used was provided by CFC Transportation Inc. (Columbus, Miss.).

Before gasification, the hardwood chips were blended with 5%, 10%, and 20% crude glycerol in weight (named HWG5, HWG10, and HWG20) and then stored in sealed drums, respectively. After a week of mixing in storage, the mixtures (called feedstock) of hardwood chip and crude glycerol were ready for gasification. It was observed that one week storage was sufficient for the crude glycerol to be absorbed and uniformly distributed into the hardwood chips without crude glycerol residue in drums by rotating the drums three times a day during the storage. Regular hardwood chips without blending crude glycerol (0% crude glycerol loading level, named HWG0) was used as the control treatment.

3. Test platform

A commercial pilot scale biomass gasification system was used for the test, which consists of a feeder unit, a gasifier unit, a char knocked-out pot, a char collecting bin, a heat exchanger, a filter set, a gas blower, and a computer control system (also named controller). The gasifier unit was a 15 kWe (electrical equivalent) fixed-bed downdraft gasifier produced and marketed by Community Power Corporation (CPC), Littleton, Colorado. It was designed for producing syngas at load levels ranging from 30 to 60 Nm^3/h. The gasification process flowchart is shown in Fig. 1a and the reactor chamber of the gasifier unit is shown in Fig. 1b. The variables monitored are listed in Table 1.

3.1. Test procedure

The gasification tests began with the gasification system initializations which included software initialization and a warming up period. After the system was warmed up, feedstock was fed into the gasifier. The feedstock' weights were recorded prior to entry into the gasifier. Primary air flow was added from the middle section of the reactor chamber by an air blower. Additional air was sucked into the gasifier from the open top of reactor due to the pressure drop inside the reactor chamber. All of the air was drawn down going through the feedstock to enter the reaction zones during the gasification. In order to get stable syngas yield and quality, total of air flow was automatically adjusted to achieve steady

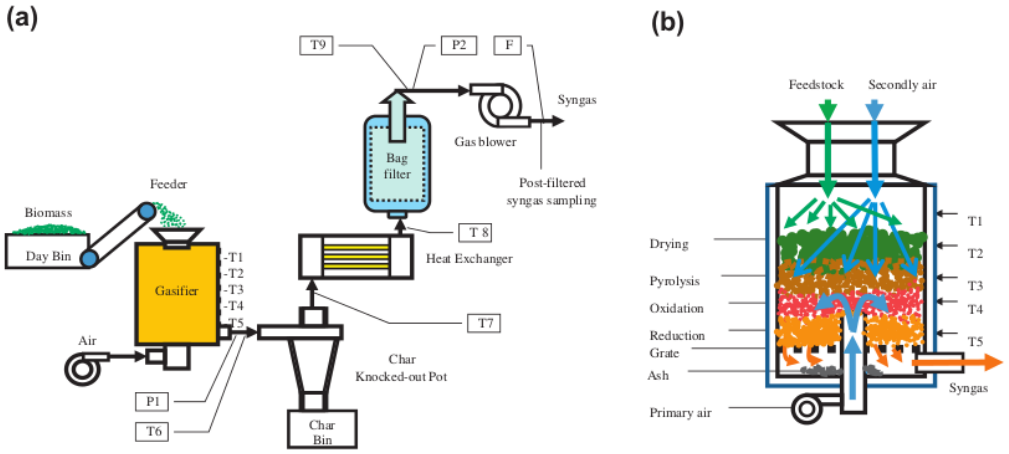

Fig. 1. The fixed-bed downdraft gasifier system and the reactor chamber.

Table 1
Ultimate analyses of crude glycerol, hardwood chips and their mix (dry matter).

Species	Carbon wt%	Nitrogen wt%	Hydrogen wt%	Oxygen wt%	Sulfur wt%	Ash wt%	Bulk density wt% kg/m^3	Heating value MJ/kg
Crude Glycerol	58.05	0.19	10.58	29.82	0.01	1.19	1270	16
HWG0	51.2	0.08	5.71	44.63	0.005	1.15	222.15	19.59
HWG20	52.58	0.1	6.61	41.05	0.01	1.54	282.83	18.71

reaction temperature by the gasifier controller. The feedstock fed in underwent drying, pyrolysis, oxidation, and reduction stages, and thus was converted into syngas (shown in Fig. 1b).

After gasification, the resulting syngas was channeled to downstream processes continually. Some ash and unconverted char residues fell through the grate at the bottom of the reactor chamber. The exiting mixture of unconverted char, ash and syngas entered a char knocked-out pot at a relatively high velocity and exited it at a reduced velocity to allow larger char particles to drop into a char collection bin. The syngas and entrained smaller particles leaving the char knocked-out pot at a temperature ranging from 600 to 700 °C entered a forced-air heat exchanger where cooling took place and the temperature dropped to approximately 90 °C. After leaving the heat exchanger, the syngas was cleaned by a filter set which removed extra-fine particulate matter and tar. After filtration, the cleaned syngas could be delivered into electricity generator sets which used it as fuel for generating electricity or delivered to storage tanks for further upgrading for productions of biofuels or chemicals. In the case of this study, the syngas produced was delivered to a gas flare and burned.

3.2. Data collection

Syngas quality is depended on its composition, heating value, and possible impurities contained. The parameters of syngas quality considered in this study include syngas composition, low heating value (LHV), and tar and particle concentrations. For syngas composition determination, syngas was sampled at the post-filtered outlet (Fig. 1a). Only CO, CO_2, H_2, and CH_4 in the syngas were measured, and the rest were assumed to be N_2 and H_2O vapor, which generally range from 40% to 55% and 1% to 10%, respectively (Maniatis, 2001; Devi et al., 2003). Continuous measurements of the CO, CO_2, H_2, and CH_4 concentrations were made with a gas analyzer (Model: NOVA 7900) at a resolution of ±0.1% (volume) during the gasification processing. The syngas sampling apparatus used for measuring syngas composition is shown in Fig. 2a. The syngas composition readings were recorded every 5 min, and the average of the readings was used as the values of syngas composition for each test run.

Tar concentration (mg/Nm^3) is defined as the total weight of tar per unit volume of syngas, and particulate concentration (mg/Nm^3) is defined as the total weight of particulates per unit volume of syngas. All of syngas volumes were counted in normal cubic meter (Nm^3) at standard temperature and pressure conditions (STP: 25 °C and 101.325 kPa) in this study unless mentioned. The syngas sampling apparatus used for tar and particulate analysis is shown in Fig. 2b. Syngas was sampled triply at the post-filtered outlet for each test run. During sampling, the pump caused the syngas to go through a coil of tubing in an ice bath and through a micro-glass fiber filter (Ahlstrom Filter, grade 151, 0.7 μm). This process caused tar to condense inside the coil and also at the filter. The particles were stopped by the filter resulting only syngas at the output and the flow rate was monitored by a mass flow rate meter. Once collected, the condensed tar were dissolved and washed using acetone and then the particulates were separated from the acetone-tar's solution and stayed on the filter paper. Finally, the tar's and particle's concentrations were estimated by computing the weights of tar and particles divided by the volumes of sampled syngas, respectively (Maniatis, 2001; Wei et al., 2009a; Devi et al., 2003).

High heating value (HHV) is defined as the amount of heat produced by the complete combustion of a unit quantity of fuel, which can be directly determined by calorific meter. By subtracting the latent heat of vaporization of the water vapor formed by combustion from the HHV, the low heating value (LHV) of fuel is determined. The combustible compounds in syngas are CO, H_2, and CH_4; the remaining compounds, like N_2, CO_2, and H_2O, are non-combustible. Since only CO, CO_2, CH_4, and H_2 were considered in this study, the LHV (MJ/m^3) of syngas produced from the gasification was determined by the relative amounts of combustible components, CO, H_2, and CH_4. Those non-combustible compounds and some traces of tar and unconverted char particulates were

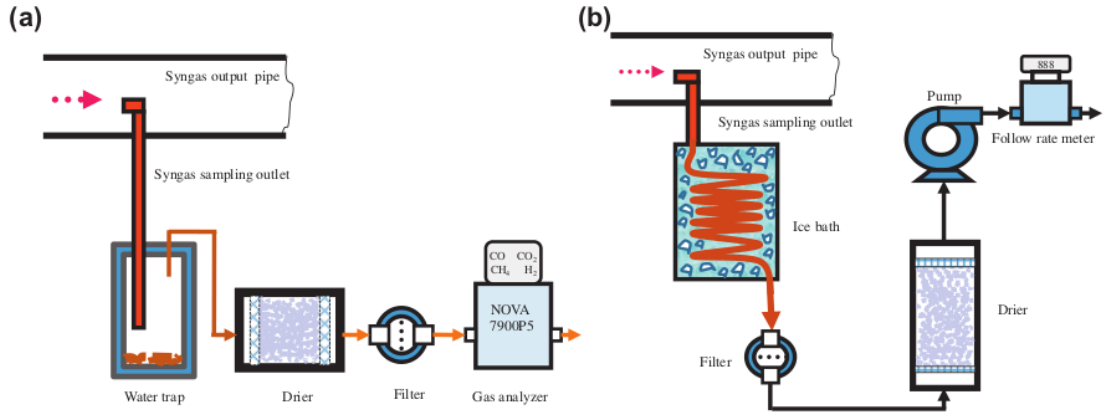

Fig. 2. Gas sampling devices for syngas composition, tar, and particulate analysis.

excluded from LHV estimates. According to a report provided by National Renewable Energy Laboratory (NREL) (Waldheim and Nilsson, 2001), the LHV of CO, H_2, CH_4 was 12.622 MJ/Nm^3, 10.788 MJ/Nm^3, and 35.814 MJ/Nm^3, respectively. The formula for calculating LHV of syngas can thus be represented as the following equation. The percentages of gases in the equation are based on volume.

$$LHV = 12.622P_{CO} + 10.788P_{H_2} + 35.814P_{CH_4}$$

where P_{CO} = the percentage of CO in syngas, P_{H2} = the percentage of H_2 in syngas, P_{CH4} = the percentage of CH_4 in syngas.

All temperatures of the system were determined by the thermocouples listed in table 1 and recorded automatically every 10 s by the controller computer. Feedstock conversion rate (FCR) was also concerned in the study. FCR (Nm^3/kg) was defined as the amount volume of syngas produced per unit weight of feedstock. The mass of feedstock consumed was determined using a scale (Model: Arlyn 22 ± 0.005 kg) before the feedstock was fed into the gasifier. The total volume of syngas produced was estimated by the gasifier's computer software, which automatically tallied the volume from the gas flow rate meter at syngas exit. And then the average of FCR was obtained by dividing the total of volume of syngas from the total of feedstock consumed.

4. Results and discussion

4.1. Gasification system performance

A research conducted by Thompson and He (2006) showed that there was no significant variation in the chemical and physical properties of crude glycerol though the technologies and feedstock used in biodiesel production might be different. Due to instrument availability in the study, the information of chemical and physical properties of crude glycerol was obtained from literature. Typically crude glycerol contains 50–60% glycerin, 14–34% soapstock, 18–20% methyl ester, 3–12% methanol, 1% water, and traces of other components (Douette et al., 2007; Thompson and He, 2006; Schröder and Südekum, 1999). Because of the use of alkali salt in biodiesel production alkali metal (either Na or K) content is generally in range of 1–3%. Other metals like Calcium, Magnesium, Manganese, etc. are less than 80 ppm or below detectable limits (Thompson and He, 2006).

To examine the effect of crude glycerol loading level on chemical composition of the mixture of hardwood chips blending with crude glycerol, the ultimate analyses of HWG0 and HWG20 were carried out by the Columbia Analytical Service Inc. at Tucson, Arizona. The analysis results are shown in table 2. The average values of typical crude glycerol are also listed in table 2 (Thompson and He, 2006; Douette et al., 2007; Hansen et al., 2009).

Table 2
Measuring devices and variables.

Symbol	Variable (unit)	Measuring device
T1	Feedstock input (°C)	Thermocouple
T2	Start drying (°C)	Thermocouple
T3	Pyrolysis (°C)	Thermocouple
T4	Oxidation (°C)	Thermocouple
T5	Grate (°C)	Thermocouple
T6	Gasifier out (°C)	Thermocouple
T7	Char out (°C)	Thermocouple
T8	Cooling out (°C)	Thermocouple
T9	Filter out (°C)	Thermocouple
P1	Gasifier pressure (kPa)	Pressure transducer
P2	Filter pressure (kPa)	Pressure transducer
F	Gas flow rate (Nm^3/h)	Flow rate meter

A total of 12 test runs involving replications were conducted by following a completely randomized sequence. The gasification system was run continually at 31.66 ± 1.54 Nm^3/h of syngas output flow rate about 2 h for each test run until all required data and samples were collected. Although originally expecting the gasifier should be run with the same feedstock feeding rate by constantly setting the syngas output flow rate at 30 Nm^3/h, the actual feedstock feeding rate varied from 21.03 to 23.02 kg/h during the tests. The feeding rate increased when crude glycerol loading level increased. This is likely caused by the bulk density variation of hardwood chips blending with crude glycerol. Table 2 shows that the bulk density of crude glycerol is much greater than that of hardwood chips. This led to the bulk density of the mixture of hardwood chips blending with crude glycerol greater than that of plain hardwood chips (HWG0). The higher crude glycerol loading level the greater bulk density of the mixture will be. The gasifier was designed to control feedstock feeding rate based on a specified level of the feedstock inside the reactor chamber. A level sensor detected the level of feedstock in the chamber and turned on the feeder to feed in new feedstock once the feedstock level fell below the set value. That was why more feedstock was fed in the reactor chamber by increasing the feeding rate while the bulk density of feedstock (the mixture of hardwood chips and crude glycerol) increased.

A total of 524.66 kg feedstock was gasified during the tests. There was no feeding trouble, feedstock "bridging" or "clogging" observed in the tests. The issue of greatest concern was that combustion of crude glycerol caused ash agglomeration that may block the gasifier grate. There was always some ash produced by gasification due to minerals contained in feedstock and the unconverted char particles. If the feedstock was woody only, mineral contents were very little and the char particles were small. Therefore the ash would be fairly easy blew through the grate and gone with syngas exiting the gasifier with very little blocking problem. There were alkali metal (Na or K) residues in crude glycerol. When the mixture of hardwood chips blending with crude glycerol was fed into the gasifer with reaction temperature high up to 900 °C, the Na or K salt residues easily volatilized and condensed on ash or unconverted char particles forming a sticky phase and accumulating on the grate, eventually might form agglomeration and block the grate. The agglomeration, in turn, resulted in a higher pressure difference inside the gasifier so that the grate must be cleaned. With plain hardwood chips, the gasifier can be operated for many runs or for extended operation without grate cleaning. With the addition of crude glycerol up to 20%, however, the grate would have to be cleaned in a shorter time when the gasifier was operated. Another solution is modifying the design of gasifier grate so that it can frequently clean the agglomeration. Otherwise, the gasifier system would shut down automatically according to a safety pressure drop set point of the system.

The test result indicates that there was no significant running problem for the downdraft gasifier if hardwood chips blended with some liquid crude glycerol and kept in solid phase. It can be concluded that downdraft gasifiers could be run well for co-gasification of hardwood chips blending with liquid crude glycerol up to 20% though agglomeration problem need further testing. This approach can overcome the drawback of solid feedstock limitation for fixed-bed downdraft gasifiers and provide a means for gasification of other liquid biomass feedstock.

The temperatures measured in the gasifier system can clearly outline the procedure of converting feedstock to syngas. The average gasification temperature profiles of various crude glycerol levels are shown in Fig. 3a. A typical hardwood chips' gasification temperatures inside the reactor chamber against processing time is shown as Fig. 3b. Fig. 3a shows that the feedstock were fed into the gasifier at T1 (about 25 °C, ambient temperature), started to be

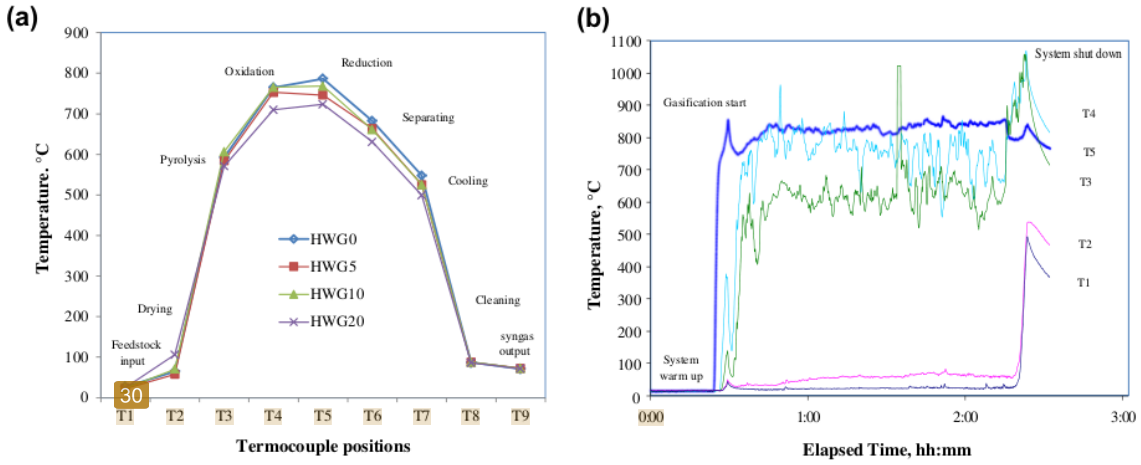

Fig. 3. Temperature profiles inside the gasification system.

dried at T2 (about 80 °C), pyrolyzed at T3 (about 600 °C), oxidized at T4 (about 800 °C), and reduced into syngas at T5 (about 900 °C). After that, syngas was exiting from the gasifier at T6 (about 700 °C) and then entered into a char knocked-out pot to be separated from the mixture of gases, unconverted char, and ash. Getting off from the char knocked-out pot, the syngas entered a heat exchanger at T7 (about 600 °C) to be cooled down to T8 (about 90 °C), and then went through a filter set to be cleaned up and finally yielded qualified syngas at T9 (about 50 °C) for consequent applications. It is found that the feedstock with higher crude glycerol loading level had a lower average temperature profile (Fig. 3a). This was probably due to the increases in crude glycerol in the mixture requiring more heat for the crude glycerol evaporation during gasification. The consuming extra heat resulted in the temperature drops inside the reactor chamber. Another possibility for the temperature drops were because the variation of feedstock feeding rate resulted in the actual air equivalence ratio (ER) changed. ER is defined as the actual air to feedstock ratio divided by the air to feedstock ratio for complete combustion. ER is one of the most important parameters for direct or auto-thermal air gasification because it establishes the reaction temperature and hence the gasifier performance. Most practical ER values range from 0.2 to 0.4 (Miskam et al., 2006; Bergh, 2005). Generally lower ER produces higher tar content in syngas produced. In contrast higher ER gives higher reaction temperature and lower tar content and lower LHV of syngas (Bergh, 2005). The gasifier unit used in this study was a direct air gasification system with a computer controller. It was designed to stabilize gasifier's performance by setting a constant reaction temperature (T5, the grate temperature) at the beginning of gasification. As the setting was determined, the actual total of air flowed into the reactor chamber was automatically adjusted to a constant because the primary air supplied by the air blower and the secondly air sucked in by the pressure drop inside the chamber were controlled by the setting. After the controller adjusted the feedstock feeding rate with the fixing amount of air flow to achieve a constant ER, the gasifer would be run in a steady status. In the case of this study, when the syngas output flow rate and the grate temperature (T5) were set at 30 Nm^3/h and 850 °C at the beginning, the actual HWG0 feeding rate was about 21 kg/h. It was estimated that the ER was about 0.293 for the gasification of HWG0. The syngas output flow rate was actually adjusted to about 31 Nm^3/h. However, the ER was about 0.269 when the feedstock feeding rate increased to 23 kg/h for the gasification of HWG20. These phenomena were observed similarly in the gasification of HWG5 and HWG10. Different ERs would establish different reaction temperature profiles. The pattern of temperature drops in Fig. 3a was reflecting the actual ER changed in the tests due to the variations of feeding rates.

The Fig. 3b shows the temperatures that were detected by the five thermocouples installed at different locations along the gasification reaction zones inside the reactor chamber. The cures of temperatures against reaction time indicate that there were distinguishable reaction zones inside the reactor chamber when feedstock was gasified (shown in Fig. 1b). During gasification, feedstock feeding and drying temperatures (T1 and T2) were stable because new feedstock were continually fed in and dried by the heat transferred from oxidation zone. This continually processing kept the temperature at a lower level. However, the pyrolysis and oxidation zone temperatures (T3 and T4) seemed to be fluctuating. It is because a lot of heat is required for pyrolysis reactions. The temperature T3 would go up when less feedstock were pyrolyzed, otherwise, it would go down if more pyrolysis reaction occurred. Meanwhile, more heat would increase to support the gasification if the feedstock combustion (oxidation) increases. The balance between pyrolysis and oxidation was automatically controlled by the gasifier controller, which resulted in the reduction zone temperature T5 being relatively stable during gasification. As mentioned earlier, when the syngas output flow rate and the grate temperature (T5) were set to a constant, the total of air supplied to the reaction chamber was fixed. The change in feedstock feeding rate would result in ER changing, and thus led to the reaction temperature profile changing. Unstable air or feedstock supplied would result in the temperature (T4) of oxidation zone fluctuating. On the other hand, a stable reduction temperature (T5) reflected a constant ER that would lead to steady syngas yield and quality.

4.2. Syngas quality evaluation

A summary of average compositions of the syngas is presented in Table 3, and a summary of average tar and particle concentrations, and LHV is presented in Table 4. The results show that the syngas produced from the mixture of hardwood chips mixed with 20% crude glycerol had the highest LHV, tar concentration, and CH_4 content. Published acceptable tolerances for syngas used in internal combustion engines (ICE) are also presented in Table 4 (FAO, 1986; Stergarsek, 2004; Heesch et al., 1999; Wei et al., 2009a; Wei et al., 2009b). It is apparent that the syngas produced from

Table 3
Averagesyngas compositions (% Vol.) at different crude glycerol loading levels (wt%).

Glycerol levels	CO	CH_4	H_2	CO_2
0	21.62 ± 0.49	2.41 ± 0.55	19.19 ± 0.65	11.58 ± 0.43
5	20.99 ± 0.52	2.12 ± 0.47	19.82 ± 0.86	11.21 ± 0.47
10	20.37 ± 1.06	2.80 ± 0.59	20.23 ± 0.26	10.96 ± 0.63
20	19.73 ± 0.86	3.82 ± 0.65	19.38 ± 0.35	11.67 ± 0.59

Table 4
Average syngas qualities at different crude glycerol loading levels.

Glycerol levels wt%	Tar mg/Nm^3	Particle mg/Nm^3	LHV MJ/Nm^3
0	47.85 ± 9.60	8.82 ± 4.55	5.66 ± 0.16
5	50.20 ± 6.68	5.75 ± 3.04	5.55 ± 0.17
10	75.40 ± 16.79	5.52 ± 1.59	5.75 ± 0.08
20	102.85 ± 6.78	4.85 ± 0.56	5.95 ± 0.04
Tolerances for ICEs	<100	<50	>4.2

the mixtures of hardwood chips and crude glycerol up to 20% compares favorably with published data, while the tar content in the syngas produced from the mixture of hardwood chips mixed with 20% crude glycerol in this study was a little bit beyond the tolerance level. It can be concluded that the syngas produced from the gasification of glycerol laden hardwood chips with the downdraft gasifier system is of acceptable quality regarding the measured parameters, and it could be directly used as a fuel in ICEs.

4.3. Effect of crude glycerol levels

The effect of addition of crude glycerol to hardwood chips on gasification was analyzed in the study. An ANOVA at $\alpha = 0.05$ level was carried out to examine the effects of crude glycerol loading levels on the composition, LHV, concentrations of tar and particles in the syngas, and FCR by using the Software SAS (Version 9.2). The ANOVA results are summarized in Table 5. The responses of those parameters to increasing levels of crude glycerol inclusion are showed in Fig. 4a–c. Table 5 indicates that crude glycerol loading levels have significant effects on the CO, CH_4, and tar concentration of the syngas while having no significant effects on H_2 and CO_2 contents, LHV, particle concentration and FCR. The CH_4 content of crude glycerol at 20% level was significantly higher than those of crude glycerol at other levels. The CO contents decreased when the crude glycerol loading levels increased. In contrast, the tar concentration significant increased as the crude glycerol loading level increased.

There were two possible factors causing those phenomena. One is the chemical composition and physical properties of crude glycerol are quite different from those of hardwood chips in terms of carbon, hydrogen, and oxygen contents, ash rate, bulk density, and LHV. Table 2 shows that the oxygen contents in crude glycerol were much lower than that of hardwood chips, but the hydrogen content and bulk density were much higher. When hardwood chips were blended with enough crude glycerol (for instance, up to 20% in weight), the changes in chemical composition and physical properties of the mixture were significant. The significant high CH_4 content in the syngas produced from crude glycerol loading level at 20% was likely caused by the higher hydrogen content (6.61%) in the mixture (Table 2). Meanwhile the lower CO content in the syngas might be due to the lower oxygen content in the mixture.

Table 5
ANOVA for the effect of crude glycerol loading levels.

Dependent Variables	*F* value	*P* value	Effect
CO	21.89	0.0003	Significant
CH_4	8.77	0.0066	Significant
H_2	0.44	0.7338	Not significant
CO_2	0.37	0.7749	Not significant
LHV	2.16	0.0222	Not significant
Tar	15.15	0.0019	Significant
Particulates	1.07	0.4123	Not significant
FCR	1.28	0.1652	Not significant

Another possible factor is the ER variations caused by the changes in feedstock feeding rates for different crude glycerol loading levels. As mentioned earlier, the changes in feedstock feeding rates led to the changes in ER, and eventually resulted in different reaction temperature profiles (Fig. 3a). Different reaction temperatures would result in different products in gasification, and thus affected the quality of syngas. Moreover, more heat might be needed for the crude glycerol evaporation in the mixture. Although the thermochemistry of gasification reactions were very complicated and haven't been fully understood yet, it's believed that those gasification phenomena were the results of the integrated effects of feedstock properties, reaction conditions, and some other factors that haven't been discovered in this test (Fermoso et al., 2010; Hannula and Kurkela, 2010; Mitsuoka et al., 2011; Wang et al., 2009). Further research is necessary for improving the understanding of mechanism of gasification.

Although mass and energy balance analyses are very important and effective ways to understand the chemistry of gasification, they weren't carried out in this study since the gasifier used in the study was a commercial scale and model that was continually operated and hardly taken apart for mass and energy data collection. Those analyses will be conducted in future research. Nonetheless the ANOVA results also implied that increasing up to 20% by

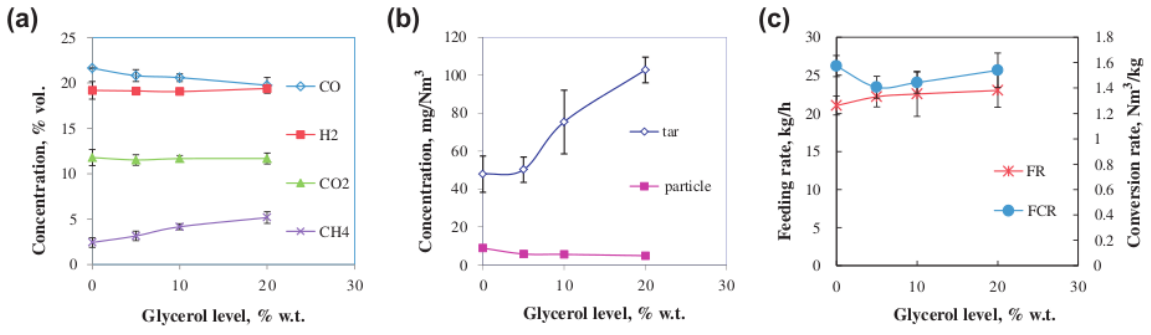

Fig. 4. Effect of glycerol loading levels on syngas composition, tar and particulate concentrations, and FCR.

weight substitution of crude glycerol did reduce the hardwood chip quantity used while not significantly affecting the syngas yield and its energy content. Though the FCR of HWG5 and HWG10 showed little lower values, the overall of FCR and LHV were not affected significantly by the crude glycerol loading levels. The causes of low FCRs in the gasification of HWG5 and HWG10 are still unknown, but further testing is suggested. In term of energy content the increasing in CH_4 can compensate that of decreasing in CO in the syngas. This means crude glycerol can substitute some hardwood chips in co-gasification to produce similar amount of syngas with almost the same energy content though the syngas compositions are different. For energy purpose, last but not least, the co-gasification of hardwood chips and crude glycerol provide a considerable way to utilize crude glycerol, a byproduct of biodiesel production that is currently in abundance, or even handle other similar liquid biomass materials.

5. Conclusion

Downdraft gasifier is suitable for co-gasification of hardwood chips mixed with crude glycerol up to 20 (wt%) to produce syngas with tar and particulate concentrations lower than the tolerances for fueling ICEs. Crude glycerol loading level had significant influence on CO, CH_4, and tar concentration while having no significant effects on H_2 and CO_2 contents, LHV, and particle concentration of the syngas produced. Crude glycerol additions can substitute similar amounts of hardwood chip quantity in weight used in gasification while not significantly affecting syngas yield and quality. Co-gasification of hardwood chips and crude glycerol can be a considerable option for utilizing crude glycerol or other liquid biomass materials.

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