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Evaluation of an Energy Production System from Sewage Sludge Using a Pilot-Scale Downdraft Gasifier

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ABSTRACT: Presently, sewage sludge from wastewater treatment systems has become a critical problem in many regions of the world because it can inflict harm on human beings and the environment. Gasification technology is widely held to be a suitable and convenient approach to convert waste materials to energy with minimal greenhouse gas emissions. In a pilot-scale experiment on sewage sludge gasification ultimately aimed at generating electricity, the reactor temperature profile, syngas characteristics, and performance of the syngas in the production of electricity were tied to the equivalence ratio (ER) and syngas flow rate (i.e., 100, 150, or 180 N m^3 h^{-1}). An increase of the ER resulted in an increase of the temperature inside the gasifier, causing a variation in syngas characteristics and the level of tar and dust contamination. Calorific values at different syngas flow rates were found to vary from 4.20 to 4.87 MJ N^{-1} m^{-3}. The syngas obtained at flow rates of 150 and 180 N m^3 h^{-1} could be used in an engine−generator set to generate 21 or 47 kW of electrical power, respectively, whereas at the flow rate of 100 N m^3 h^{-1}, the syngas could only run the engine without electrical load. The specific sewage sludge consumption, which is the amount of feedstock required to generate electricity, decreased with an increase in the syngas flow rate. The performance evaluation of the sewage sludge gasification system, i.e., gasification efficiency, engine−generator set efficiency, and electrical efficiency, showed that these were in the range of those obtained from biomass, such as agricultural residues. Overall, sewage sludge can serve as a feedstock for electricity generation using a pilot-scale downdraft gasification system.

1. INTRODUCTION

Crucial energy source issues presently arising from the decline in fossil fuel supplies must be addressed immediately. Many countries have become increasingly aware of the importance of renewable energy and have placed greater emphasis on approaches to an efficient use of potential alternative energy sources. Moreover, environmental problems arising from various energy production processes are also an issue of concern to many. Given this situation, organizations responsible for dealing with these problems strive to develop innovative technologies of energy production, which are not only beneficial in terms of efficiency and economy but also environmentally sound.

Sewage sludge is the waste generated in wastewater treatment plants. With the installation of water purification systems in more locales, the quantity of such sludges has risen over the years,[1] and its disposal has become increasingly problematic. Currently, the most widely used management methods for sewage sludge are incineration and landfill, along with its use as an agricultural fertilizer. The disposal of sewage sludge by means of landfill has become much less acceptable in the European Union (EU). In addition, because sewage sludge contains pathogens, heavy metals, polychlorinated biphenyls, and dioxin,[2] strong opposition exists for its incineration and use in cultivation given environmental and health concerns. Therefore, the development of alternative methods for sewage sludge disposal is encouraged.

Gasification is an attractive high-temperature thermal process by which the hydrocarbon in the feedstock is converted into syngas consisting mainly of CO_2, H_2, and CH_4 at high temperature with a controlled amount of air/oxygen lower than the complete combustion process. The gas produced can be used in either an internal combustion engine or direct heat applications.[3] Gasification is regarded as an appropriate technology for energy production because it provides an overall more efficient conversion of a given feedstock resource into electrical power than traditional combustion-based technologies.[4] Additionally, gasification is considered an environmentally friendly technology because it limits emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), heavy metals, and fly ash and the potential production of dioxins and furans as a consequence of the reducing atmosphere (versus the oxidizing atmosphere typical of incineration).[5] However, the presence of sulfur, nitrogen, chloride, and fluoride in sewage sludge may be released as H_2S, NH_3, HCl, and HF because of gasification reducing conditions. These compounds lead to the formation of respective oxides during syngas use; therefore, the contents of S and N compounds in syngas need to be monitored and controlled.[6]

To date, a number of studies have reported the successful disposal of sewage sludge by means of gasification;[1,2,5,6] however, most such systems were operated at an experimental or laboratory scale. The efficacy of sewage sludge gasification at the pilot scale, which would be suitable for the amount of sewage sludge produced by a wastewater treatment plant, has been little studied. In the present study, sewage sludge was used

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to produce electricity using a pilot-scale downdraft gasification power plant. The capability and efficiency of the gasification system are evaluated. These results will inform the future development of sewage sludge gasification systems in a concrete manner.

2. EXPERIMENTAL SECTION

2.1. Sample. Sewage sludge was supplied from activated sludge wastewater treatment plants located on the Kabinburi Industrial Estate, Prachinburi province, Thailand. The companies mostly relate to bleaching and dyeing processes. Because raw sewage sludge contained lots of water (approximately 80%), it was sun-dried on a cement floor for 4−5 days (Figure 1a) until the moisture content decreased to approximately 20%. The dried sewage sludge was ground to minimize its size (<10 mm) before subsequently briquetting into cylindrical shape (45 mm in diameter and 40−50 mm in length; Figure 1b) using a conical extruder. The moisture content after briquetting was less than 15%. Characteristics of sewage sludge were determined by means of proximate analysis (ASTM D1762-84 and ASTM D2015-77 standards) and ultimate analyses [CHNS element analysis (LECO, CHNS-932) and an energy-dispersive X-ray fluorescence spectrometer (EDXRF, ED 2000)].

Figure 1. Photographs of (a) dried sewage sludge and (b) briquetted sewage sludge.

2.2. Experimental Apparatus and Procedure. A pilot-scale open top downdraft gasification system was collaboratively designed and developed by the Suranaree University of Technology, Thailand, and Satake Corporation Co., Ltd., Japan. The gasifier was manufactured from mild steel and equipped with an inner lining of insulation and high-temperature ceramic. The gasifier height and inner diameter were 3.11 and 0.75 m, respectively. A grate was placed at the bottom of the gasifier to hold feedstock. Below the grate, a screw conveyor with a water jacket was installed for charcoal removal. Nine air nozzles with a diameter of 10 cm were installed around the combustion zone. The gas cleaning and cooling system was located next to the gasifier, including a cyclone collector, water scrubber, chilled water scrubber, biomass filter, and bag filter. To assess electricity production, an engine−generator set with a maximum power output of 85 kW was used. The various elements of the downdraft gasification power plant are shown in Figure 2.

Briquetted sewage sludge was manually loaded into the gasifier until it reached a predetermined level. All nozzle valves were opened to allow air to flow through the gasifier. The scrubber circulating pump was switched on to start up operations. The sewage sludge was then ignited through an ignition port located at the combustion zone using a pilot lighter. The heat generated in this zone evaporates moisture within the biomass in the drying zone and drives pyrolysis and gasification reactions. Once the gasification process had been completed, the syngas left the gasifier through the gas cleaning and cooling system. Contaminants, such as dust, pyrolytic product (tar), and water vapor, were initially removed by directing them through a cyclone collector, followed by water scrubbers and a chilled-water scrubber. Because tar vapor condenses at low temperatures, most of the tar was trapped by the cold water in the chilled-water scrubber. The moisture in the wet gas from the chiller scrubber was removed by passing the gas through a biomass filter containing wood chips. Finally, bag filters, which can entrap particulate matters as small as 0.1 mm, served to ensure that the gas produced would be clean enough for the gas engine.

The effects of air supply on the gasification process were investigated by varying the syngas flow rates (i.e., 100, 150, or 180 N m^3 h^{-1}) using a blower installed in the gas line. The blower speed was adjusted using an invertor. The syngas flow rates were measured using an electronic flow gas meter (model DIG-SIDO-O, Nippon Flow Cell, Japan) located between the bag filters and the engine−generator set. At the beginning of each experimental run, syngas

No.	Description	No.	Description
1	Gasifier	6	Biomass filter
2	Cyclone collector	7	Bag filter
3	Water scrubbers	8	Flare
4	Flocculation tank	9	Control unit
5	Buffer tank	10	Engine-generator set

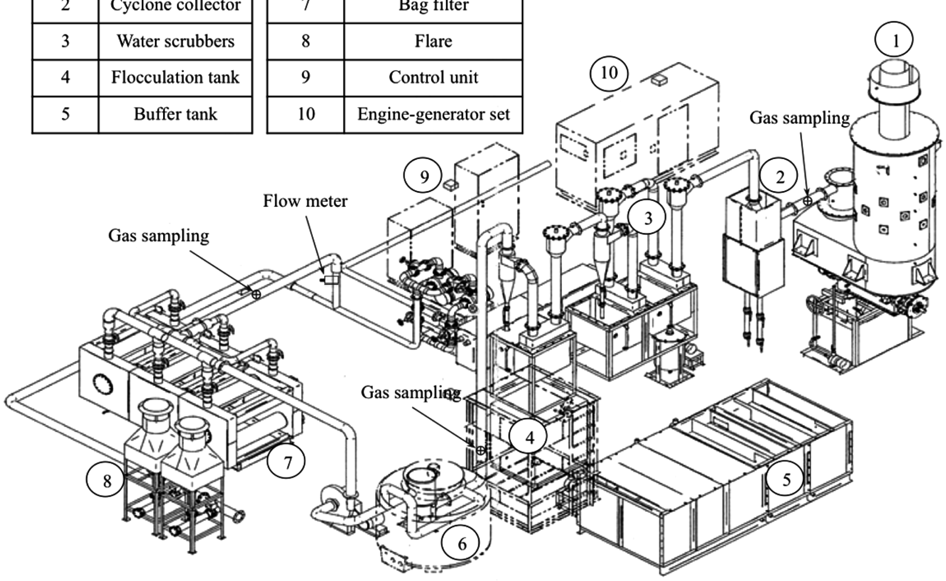

Figure 2. Schematic of the downdraft gasification system and gas sampling positions.

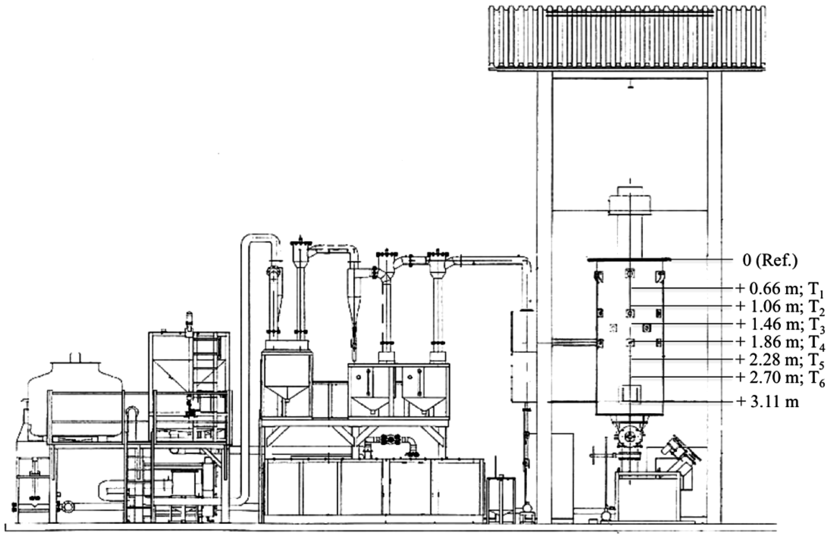

Figure 3. Position of thermocouples installed to the gasifier.

composition was examined prior to its introduction into the engine–generator set. Until a sufficiently high-quality mix was obtained, any gas produced was burned at the flare. Once the gas quality was sufficient for the engine to operate (gas calorific value > 4.2 MJ N^{-1} m^{-3}),[7] all measurements were performed. For each operating condition, the gasification system was operated continuously for 24 h and the data (syngas composition, tar and dust contents, biomass consumption, and ash discharge) were collected every 30 min and presented on average values.

To monitor the temperature inside the gasifier, six K-type thermocouples, installed vertically 0.66, 1.06, 1.46, 1.86, 2.28, and 2.70 m downward from the top of the gasifier (Figure 3), were used to measure the temperature distribution inside the reactor. The temperatures are measured at intervals of 30 s to record the thermochemical conversion phases: drying, pyrolysis, combustion, and reduction.

To reduce the number of parameters, the equivalence ratio (ER) is used to reflect the combined effect of the air flow rate, rate of sewage sludge supply, and duration of the run. The ER is calculated by

$$\mathrm{ER} = (\text{air flow rate/sewage sludge consumption rate}) / (\text{air flow rate/sewage sludge consumption rate})_{\text{stoichiometric}} \quad (1)$$

The performance of the gasification system was evaluated by the following parameters:[8]

$$\eta_g = \frac{V_g \mathrm{LHV}_g}{m_{\text{sludge}} \mathrm{LHV}_{\text{sludge}}} \quad (2)$$

$$\eta_e = \frac{3.6 P_e}{V_g \mathrm{LHV}_g} \quad (3)$$

$$\eta_{el} = \frac{3.6 P_e}{m_{\text{sludge}} \mathrm{LHV}_{\text{sludge}}} \quad (4)$$

where η_g is the gasification efficiency (%), η_e is the engine–generator set efficiency (%), η_{el} is the electrical efficiency (%), m_{sludge} is the sewage sludge consumption rate (kg h^{-1}), LHV_g is the calorific value of gas produced (MJ N^{-1} m^{-3}), $\mathrm{LHV}_{\text{sludge}}$ is the low heating value of sewage sludge (MJ kg^{-1}), P_e is the electrical power output (kW), and V_g is the volume flow rate of gas produced (N m^3 h^{-1}, dry gas).

2.3. Gas Quality Analysis. Gas generated from the briquetted sewage sludge was collected at the sampling port located between the bag filters and the engine–generator set (Figure 2) and analyzed by means of gas chromatography (SIMADSU, GC-14B). Calorific values [low heating value (LHV)] were calculated from the combustible gases, using the heating value of 13.1 MJ N^{-1} m^{-3} for CO, 11.2 MJ N^{-1} m^{-3} for H_2, and 37.1 MJ N^{-1} m^{-3} for CH_4.[9] Gas impurities in the form of tar and dust were quantified at three different positions, i.e., after gasifier, after water scrubbers, and after bag filters, by drawing the produced gas using a vacuum pump. In brief, the moisture content of the produced gas was gravimetrically measured by passing it through a U tube containing $CaCl_2$, which was submerged in ice. Then, approximately 300 L of syngas was passed through a filter paper (GF/B) with 47 mm in diameter. The total tar and dust was quantified by drying the filter paper in an oven at 105 °C for about 6 h.[8] The dried filter was then rinsed with anisole to wash away tar from the filter. The difference in the weight of the filter after drying was used to calculate tar and dust contents with respect to the dry gas volume.

3. RESULTS AND DISCUSSION

3.1. Sewage Sludge Characteristics. Physical properties along with proximate and ultimate values of sewage sludge components are presented in Table 1. Sewage sludge obtained from waste treatment plants had a moisture content of approximately 80% [wet basis (wb)]. Once sewage sludge was sun-dried for 4–5 days, its moisture content dropped to roughly 20% (wb). The dried sewage sludge formed spherical aggregates approximately 2–10 mm in diameter. Because feedstocks of a small size are not compatible with downdraft gasification technology, the dried sewage sludge was briquetted into cylinders 45 mm in diameter and 40–50 mm in length. The moisture content and bulk density after briquetting were approximately 15% (wb) and 380 kg m^{-3}, respectively. The upper limit of the moisture content for downdraft gasification is usually no more than 20% (wb) because heat loss as a result of water evaporation is considerable and can reduce the overall gasifier temperature, impairing gasification reactions.[10]

Proximate values of sewage sludge include moisture content, volatile matter, fixed carbon, ash content, and heating value (Table 1). The volatile matter and heating value of sewage sludge were fairly high and comparable to those of other forms of biomass.[11] The heating value generally indicates the potential of feedstock to generate heat during combustion, resulting in the release of important volatile components used in syngas production. However, sewage sludge was found to have a high ash content (30.45% on average). This could potentially cause difficulties in system operation because the ash produced would

Table 1. Characteristics of Sewage Sludge Derived from Activated Sludge Wastewater Treatment Plants (Bleaching and Dyeing Processes)

analysis	parameter	value I	value II	value III
physical properties	density (kg m^{-3})	N/A	204	380
	size (mm)	N/A	1−10	45 × 45
	moisture content (wt %, wb)	80	20	15
proximate analysis	moisture content (%) as received		15.00 ± 1.55	
	moisture content (%) as air dry		6.44 ± 0.50	
	volatile matter (wt %, db)		56.00 ± 2.97	
	fixed carbon (wt %, db)		7.11 ± 2.30	
	ash (wt %, db)		30.45 ± 1.24	
	net calorific value (MJ kg^{-1}) as received		13.55 ± 0.48	
	net calorific value (MJ kg^{-1}) as air dry		15.32 ± 0.55	
	gross calorific value (MJ kg^{-1}, db)		17.11 ± 0.45	
ultimate analysis (wt %, db)	carbon (C)		36.38 ± 0.06	
	hydrogen (H)		5.86 ± 0.17	
	nitrogen (N)		5.22 ± 0.16	
	sulfur (S)		0.98 ± 0.05	
	oxygen (O)		47.98 ± 0.28	
heavy metal and chlorine (g kg^{-1}, db)	copper (Cu)		12.90 ± 0.03	
	iron (Fe)		23.60 ± 0.87	
	zinc (Zn)		3.31 ± 0.03	
	cadmium (Cd)		0.01 ± 0.00	
	lead (Pb)		0.26 ± 0.10	
	chlorine (Cl)		7.40 ± 0.16	

need to be removed from the gasifier frequently. In addition, the high ash content promotes clinker formation, which generally occurs in the combustion zone if the temperature reaches 1100 °C.[12] As a result, the quality of syngas is decreased. It has been suggested that the ash content above 5% is likely to cause clinkering and slagging problems.[13] In addition to the quantity mineral matter, its composition is also very important, because of the possibility of sintering and slagging formation.[14]

From the ultimate analysis, the empirical formula for sewage sludge is $CH_{1.93}O_{0.99}$ and the stoichiometric air/fuel ratio is 5.06. The carbon and hydrogen of sewage sludge, which are the main elements in syngas production during thermochemical reactions, are similar to those of other forms of biomass.[11] This implies that sewage sludge could be used as a feedstock for energy production using gasification technology. The amount of sulfur contained in sewage sludge was found to be relatively high (0.98%) when compared to biomass (0.01−0.07%),[15] indicating its adverse effect on air pollution (SO_2 and H_2S are also high). However, because gasification works at limited air supply conditions, the production of SO_x tends to be much lower than combustion.[16] The sulfur is mostly in the form of H_2S;[17] therefore, special care must be taken while gasifying with this material. In the long run, H_2S in both liquid (scrubbing water) and gaseous (exhaust gas) phases needs to be monitored. An adjustment of experimental conditions and the use of effective sorbents are most advisable. The amount of chlorine found was less than many types of biomass generally used in energy production.[15] However, sewage sludge contained a relatively high iron (Fe) content. This is attributable to the iron compound $FeCl_3$ being used during primary wastewater treatment. Other heavy metals, such as Cu, Zn, Cd, and Pb, were found to be more in sewage sludge than in biomass.[15] In general, sewage sludge with a high heavy metal content requires special management. For gasification technology, even though most of the heavy metals are still retained in the product char,[18,19] it has been reported that their release was quite low, complying with the EU limits for landfill inert residues and also with the limit in use in the U.S.A.[20]

3.2. Temperature Profile.

A typical temperature distribution showing the various phases, drying, pyrolysis, combustion, and reduction, is shown in Figure 4. In general, the temperature

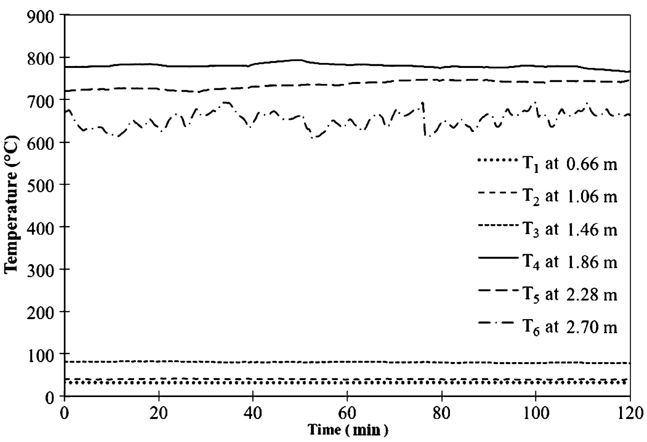

Figure 4. Example of the temperature distribution with respect to experimental time (at 100 N m^3 h^{-1}).

at different locations is quite stable along the height of the gasifier. The average temperature difference between the 0.66 and 1.46 m positions was small at less than 100 °C. The main process taking place in this zone is drying. The moisture contained in the feedstock is driven off until the temperature increases up to 200 °C.[10] The temperature then increased rapidly from the 1.46 to 1.86 m position (∼800 °C), where air was supplied to the gasifier. Sewage sludge was pyrolyzed in this zone at temperatures ranging from 280 to 500 °C, leaving solid char behind and releasing volatiles consisting mainly of CO_2 and tar.[10] The highest temperature was obtained at 1.86 m, which is the heat heart of the gasifier (combustion zone). At the last stage, the temperature decreased to an average value of 500 °C because of endothermic reactions by which the product gases produced from the upper zone are reduced with carbon (charcoal), producing syngas consisting mainly of CO and H_2. In general, the temperature in this zone should be above 500 °C.[21] The average gas temperature at the gasifier exit was 520 °C.

In this study, the system was controlled to obtain different syngas flow rates at 100, 150, and 180 N m^3 h^{-1} and used for generating electricity. Ultimately, changes in the syngas flow rate change the ER for the gasification process, which is a crucial parameter in the development of syngas quality. Figure 5 shows temperature profiles of the gasifier burning sewage sludge according to the ER. As expected, temperatures inside the gasifier were found to be proportional to the ER; that is, the greater the ER value, the higher the temperature profile level.

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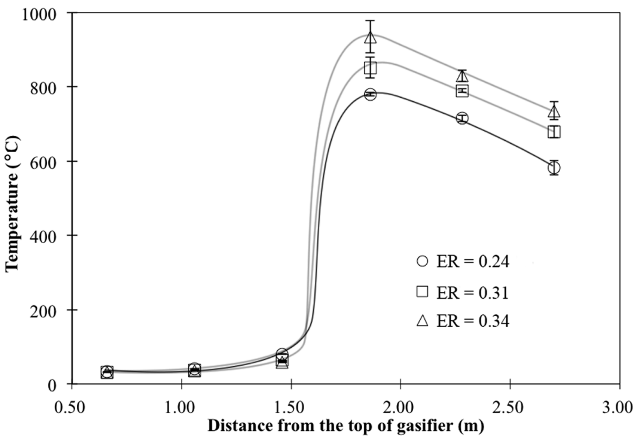

Figure 5. Temperature profiles of sewage sludge along the gasifier at different ER values.

The increase of the temperature is attributed to the increase of air available for exothermic reactions as the ER increases. The temperature profile pattern of sewage sludge in this study was similar to that of high bulk density biomass feedstocks, such as briquetted rice husk and briquetted cassava peel.[15] In addition to the gas flow rate, temperature profiles are dependent upon combustible characteristics, such as size, texture, bulk density, etc.[13,21]

3.3. Syngas Composition. Results show that the syngas composition obtained from sewage sludge under different ER values (Table 2) is more or less the same as that obtained from other types of biomass.[22−25] The syngas consisted of CO, H_2, CH_4, O_2, CO_2, and N_2. With the increase of ER from 0.24 to 0.34, the concentration of combustible gases, i.e., CO, H_2, and CH_4, tended to decrease. As a result, calorific values (LHV) calculated from the combustible gases decreased from 4.87 to 4.20 MJ N^{-1} m^{-3}. Partial combustion of tar and syngas at higher ER values may explain the reduction in the LHV, as illustrated by the inverse relationship between combustible gases and CO_2. Moreover, the decrease of the LHV is attributable to the increase of the nitrogen dilution amount because of the increases of air supplied to the gasifier.[26] However, even though the increase of air flow rates causes a reduction in LHV, the LHV of the syngas obtained in this study was sufficiently high enough for its use in a gas engine with a minimum energy requirement of approximately 4.2 MJ N^{-1} m^{-3}.[7]

3.4. Tar and Dust. Tar and dust play an important role in the gasification process and engine operation. High tar and dust contents in the syngas cause the shutdown of gasification facilities because of blocking and fouling of downstream applications, such as turbines and engines, thus requiring post-treatment, maintenance, and complicated cleaning.[27] Table 3 presents tar and dust contents in the gas produced at different ERs and locations, i.e., after gasifier, after water scrubber, and after bag filter. Increasing the ER from 0.24 to 0.34 led to a small reduction in the tar content immediately after the gasifier. This reduction of tar could be explained that a part of tar was burnt with the supply air and the other part was further thermally cracked into the secondary tar in a local high-temperature zone.[26] However, the increase of ER slightly increased the dust content. This is probably due to the fact that the increase of the flow rate in the system causes turbulence flow, which results in more dispersion of dust in the gas line system. After the gasifier, the syngas flowed through water and chilled water scrubber units, removing 46−82% of the total tar and dust contents. Despite efficiently trapping particulates in the syngas, the water causes a great reduction of syngas temperature, especially in the chilled water scrubber. When tar aerosols contacted the water surface, the water would absorb soluble tar, while insoluble tar would condense to become liquid phase and was washed away with the water. As a result, a considerable amount of tar was removed (58−92%) from the gas stream. This result was slightly better than those reported by Phuphuakrat et al.[28] (47−74%), who conducted experiments without including the chilled water scrubber unit. The

Table 2. Experimental Results of the Gasification Test

parameter	unit	equivalence ratio (ER) 0.24	0.31	0.34
syngas flow rate (dry gas)	N m^3 h^{-1}	100	150	180
power output (electricity)	kW	0	21	47
A/F ratio	N m^3 kg^{-1}	1.20	1.55	1.71
SS[a] consumption rate	kg h^{-1}	68.23 ± 0.98	79.00 ± 1.02	98.26 ± 0.87
specific SS consumption	kg kW^{-1} h^{-1}		3.76 ± 0.14	2.09 ± 0.20
ash discharge rate	kg h^{-1}	21.90 ± 0.33	23.80 ± 0.38	29.80 ± 0.40
	%	32.10 ± 0.69	30.13 ± 0.49	30.33 ± 0.36
composition (db)				
CO	%	15.11 ± 0.40	14.13 ± 0.57	13.19 ± 0.63
H_2	%	18.20 ± 0.54	15.51 ± 0.46	14.89 ± 0.56
CH_4	%	2.39 ± 0.16	2.23 ± 0.26	2.14 ± 0.27
N_2	%	50.01 ± 1.20	51.10 ± 1.45	53.10 ± 1.43
O_2	%	0.57 ± 0.10	0.98 ± 0.13	1.11 ± 0.19
CO_2	%	13.72 ± 0.57	15.98 ± 0.47	17.01 ± 0.84
LHV	MJ N^{-1} m^{-1}	4.87 ± 0.09	4.41 ± 0.13	4.20 ± 0.12
specific syngas yield	N m^3 kg^{-1}	1.47 ± 0.02	1.90 ± 0.05	1.83 ± 0.03
η_g	%	52.67 ± 0.23	61.65 ± 0.41	56.29 ± 0.33
η_e	%		11.45 ± 0.12	22.57 ± 0.23
η_{el}	%		7.06 ± 0.16	12.71 ± 0.09

[a]SS = sewage sludge.

Table 3. Tar and Dust Contents at Different ER Values and Pipeline Positions

	impurity (mg N^{-1} m^{-3})								
	after gasifier			after scrubber			after bag filter		
ER	tar	dust	total	tar	dust	total	tar	dust	total
0.24	76.78 ± 6.25	47.54 ± 6.95	124.32 ± 2.06	6.51 ± 2.30	15.41 ± 2.19	21.92 ± 0.43	0.00 ± 00	0.00 ± 0.00	0.00 ± 0.00
0.31	74.91 ± 5.76	41.91 ± 5.89	116.82 ± 1.84	31.60 ± 3.93	31.24 ± 2.41	62.84 ± 3.72	1.84 ± 0.97	1.34 ± 0.81	3.18 ± 0.16
0.34	72.86 ± 6.50	62.35 ± 4.79	135.21 ± 3.52	14.09 ± 5.82	28.65 ± 3.99	42.74 ± 1.82	4.06 ± 0.66	6.92 ± 0.63	10.98 ± 0.29

performance of scrubber units depends upon the flow rate of syngas, the inlet tar components, and their concentrations.[29] Finally, most of the remaining tar and dust was trapped by the bag filters, resulting in final total tar and dust contents of less than 11.00 mg N^{-1} m^{-3}. Typical tar and dust generated from biomass in a downdraft gasification system have been reported to range between 50 and 500 mg N^{-1} m^{-3},[30,31] depending upon the raw material, gasifier design, experimental conditions, and tar collection methods.[32] Using sewage sludge in gasification, Dogru et al.[12] reported that the tar and dust collected after the gasifier were 637−838 mg N^{-1} m^{-3}, while Phuphuakrat et al.[28] obtained 1300 mg N^{-1} m^{-3}. This indicates that the gasification system used in this study can produce very good quality syngas, clean enough to use in a gas engine−generator set.[8]

3.5. Electrical Power Output. Clean syngas, having passed through the bag filter, was used to generate electricity using an engine−generator set, whose specifications are presented in Table 4. The power consumed was determined using an electrical load. The effect of the syngas flow rate on ultimate syngas power output is shown in Table 2. Syngas flow rates of 150 and 180 N m^3 h^{-1} could be used to generate electricity, with maximum power outputs of 21 and 47 kW, respectively. However, the syngas flow rate at 100 N m^3 h^{-1} was not able to generate electricity; the syngas energy was just enough to run the engine without an electrical load.

Table 4. Specification of the Gas Engine−Generator Set

engine	engine make		Cummins
	model		G855-G-BO
	bore and stroke	mm	140 × 152
	compression ratio		10:1
	number of cylinders		6
	power	hp	160
generator	output	kW	85
	engine speed	rpm	1500
	voltage	V	400
	frequency	Hz	50

3.6. Sewage Sludge Consumption Rate. Sewage sludge consumption increased with an increase in the syngas flow rate (Table 2). The sewage sludge consumption rates at 100, 150, and 180 N m^3 h^{-1} syngas flow rates were 68.23, 79.00, and 98.26 kg h^{-1}, respectively. The increase of sewage sludge consumption is due to the fact that, when the syngas flow rate increases, the air flow rate also increases, providing more oxygen to oxidize and a higher amount of biomass to become combusted. The biomass consumption rate increases because of not only a higher combustion rate but also an enhanced pyrolysis and drying rate.[33] However, when the amount of biomass required to generate electricity (specific sewage sludge consumption) was taken into account, it was found that it decreased as the syngas flow rate increased. This indicates that the sewage sludge needed for electricity generation at higher power outputs is less than that required at lower power outputs. On average, the specific sewage sludge consumption at 150 and 180 N m^3 h^{-1} syngas flow rates were 3.76 and 2.09 kg kWh^{-1}. In comparison to other studies, the amount of sewage sludge required to produce the same power output was similar to that of other forms of biomass.[15,25]

3.7. Charcoal Removal. Charcoal removal from the gasifier is crucial in operating the gasification system. The charcoal removal rate was dependent upon the ash content of each biomass; the higher the ash content, the higher the charcoal removal rate. The rate of charcoal removal can be calculated as follows:

$$\begin{aligned}&\text{percentage of charcoal removal}\\&\quad = \text{charcoal removal rate (kg h}^{-1})\\&\qquad /\text{sewage sludge consumption rate (kg h}^{-1})\end{aligned} \tag{5}$$

The percentage of charcoal removed from the gasifier is usually equal to the ash content obtained from the proximate analysis. In this study, the ash content of sewage sludge was 30.45%; therefore, the percentage of charcoal removal was controlled at approximately 30%. As the feedstock consumption rate increased with an increase in the syngas flow rate, the charcoal removal rate increased proportionally (Table 2). The charcoal removal rates under the 100, 150, and 180 N m^3 h^{-1} syngas flow rates were 21.90, 23.80, and 29.80 kg h^{-1}, respectively. In addition to a charcoal removal of 30%, the charcoal removals above or below 30% were also investigated. Charcoal accumulated inside the gasifier was melted and turned into slag, which attached itself to the gasifier wall if the percentage of charcoal removal was lower than 30%. After a period of time, this slag accumulation was sufficient to obstruct the movement of feedstock from the top and eventually shutdown the gasification system. Comparatively, operation with the charcoal removal of 40% resulted in system termination by extinguishing the flame inside the gasifier. Therefore, it is necessary to establish the percentage of charcoal removal of high ash content feedstock prior to real operation. On average, the volume of gasified sewage sludge was reduced by 70% compared to that of the initial.

3.8. Efficiencies of the Gasification System. The gasification system was evaluated on the basis of specific syngas yield, gasification efficiency (η_g), engine−generator set efficiency (η_e), and electrical efficiency (η_{el}). As shown in Table 2, an increase in the ER trended to increase the specific syngas yield, with the highest value of 1.90 N m^3 kg^{-1}. The result obtained in this study is in accordance with those reported by other researchers.[6] The value of η_g increased from 52.67% at ER = 0.24 to 61.65% at ER = 0.31 and then declined to 56.29% at ER = 0.34. The increase in η_g was probably attributable to the increase of the air flow rate when the ER increased. As the air flow rate increases, the oxidation reaction is enhanced by the increased oxygen feeding rate, and the greater heat in the oxidation zone promotes more endothermic gasification reactions. As a result, the η_g increases with an increase in the ER.[34] However, as the CO_2 content in the syngas increases with the combustion reaction, the heating value of synthetic gas decreases, thus decreasing the η_g. In this study, the gasification efficiency for sewage sludge was found to be in the range of those derived from biomass feedstocks.[3,34]

The η_e was calculated as the ratio of energy equivalent of electrical power output to the rate of energy supplied to the engine. The result of the η_e as a function of electrical power output is shown in Table 2. The η_e increased with an increase in the electrical power output. At the maximum power output achieved in this study (47 kW), the engine−generator set efficiency was as high as 22.57%. Similar trends were observed for η_{el} as with η_e (Table 2). The η_{el} values at 21 and 47 kW were 7.06 and 12.71%, respectively. The η_e and η_{el} obtained in this study with sewage sludge are similar to those achieved with various types of biomass using the same gasification system.[15] This means that sewage sludge can be efficiently used as feedstock for producing electricity.

4. CONCLUSION

In this study, sewage sludge was used to produce electricity using a pilot-scale downdraft gasification power plant. The effects of the ER and syngas flow rate in the system on gasification system parameters were investigated. Temperatures inside the reactor were proportional to the ER. Calorific values tended to decrease as the ER increased from 0.24 to 0.34, with values ranging from 4.20 to 4.87 MJ N^{-1} m^{-3}. For electricity generation, the syngas flow rates at 150 and 180 N m^3 h^{-1} could be used in an engine−generator set to generate electricity with electrical power outputs of 21 and 47 kW, respectively, while the syngas flow rate at 100 N m^3 h^{-1} could run the engine without electrical load. The feedstock consumption rate was found to increase with the syngas flow rate, but the specific feedstock consumption decreased as the syngas flow rate increased. An appropriate percentage of charcoal removal was approximately 30% of the biomass consumption rate, while discharge rates above or below 30% caused system termination by blocking the movement of the feedstock as a result of slag formation or extinguishing the flame inside the gasifier, respectively. Gasification efficiency was at a maximum at a syngas flow rate of 150 N m^3 h^{-1}, whereas engine−generator set efficiency and electrical efficiency increased with an increase in the syngas flow rate or electrical power output. The results obtained in sewage sludge gasification were comparable to those obtained from biomass. Overall, sewage sludge can be used to generate electricity using a pilot-scale downdraft gasification system.

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Notes

The authors declare no competing financial interest.

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