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2019

Chan, W. P., Veksha, A., Lei, J., Oh, W.-D., Dou, X., Giannis, A., ... Lim, T.-T. (2019). A novel real-time monitoring and control system for waste-to-energy gasification process employing differential temperature profiling of a downdraft gasifier. *Journal of Environmental Management*, 234, 65-74. doi:10.1016/j.jenvman.2018.12.107

<https://hdl.handle.net/10356/143373>

<https://doi.org/10.1016/j.jenvman.2018.12.107>

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**A novel real-time monitoring and control system for waste-to-energy gasification process
employing differential temperature profiling of a downdraft gasifier.**

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Highlights:

- Developed a rapid and accurate control system for consistent syngas production
- Integrated the reaction dynamics and scenarios into the monitoring and control system
- Simplified the control of gasifier to the monitoring of differential temperatures
- Correlated the differential temperatures and fuel feeding rates with clustered data
- Analysed the impacts of instability of the gasifier on the properties of syngas

Abstract

A novel, cost-effective and real-time process monitoring and control system was developed to maintain stable operation of waste-to-energy gasification process. It comprised a feedback loop control that utilized the differential temperatures of the oxidation and reduction zones in the gasifier to determine the regional heat-flow (endothermic or exothermic), to assess the availability of oxidizing agent (for instance, air or O₂) at the char bed and to calculate the fuel feeding rate. Based on the correlations developed, the air-to-fuel ratio or the equivalence air ratio (ER) for air gasification could be instantaneously adjusted to maintain stable operation of the gasifier. This study demonstrated a simplification of complex reaction dynamics in the gasification process to differential temperature profiling of the gasifier. The monitoring and control system was tested for more than 70 h of continuous operation in a downdraft fixed-bed gasifier with refuse-derived fuel (RDF) prepared from municipal solid wastes (MSW). With the system, fuel feeding rate could be adjusted accurately to stabilize the operating temperature and ER in the gasifier and generate syngas with consistent properties. Significant reductions in the fluctuations of temperature profiles at oxidation and reduction zones (from higher than 100 °C to lower than 50 °C), differential temperatures (from ± 200 to ± 50 °C) in gasifier and the flow rate (from 16 ± 6.5 to 12 ± 1.8 L/min), composition of main gas components, LHV (from 6.2 ± 3.1 to 5.7 ± 1.6 MJ/Nm³) and tar content (from 8.0 ± 9.7 to 7.5 ± 4.2 g/Nm³) of syngas were demonstrated. The developed gasifier monitoring and control system is adaptable to various types (updraft, downdraft, and fluidized-bed) and scales (lab, pilot, large scale) of gasifiers with different types of fuel.

Keywords: Gasification; Municipal solid waste; Equivalence air ratio; Real-time process control; Differential temperature profiles; Reaction dynamics.

1. Introduction

Gasification is an advanced thermochemical process which converts MSW or biomass (fuel) into syngas that can be utilized in gas engines, combined cycle gas turbines (CCGTs), solid oxide fuel cells (SOFCs), or hybrid systems with higher electrical efficiency and better environmental performance (Azizi and Brouwer, 2018; Ebrahimi and Moradpoor, 2016; Palsson et al., 2000; Tanigaki et al., 2012). There are multiple simultaneous reactions occurring inside the gasifier, which result in the formation of several zones including drying, pyrolysis, oxidation and reduction zones (Antonopoulos et al., 2011; Watson et al., 2018). It is highly challenging to maintain stable operation of the gasifier to generate syngas with consistent properties at a constant production rate, which is important for the subsequent downstream applications (Higman and van der Burgt, 2008; Lombardi et al., 2015). Performance of the gasifier could be affected by various factors such as characteristics of fuel (particle size, composition, moisture, ash and energy contents), fuel feeding rate, air flow rate, equivalence air ratio, gasifier design, reaction/residence time, gasifying agent, temperature profiles and pressure (Mikulandrić et al., 2016; Mikulandrić et al., 2015; Wang et al., 2008). It is therefore important to simplify the monitoring system that would allow for the accurate control and fast respond to the changing operational conditions (Majanne et al., 1995). In addition, one of the key necessities for control and optimization of a gasification system, is to integrate the dynamics of the gasification process and the corresponding scenarios into the actual monitoring and decision-making tool (Mikulandrić et al., 2015). Air-to-fuel ratio (A/F) or equivalence air ratio (ER) for air gasification, is considered an important parameter (Masmoudi et al., 2017; Ögren et al., 2018; Zheng et al., 2016). While the air supply is relatively easy to measure and adjust, the measurement and control of fuel feed during operation of the gasifier is challenging (Dai et al., 2012). The effective feeding rate fluctuates due to changes in the size of fuel particles/pellets, fuel compaction, composition and feeder plugging (Dai et al., 2012;

Kotteeswaran and Sivakumar, 2014; Weiland et al., 2015). The inconsistent feeding rate causes unstable operation of gasifier with undesirable fluctuations of temperature, pressure, syngas composition, heating values and flow rate (Lopez et al., 2018; Melgar et al., 2009; Sharma et al., 2015). Therefore, the development of a real-time system that is able to monitor and provide instantaneous control of feeding rate and ER with high accuracy is important for a stable and efficient gasification process (Gandhi et al., 2012).

A wide range of parameters are monitored and controlled to stabilize and optimize the operation of gasifier including composition and characteristics of syngas, amount and properties of fuel, and temperature of gasifier and syngas (Bender et al., 2012; Fronk and Reich, 2017; Gulko et al., 1998; Kiso et al., 2017; Melgar et al., 2009; Neves et al., 2014; Nickerson et al., 2016; Tsangaris and Swain, 2016). However, continuous and accurate analysis of syngas composition requires complicated gas sampling mechanism and purification system to remove impurities (i.e., particles, tar compounds, corrosive gases and moisture) that would otherwise contaminate downstream analytical equipment (Sampson and Leroy, 2013). Advanced sensing devices that can measure the composition of syngas operating in a harsh environment are still under development (Ghosh and Loloee, 2007; Ögren et al., 2018; Pallozzi et al., 2016). While the fuel could be homogenized and controlled by applying different pre-treatment systems (e.g. shredder, magnetic separator and slurry feeding system), additional cost is needed to build and operate these systems and it is highly challenging to handle the unsorted, wet and heterogeneous real wastes. The amount of fuel or fuel pile level inside a updraft gasifier could also be determined by using a height indicator (Bender et al., 2012). However, when the effective A/F or ER fluctuates during the operation of gasifier, the proportions of fuel, char and ash will change accordingly but may not be reflected in the height of fuel pile. The temperature of the gasifier and syngas at the outlet could be monitored closely to determine the need to increase the feeding rate of fuel or provide additional heat through the addition of auxiliary fuel

to maintain the operating temperature and stability of gasification process (Fronk and Reich, 2017; Nickerson et al., 2016). However, with only the determination of overall temperature of the gasifier or syngas, the effective A/F or ER ratios or fuel feeding rate cannot be accurately and quantitatively determined (Kamble et al., 2017). Therefore, it is highly challenging to identify the contributing factors and respond instantaneously and accurately. Temperature profiles at different positions of the gasifier could provide additional insights into the reaction conditions (Plis and Wilk, 2011). Availability of air/oxygen, fuel feeding rate and properties of fuel are the key factors affecting the varying temperatures at different positions of the gasifier (Erlich and Fransson, 2011; Simone et al., 2012). Exothermic oxidation reactions occurred at the oxidation zone of gasifier (where the air is input and react with the fuel) increase the temperature of syngas and the region, while endothermic reduction reactions occurred at the reduction zone (where the hot gases react with the char bed) reduce the syngas temperature (Balu and Chung, 2012; Patel et al., 2017). In addition, the change of ER can alter the temperatures at different locations in the gasifier (Guo et al., 2014). However, further research is required to establish the methodology that can quantitatively apply the temperature profile within the gasifier as the key monitoring parameter for the development of a real-time process monitoring and control that can stabilize and optimize the gasification process.

In this study, a simple, cost-effective real-time monitoring and control system to maintain the stable operation of the gasifier was demonstrated. This system addressed challenges in the development of an accurate real-time monitoring and control system and the needs to integrate reaction dynamics/scenarios inside the gasifier into the control system. Two thermocouples were positioned in the oxidation and reduction zones in the gasifier to provide the real-time differential temperatures, which were correlated to the ER by a cluster analysis to produce an approximated linear correlation. With this correlation, feeding of refuse-derived fuel (RDF) or input of air could be adjusted in response to the differential temperatures. Hence,

a simplified real-time feedback loop control system is established. This system was developed and tested based on more than 70h continuous operations of the downdraft fixed-bed gasifier. Temperature profiles, RDF feeding rate and composition of syngas were analysed to understand the impacts of feeding rate and ER on the operation of gasifier and syngas production.

2. Materials and Methods

2.1. Preparation and characterization of RDF

For the operation of a lab-scale gasifier, MSW generated on the campus of Nanyang Technological University (Singapore) was converted into a refuse-derived fuel (RDF). Approximately, 200 kg of residential and agricultural waste were sorted, weighed and dried according to ASTM D5231. Non-combustible fractions, such as glass, metals, liquids, ceramics and electronic waste, were discarded while the combustible fractions were crushed (Cutting Mill, Retsch SM2000 and Plastic Crusher, DJ400) and pelletized (ZLSP150C). The prepared RDF pellets with a diameter of 4 ± 1 mm and a length of 10 ± 3 mm contained: 35% plastics, 23% papers, 7.7% textiles, 6.9% woods, 16% food residues and 11.4% horticultural wastes by mass on a dry basis. The RDF pellets were characterized based on the methods described previously (Chan and Wang, 2016). Higher heating value (HHV) was determined by calorific bomb (IKA C2000) according to ASTM E711. Lower heating value (LHV) could be obtained after deducting the energy loss of water evaporation as follows: $LHV = HHV - 2.26 \times (9H / 100)$ where H represents the weight percentage of hydrogen in the RDF pellets, 2.26 represents the heat of vaporisation of water in MJ/kg and the digit nine referred to the water produced during combustion in relation to the hydrogen content.

Ash contents, Ash₅₅₀ and Ash₈₅₀ were recorded as the mass of solid residues remaining after combustion of RDF in a furnace at 550 °C and 850 °C for 3 h respectively. Volatile matter (VM) of the dried sample was determined as the mass loss after heating at 30 °C/min in a crucible using STA 449 Jupiter® (Netsch) to 950 °C and maintained for 7 min in an inert environment with 60 mL/min nitrogen gas flow according to ASTM D7582. Fixed carbon (FC) was calculated by the difference between mass of dry sample and masses of Ash₈₅₀ and VM. CHNS analysis was conducted by using Vario EL cube (Elementar) according to the ASTM E870. Oxygen content was calculated as the difference between 100% and C, H, N and S contents. To quantify chloride content, RDF pellets (0.3 ±0.05 g) were combusted in calorific bomb (IKA C2000) with 5 mL of Na₂CO₃ solution (50 g/L) according to ASTM D808 and then tested using anion chromatography (Dionex ICS-1100).

2.2. Gasification and temperatures monitoring system

The gasifier and temperatures monitoring system are illustrated in Fig. 1. A downdraft fixed-bed gasifier was used for the air gasification of RDF. Gasification experiments were carried out at 850 °C, equivalence air ratio of 0.3 and water content of 25 wt%. The typical experimental duration of the gasifier was around 150 min for each run. A typical experiment was started with the pre-heating of gasifier. During heating, 300 mL/min of N₂ was purged into the gasifier to maintain an inert environment. After pre-heating and stabilization of the temperatures in gasifier, feeding of RDF pellets was started. Simultaneously, air was introduced by using a mass flow controller (FMA5500A, Omega) and water was injected through a peristaltic pump (Masterflex L/S®, Cole Palmer). The feeding rate of RDF pellets, air and water were 4.4 ±0.3 g/min, 9.2 L/min and 1.47 mL/min, respectively. RDF pellets were fed continuously into the gasifier through a screw-feeder which consisted of a fuel holder and

a screw conveyor installed at the top of gasification chamber (Fig. 1). Concurrently, water was introduced from the top while air was supplied through a circular distributor near the central region of the gasifier. The center region is designated as the oxidation zone where the O_2 containing in the air enter the gasifier and react with volatile compounds and char, formed from drying, torrefaction and pyrolysis of RDF pellets (Watson et al., 2018). After passing through the oxidation zone, unreacted char and ash residues were accumulated on a stainless-steel mesh to form the char bed. Char bed is designated as the reduction zone where the char is further converted into syngas and ashes through various oxidation and reduction reactions (Antonopoulos et al., 2011). Ashes were then dropped through the stainless-steel mesh to the ash tray at the bottom of gasifier. The generated syngas was discharged through a pipe at the bottom of the gasifier.

A temperatures monitoring system was applied in the gasifier, which could be coupled with the calculation of RDF feeding rate and syngas production rate, for the development of a real-time monitoring and control system. Two K-type thermocouples (OMEGA), TC1 and TC2 (Fig. 1) were placed at the center of gasifier (oxidation zone) and char bed (reduction zone) respectively to measure in real-time, the in-situ temperature profiles throughout the experiments. Positions of the thermocouples can be determined according to the operational design of the gasifier. RDF pellets were fed from the top of gasifier, underwent drying and pyrolysis to form volatiles and char. Volatiles and char subsequently react with the oxygen at the middle section of the gasifier (oxidation zone). Rigorous exothermic oxidation reactions occur and increase the local temperature to the highest level inside the gasifier. Afterwards, the hot gases from the oxidation zone travel downwards to contact with the char bed (reduction zone). Endothermic reduction reactions occur and reduce the local temperature as compared to the oxidation zone. Differential temperature, $\Delta T = T_{\text{Oxidation}} - T_{\text{Reduction}}$, of these two zones provides an indication of the dominance of endothermic or exothermic reactions at the char

bed. Targeted or optimal differential temperature, ΔT_o can be quantified based on the correlations between the differential temperatures at different calculated ERs and RDF feeding rates.

2.3. Sampling and analysis

Mass of RDF pellets in the fuel holder of the screw-feeder before and after the experiment was measured to quantify the total amount of feed during an experiment. To analyze gas composition, 100 mL/min of syngas was pumped through two impinger traps with deionized water and then passed through a trap with silica gel. Dried and clean syngas was then collected in a gas sampling bag. The collected syngas was analyzed by a gas chromatograph (7890B, Agilent) equipped with two thermal conductivity and one flame ionization detectors. Lower heating value (LHV) of syngas was calculated based on the heating values of the gaseous components (Table S1).

Tar was sampled using the solid phase adsorption (SPA) method and was denoted as “SPA tar”. SPA tubes contained 500 mg of aminopropyl-bonded silica gel (Bond Elut NH₂, Agilent) as an adsorbent. Approximately 150 mL of syngas was pumped every 30 min through SPA tubes using a sampling pump (GilAir Plus, Sensidyne). After the tar collection, SPA tubes were sealed and stored in a dark cold room at 4 °C for 24 h before elution and analysis. A mixture of dichloromethane, acetonitrile and isopropanol with a volume ratio of 8:1:1 was used to extract tar compounds from the SPA tubes as dichloromethane is shown to be suitable for extracting non-polar tar compounds while acetonitrile and isopropanol, when added into dichloromethane, are suitable for extracting polar tar compounds (Israelsson et al., 2013). 2 mL of the solvent mixture was used to extract tar from a single SPA tube. Quantification of tar compounds was carried out using gas chromatography – mass spectrometry (HP7890 GC with

a 5975I MS, Agilent). The gas chromatograph was equipped with a HP-INNOWAX capillary column (I.D. of 0.250 mm and a film thickness of 0.25 μ m). Helium was used as a carrier gas with the flow rate of 1.0 mL/min. Chromatograms were recorded in total ion current mode and peaks were identified by comparing their mass spectra to the NIST 11 mass spectra library. 33 tar compounds were quantified in the SPA tar using 5-point calibration curves for each compound and deuterated d8-toluene and d8-naphthalene as internal standards. Details of tar compounds quantified are shown in Table S2.

The results are reported as means $\pm$ standard deviations (SDs) of at least three runs. Relative standard deviation (%RSD) is calculated by dividing SD (numerator) by the mean (denominator). Cluster analysis, bias error and absolute error were applied as statistical tools to analyze the data. 2-sample t-test was carried out using Minitab® 17 to determine the statistical significance of the experimental results, with 95% confidence interval.

3. Results and Discussion

3.1. Properties of MSW and RDF

The compositions of MSW (wet basis) and prepared RDF pellets (dry basis) are shown in Fig 2. Six main combustible components (plastics, papers, textiles, woods, food residues and horticultural wastes) represented 82 wt% of the MSW generated on university campus. Characteristics of the RDF pellets are summarized in Table 1. Based on the reaction between C, H, N, S and O contents of the RDF pellets and O₂ in air to form CO₂, H₂O, NO₂ and SO₂, the calculated stoichiometric A/F ratio of the RDF pellets was 6.96 L/g (Fig. S1).

3.2. Operational issues of gasifier

In the preliminary experiments without the implementation of the real-time monitoring and process control system, significant fluctuation of the temperatures (higher than 100 °C) at the oxidation and reduction zones occurred (Fig. 3a). Comparable findings on fluctuation of temperatures during the operation of gasifiers were reported in previous studies (Masmoudi et al., 2017; Melgar et al., 2009; Nougues et al., 2000), indicating an unstable gasification process. Highly endothermic (15-75 min, $T_{\text{Reduction}} \ll T_{\text{Oxidation}}$) and exothermic (100-130 min, $T_{\text{Reduction}} > T_{\text{Oxidation}}$) conditions at the char bed were observed, respectively. The calculated differential temperatures, $\Delta T = T_{\text{Oxidation}} - T_{\text{Reduction}}$, varied significantly, i.e., ± 200 °C (Fig. 4a). A positive ΔT higher than the targeted or optimal differential temperature, ΔT_o , reflected a highly endothermic condition at the char bed which suggested insufficient ER and excessive feeding rate of RDF pellets. A negative ΔT or a positive ΔT lower than ΔT_o , reflected a highly exothermic condition at the char bed which suggested excessive ER and insufficient feeding rate of RDF pellets. Since the input of air and water can be controlled with relatively high consistency, the main reason for this fluctuation is the inconsistent feeding rate of RDF pellets and varying ER during the experiment.

Actual feeding rate increased significantly at the initial stage (0-90 min) of the experiment and stayed at a level higher than the targeted feeding rate. This could be caused by the compaction of RDF pellets by the screw conveyor. As the spiral blade of the conveyor started to rotate, the RDF pellets near the outlet of the conveyor were pushed directly into the gasifier. Subsequent RDF pellets were crushed and compacted between the different layers of the spiral blade before reaching the outlet of the conveyor. This could therefore increase the actual feeding rate even when the conveyor was maintained at the same rotating speed. Over time, the actual feeding rate reduced and eventually (90-150 min) stayed at a level lower than the targeted feeding rate. This could be caused by the accumulation of compressed pellets and deposition of char near the outlet of conveyor. The texture of RDF pellets changed from rigid

to sticky when heated, which could be attributed to the presence of food residues and plastic in the MSW. As the pellets were continuously pushed into the gasifier, accumulation of sticky RDF and the char particles was observed near the outlet of conveyor. This eventually caused clogging and slowed down the actual feeding rate. It is important to note that the changes in the feeding rate could also happen throughout the experiments and therefore high and low ΔT could be observed at different operation time in different experiments (Fig. 4a). Fluctuations in syngas composition were also observed (Fig. 5a) confirming unstable operation of gasifier before the implementation of the real-time monitoring and process control system.

3.3. Real-time monitoring and process control system

The operation of real-time monitoring and control system is illustrated in Fig. 6. The procedure consists of three steps: (1) experimental data collection, (2) formulation of correlations, and (3) system validation. To facilitate the data collection and formulation of correlations, the system is designed to include three main operating components: (1) real-time monitoring of the differential temperatures for oxidation and reduction zones in the gasifier; (2) calculation of RDF feeding rate based on syngas flow rate, followed by the determination of the corresponding A/F or ER; and (3) real-time adjustment of the fuel feed rate setting, air flowrate controller and water pump according to reaction conditions inside the gasifier, as assessed through the correlations formulated by the two complementary components, (1) and (2). A feedback loop of fuel feeding and differential temperature is then established for real-time monitoring and control of the gasifier.

Experimental data of RDF feeding rate (g/min) and the corresponding syngas flow rate (L/min) were collected through the operation of gasifier. Correlation (Fig. 7) of these two parameters was then established to enable the calculation of the instantaneous feeding rate

based on composition of syngas. The fraction of N₂ in syngas is used to calculate the flow rate of syngas as described by Eq. 1, based on input of N₂ from air as described by Eq. 2. Fig. 7 illustrates the correlation formulated as described by Eq. 3 with a satisfactory coefficient of determination, R² of 0.81. ER can be calculated based on the calculated feeding rate, stoichiometric air ratio and the flow rate of air input into the gasifier.

$$\text{Flow rate of syngas (L/min)} = \text{input of N}_2 \text{ (L/min)} / \text{fraction of N}_2 \text{ in syngas} \quad (1)$$

$$\text{Input of N}_2 \text{ (L/min)} = \text{input of air (L/min)} \times \text{fraction of N}_2 \text{ in air} \quad (2)$$

$$\text{Calculated feeding rate (g/min)} = 0.3326 \times \text{flow rate of syngas (L/min)} + 0.5232 \quad (3)$$

Calculated ER was further correlated with the temperature difference between oxidation and reduction zones as shown in Fig. 8a. Highly dispersed data points with no apparent correlation were observed. This was caused by highly fluctuating differential temperatures at different calculated values of ER. Nevertheless, it is hypothesized that the mean of these dispersed data points could be correlated with the ER after grouping, therefore a cluster analysis was applied based on five different ranges of ER as shown in Fig. 8b. Mean values of ΔT for clustered data groups at different calculated ER were then calculated. Correlation of clustered means of ΔT with A/F or ER was then established as illustrated in Fig. 9 and described by Eq. 4 and 5 with a R² of 0.99. This approximated linear model can help in simplification of the monitoring process and the algorithm development of an automatic controller (Nikačević et al., 2012). These findings suggested that the temperatures in the gasifier could be fluctuating significant during the operation but the mean values calculated based on appropriate clustering of data could reveal the general trend of the temperature profiles. In addition, the automatic controller should be designed based on the mean values of differential temperatures in the gasifier for a short period of time to reduce the risk of overcorrections. Afterwards, dual thermocouples could work independently to monitor and control the reaction conditions inside

the gasifier. The observed temperature difference is quantitatively compared to the desirable ΔT as determined based on the correlations established and the feeding rate is controlled in real-time to maintain the actual ΔT close to the desirable ΔT_0 .

$$\text{Calculated air-to-fuel ratio, } A/F = -0.0631 \times \Delta T + 3.0156 \quad (4)$$

$$\text{Calculated equivalence air ratio, } ER = -0.0091 \times \Delta T + 0.4335 \quad (5)$$

For air gasification of RDF pellets at ER of 0.3 in this downdraft gasifier, the desired ΔT_0 is calculated at 15 ± 5 °C, which correspond to the calculated ER of 0.3 ± 0.03 . In principle, if the observed $\Delta T > \Delta T_0$, the effective ER in the gasifier is lower than the desirable level as the char bed is highly endothermic with lower $T_{\text{Reduction}}$. This could be caused by the high feeding rate of fuel and then the accumulation of char at the char bed. Therefore, fuel feeding rate needs to be reduced or air flow rate should be increased to increase the ER back to the optimal level. If the observed $\Delta T < \Delta T_0$, then the effective ER in the gasifier is higher than the desirable level due to the excess of oxidizing agent, which reacts with the char bed increasing temperature.

3.4. System validation and demonstration

With the development of the real-time monitoring and control system, adjustment of the feed setting can be carried out instantaneously according to the changes in differential temperatures measured during the operation of gasifier. Significant improvement in stability of the temperatures in the oxidation and reduction zones (Fig. 3b) were achieved with real-time response to the changes of reaction dynamics by adjusting the RDF feeding rate and/or air input. The temperatures for oxidation and reduction zones were maintained stable with fluctuations lower than 50 °C. Differential temperatures ΔT , after the implementation of the control system, are illustrated in Fig. 4b where the range of fluctuations reduced from ± 200 to ± 50 °C. The

mean values of ΔT could be consistently maintained within the range 10-20 °C. Sharp fluctuation peaks (Fig. 4b) could be observed as compared to the broad fluctuation peaks (Fig. 4a) which indicated that the unstable operation of the gasifier was instantaneously corrected by the control system during the experiments. In addition, consistent composition of syngas could be observed throughout the experiment (Fig. 5b). No significant decreased of N_2 and increased of CO , CO_2 , H_2 , CH_4 and C_2-C_5 gases during 0-60 min was observed. Consistency of the syngas composition is considered as a key criteria for producing high quality syngas to maintain the stability of the downstream applications of syngas.

The calculated the RDF feeding rate based on syngas flow rate by using the Eq. 3 is illustrated in Table 2. The results were compared to actual measured data for statistical analysis. Bias errors were distributed from -18% to +19% with a mean of 0.3% indicating that the calculation posed no significant systematic error. Absolute error with a mean of 8.4 ± 6.4 % agreed well with the R^2 of Eq. 3 at 0.81. Therefore, the calculation of RDF feeding rate was satisfactory. It is essential to note that this correlation (Eq. 3) would be altered for different types of fuel, gasifier designs and targeted operating conditions, but the method to develop this correlation can be generally applied. This is partially illustrated in Fig. S2, since syngas flow rate to RDF feed ratio increased as the ER increased, an alteration on the coefficients of Eq. 3 is required when the ER changes. In practice, this can be carried out by changing the input of air to reach the new ER values and then followed by the additional data collection on the feeding rate of RDF over several experiments to establish a new correlation. Existing data with calculated ER close to the new ER could also be added to the new correlation to improve the R^2 and reduce the calculation errors.

Calculated ER and RDF feeding rate during the experiments are illustrated in Fig. 10 and Table S3. It was noticed that the ER decreased and RDF feeding rate increased from the beginning of experiments while the ER increased and RDF feeding rate decreased towards the

end of the experiments. This agreed well with the observations based on temperature profiles and composition of syngas, before the control system was applied. Stability of the calculated ER and RDF feeding rate were significantly improved after the implementation of the control system. This aspect is extremely important since the gasification process should always be operated and maintained at the optimum ER according to the types of fuel and gasifier.

Stabilization of syngas quantity and quality, as indicated by flow rate and LHV of syngas respectively, are illustrated in Fig. 11 and Table S4. Flow rate and LHV of syngas were maintained at 12 ± 1.8 L/min and 5.7 ± 1.6 MJ/m³ as compared to 16 ± 6.5 L/min and 6.2 ± 3.1 MJ/m³ respectively, before the implementation of the real-time monitoring and process control system. According to SD values, the fluctuations of flow rate and LHV of syngas decreased by 72% and 48%, respectively. The main gas components in syngas were CO, CO₂, CH₄, H₂, N₂ and C₂-C₅ hydrocarbon gases. Details of gas components are shown in Table S5. Higher composition of CH₄, H₂ and C₂-C₅ gases but lower percentage of N₂ at 0-30 min of gasification agreed well with the higher calculated RDF feeding rate during that period. Higher fluctuations were observed for syngas composition before the implementation of the real-time monitoring and process control system as indicated by the high SD and %RSD values (Table 3 and Table 4). The ranges of fluctuation of the main gas components in syngas are comparable to the previous studies on gasifier (Melgar et al., 2009; Mikulandrić et al., 2016). Based on the calculated mean concentrations, after the implementation of the control system, the fluctuations of CO, CO₂, CH₄, H₂, and C₂-C₅ gases were lower than 5 vol% while fluctuation of N₂ is lower than 10 vol%. According to summarized SD values (Table 5), the fluctuations of the main gas components in syngas decreased by $47 \pm 4\%$.

33 different tar compounds in SPA tar (Table S6) were quantitatively determined. Toluene, styrene and naphthalene were the main tar compounds which accounted for more than 74 wt% of the total tar content in syngas. SPA tar contents are illustrated in Fig. 12. Before the

implementation of process control system, the content of tar in syngas collected after 30 min was significantly higher, i.e. 24 ± 9.5 g/Nm³ (Fig. 12 and Table S7) compared to the samples collected after 60-150 min of gasification, due to the high RDF feed rate and low ER (Veksha et al., 2018). After the implementation of the control system, this fluctuation was eliminated as the RDF feed rate and/or air input could be instantaneously adjusted. The mean tar contents in the syngas before and after the implementation of process control system were 8.0 ± 9.7 and 7.5 ± 4.2 g/Nm³ (Fig. 12), respectively, suggesting a 57% reduction on the fluctuation of tar contents in syngas according to the SD values. Therefore, by maintaining stable gasification process, syngas containing low and consistent tar content could be produced. This is important for downstream treatment and application of syngas as the instant increase in tar content can significantly reduce the efficiency of the tar removal system and increase the tar dew point which in turn could cause condensation of tar compounds in the pipes and downstream equipment (Rakesh and Dasappa, 2018).

4. Conclusions

A real-time monitoring and control system was successfully developed and tested in a lab-scaled downdraft fixed-bed gasifier for more than 70 h of operation. Monitoring of the differential temperature, ΔT based on the real-time and complementary measurements of dual temperature profiles at oxidation and reduction (char bed) zones inside a gasifier provided quantitative information about the availability of air/oxidizing agent and overall flow of heat (endothermic or exothermic conditions) at the char bed. The approximated linear correlation could be used to instantaneously determine the reaction conditions inside the gasifier. The monitoring and control of the operation of gasifier was therefore simplified to the measurement of the differential temperatures and the use of operational correlations established for ΔT versus

A/F or ER to regulate the fuel feeding rate, without the need of continuous sampling and analysis of syngas. The significant decrease in fluctuations of temperatures in oxidation and reduction zones (from higher than 100 °C to lower than 50 °C), variations of differential temperatures (from ± 200 to ± 50 °C) and the fluctuations of flow rate (from 16 ± 6.5 to 12 ± 1.8 L/min), composition of main gas components, LHV (from 6.2 ± 3.1 to 5.7 ± 1.6 MJ/Nm³) and tar content (from 8.0 ± 9.7 to 7.5 ± 4.2 g/Nm³) of syngas were demonstrated. This methodology could be further incorporated as a complementary or independent feedback control loop into a comprehensive control system for the monitoring and control of the gasification process. Positioning of temperature probes or thermocouples can be flexibly shifted to be used in different types of gasifiers such as updraft fixed-bed, downdraft fixed-bed and fluidized bed gasifier, according to the principle established in this method, the flow direction of syngas and location of the oxidation and reduction zones in the gasifier.

Acknowledgements

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore and the National Environment Agency, Ministry of the Environment and Water Resources, Singapore, under the Waste-to-Energy Competitive Research Programme (WTE CRP 1501 105). The authors also acknowledge the management of Nanyang Environment and Water Research Institute and Economic Development Board, Singapore for the support.

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Table 1 Characteristics of RDF pellets.

Characteristics of RDF pellet		Statistical analysis		
		Mean	SD	%RSD
Mass%, dry basis	C	56.3	6.2	11
	H	8.4	1.3	15
	N	1.1	0.2	19
	S	0.3	0.1	22
	O*	25.4	7.3	29
	Ash ₈₅₀	8.5	0.6	7
	Ash ₅₅₀	10.5	1.1	11
	Cl	1.1	0.1	10
	VM	78.4	3.2	4
	FC	13.1	3.2	25
Heating Value, MJ/kg	HHV	24	1.3	5
	LHV	23	1.2	5

*Oxygen content is calculated by difference.

Table 2 Statistical analysis on the calculated and actual of RDF feeding rate through screw-feeder into the gasifier.

Test No.	Feeding of RDF pellets (g)		Error (%)	
	Calculated	Actual	Bias	Absolute
Run 1	880	928	-5.2	5.2
Run 2	769	777	-1.0	1.0
Run 3	1346	1303	3.3	3.3
Run 4	999	846	18.0	18.0
Run 5	643	644	-0.1	0.1
Run 6	610	728	-16.3	16.3
Run 7	660	789	-16.3	16.3
Run 8	501	557	-10.1	10.1
Run 9	909	1024	-11.3	11.3
Run 10	636	771	-17.6	17.6
Run 11	966	921	4.8	4.8
Run 12	1146	1001	14.5	14.5
Run 13	956	978	-2.3	2.3
Run 14	1200	1219	-1.5	1.5
Run 15	1159	1021	13.5	13.5
Run 16	867	765	13.4	13.4
Run 17	728	766	-4.9	4.9
Run 18	1067	942	13.2	13.2
Run 19	1096	923	18.8	18.8
Run 20	847	937	-9.6	9.6
Run 21	895	918	-2.5	2.5
Run 22	1084	939	15.5	15.5
Run 23	663	659	0.6	0.6
Run 24	635	666	-4.6	4.6
Run 25	669	674	-0.7	0.7
Run 26	713	705	1.1	1.1
Run 27	719	797	-9.9	9.9
Run 28	688	659	4.4	4.4
Statistics	Feeding of RDF pellets (g)		Error (%)	
	Calculated	Actual	Bias	Absolute
Mean	859	852	0.3	8.39
SD	217	174	10.65	6.37
%RSD	25%	20%	3994%	76%
Min	501	557	-17.6	0.1
Max	1346	1303	18.8	18.8

Table 3 Composition (vol%) of syngas produced during gasification experiments, before and after the implementation of real-time monitoring and process control system for CO, CO₂, and CH₄.

CO (vol%)		Time (min)					
		10	35	60	90	120	150
Before	Mean	12.0	15.2	17.2	13.9	12.1	11.6
	SD	2.0	2.6	5.9	5.9	6.1	5.0
	%RSD	17%	17%	34%	43%	50%	43%
After	Mean	9.5	11.5	12.0	12.2	13.1	14.5
	SD	1.7	4.1	3.8	3.2	2.7	2.4
	%RSD	18%	36%	31%	26%	20%	16%
CO ₂ (vol%)		Time (min)					
		10	35	60	90	120	150
Before	Mean	9.8	12.5	9.7	10.8	11.7	12.1
	SD	1.5	2.0	2.5	2.5	2.7	2.0
	%RSD	16%	16%	26%	23%	23%	16%
After	Mean	10.5	11.9	11.9	11.4	11.4	10.7
	SD	0.8	1.1	1.1	1.2	1.3	1.1
	%RSD	8%	9%	9%	10%	11%	11%
CH ₄ (vol%)		Time (min)					
		10	35	60	90	120	150
Before	Mean	4.9	6.2	1.7	1.6	2.2	2.5
	SD	1.2	1.9	1.2	0.9	1.2	1.4
	%RSD	25%	31%	69%	56%	55%	56%
After	Mean	3.7	3.0	3.3	2.8	3.4	3.2
	SD	0.5	1.2	1.1	1.1	1.1	0.8
	%RSD	14%	38%	34%	41%	33%	26%

Table 4 Composition (vol%) of syngas produced during gasification experiments, before and after the implementation of real-time monitoring and process control system for H₂, N₂ and C₂-C₅ gases.

H ₂ (vol%)		Time (min)					
		10	35	60	90	120	150
Before	Mean	13.7	16.8	11.6	10.5	10.6	11.2
	SD	3.1	2.3	3.1	4.0	4.6	4.6
	%RSD	23%	13%	27%	38%	43%	41%
After	Mean	9.0	9.8	10.8	10.7	12.5	12.9
	SD	1.7	3.2	2.7	2.8	2.4	2.1
	%RSD	19%	33%	25%	26%	19%	17%
N ₂ (vol%)		Time (min)					
		10	35	60	90	120	150
Before	Mean	55	42	58	62	62	61
	SD	8.1	7.0	8.5	8.6	9.6	9.9
	%RSD	15%	17%	15%	14%	16%	16%
After	Mean	64	61	59	61	57	56
	SD	3.8	9.1	7.5	6.7	5.8	4.9
	%RSD	6%	15%	13%	11%	10%	9%
C ₂ -C ₅ (vol%)		Time (min)					
		10	35	60	90	120	150
Before	Mean	4.6	7.1	2.0	1.2	1.3	1.6
	SD	1.3	2.3	1.4	0.7	0.8	1.2
	%RSD	29%	32%	71%	56%	63%	77%
After	Mean	3.6	3.2	2.9	2.1	2.5	2.3
	SD	0.6	1.7	1.3	1.0	1.1	0.8
	%RSD	16%	54%	45%	48%	44%	36%

Table 5 Summary of composition (vol%) of syngas before and after the implementation of real-time monitoring and process control system.

Syngas (vol%)	Before			After			Reduction of fluctuation	
	Mean	SD	%RSD	Mean	SD	%RSD	Δ SD*	%Reduction
CO	13.3	5.7	42	12.4	3.3	27	2.3	41
CO ₂	11.0	2.7	24	11.3	1.3	11	1.4	53
CH ₄	3.1	2.2	71	3.3	1.1	33	1.1	51
H ₂	12.0	5.0	42	11.2	2.7	24	2.3	45
N ₂	57.8	11.9	21	59.0	6.6	11	5.3	45
C ₂ -C ₅	2.8	2.5	91	2.8	1.3	47	1.2	47

Δ SD = SD_{Before} - SD_{After}

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