Technical assessment of the CLEERGAS moving grate-based process for energy generation from municipal solid waste

Marcella R Lusardi1, McKenzie Kohn2, Nickolas J Themelis1 and Marco J Castaldi2

Abstract
A technical analysis has been completed for a commercial-scale two-stage gasification-combustion system. The CLEERGAS (Covanta Low Emissions Energy Recovery GAStification) process consists of partial combustion and gasification of as-received municipal solid waste (MSW) on a moving grate producing syngas followed by full combustion of the generated syngas in an adjoining chamber and boiler. This process has been in operation since 2009 on a modified 330-tonne day⁻¹ waste-to-energy (WTE) line in Tulsa, Oklahoma. Material balances determined that the syngas composition is 12.8% H₂ and 11.4% CO, the heating value of the gas in the gasifier section is 4098 kJ Nm⁻³, and an aggregate molecular formula for the waste is C₆H₁₄.₅O₅. The analysis of gas measurements sampled from the Tulsa unit showed that the gasification-combustion mode fully processed the MSW at an excess air input of only 20% as compared to the 80–100% typically found in conventional WTE moving grate plants. Other important attributes of the CLEERGAS gasification-combustion process are that it has operated on a commercial scale for a period of over two years with 93% availability and utilizes a moving grate technology that is currently used in hundreds of WTE plants around the world.

Keywords
Gasification, large-scale, municipal solid waste, syngas, moving grate, NOₓ reduction

Introduction
The management of municipal solid waste (MSW) is gaining more attention because landfilling space near cities is becoming scarce and because it is recognized that valuable energy and materials can be recovered from waste streams. On average, about 2.5 kg of MSW per day per capita is generated in the US (Van Haaren et al., 2010) and about 1.4 kg per day per person is generated in Europe (Eurostat, 2013) and Japan. In 2011 it was estimated that 2 billion tonnes of waste were generated worldwide and this number is expected to grow to 2.9 billion tonnes by 2022 (Lawrence and Adamson, 2012). Apart from recycling, this growth rate can only be managed by two processes: landfilling or thermal conversion systems. Thermal processes are environmentally preferable to landfilling because they result in a large reduction in mass and volume of the waste (Malkow, 2004; Scholz et al., 1994) and because they concentrate inorganic contaminants, making them easier to sequester and treat (Brunner and Rechberger, 2004). Thermal conversion systems include combustion, gasification or pyrolysis as a thermal pre-treatment technology. At this time, combustion of as-received MSW on a moving grate is the dominant thermal treatment process composing 84% of the total (Themelis et al., 2013). Recently, combustion systems have been shown to achieve up to 32% efficiency comprised of about 28% from electricity generation (Murer et al., 2011). While increasing the efficiency of the plant operation, the potential to increase the energy to the public is very promising. For example, in Vienna both electricity and heat are provided to the surrounding community. However, there is a potential to provide an additional 30–50 GWh year⁻¹ for cooling purposes in the summer months (Ragoßnig et al., 2008). These and other systems with different efficiencies can be quantitatively evaluated using a rigorous calculation model. The models vary by country but are similar in that they define a specific plant boundary and consider the energy (electricity and heat) produced from the process. For a good review on the topic see Gohlke (2009).

Gasification is an alternate thermal treatment method with the potential to be more efficient and versatile than complete

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combustion. Typical gasification systems currently process hundreds of tonnes per day, whereas moving grate combustion systems process thousands of tonnes per day. Gasification is the partial combustion of a fuel, such as MSW, in sub-stoichiometric oxygen to produce H₂ and CO, or syngas. Gasifiers can be used for heat and power production and may be heated directly by partial combustion of the MSW or indirectly by electricity or fuel combustion external to the system. The fuel (MSW) in gasifiers may be dried, sorted or shredded before gasification depending on the configuration. The energy in the syngas may be recovered by gas-cleaning followed by combustion in an external gas engine or turbine (power production), or combustion in the boiler followed by flue gas-cleaning producing heat or electricity with a steam cycle (Arena, 2012). There also is the possibility offered by some direct-melting systems of a complete and immediate reutilization of solid residues (Arena and Di Gregorio, 2013; Jung et al., 2005; Rocca et al., 2012; Parkpaim et al., 2000). The pressure in the gasifier is typically atmospheric, but can be higher, and the temperatures range from 550°C to 900°C for air gasification. In addition to H₂ and CO, the syngas product may contain CO₂, H₂O and CH₄. For a comprehensive coverage of MSW thermal conversion systems, the reader is referred to Combustion and Incineration Processes (Niessen, 2002) and Waste to Energy Conversion Technology (Klinghoffer and Castaldi, 2012).

There are many benefits to MSW gasification compared to combustion. The gasification reaction atmosphere reduces NOₓ (Malkow, 2004), thus reducing the burden on the downstream air pollution control (APC) systems. Also, the resulting syngas can be burned more efficiently than solids in a gas turbine or boiler (Arena, 2012). The low excess air requirement should result in more compact and less costly waste-to-energy (WTE) plants. However, fouling and slagging of refractory materials and the boiler due to ash melting increases. There are many endothermic and exothermic reactions involved in the conversion of solid waste to syngas that occur simultaneously (Arena, 2012). Therefore, it is valuable to have measurement of large-scale systems that operate on realistic fuels to further the understanding and development of the technology.

A pilot-scale reverse acting grate apparatus was developed and tested in 1994 to understand the influence of various operating parameters on the gasification post-combustion process. Special emphasis was given to the decomposition of organic trace compounds and the measurement of polychlorinated dibenzodioxin/furan PCDD/F compounds utilizing an online resonance-enhanced multiphoton ionization mass spectrometer. The temperature, oxygen concentration and residence time was considered simultaneously. It was determined that a high temperature and mixing rate in the sub-stoichiometric region followed by near plug flow conditions downstream resulted in good organic and nitric oxide decomposition (Beckmann and Zimmermann, 1998).

Companies currently operating commercial-scale MSW gasifiers include AlterNRG, Ebara, EnEco, Energos, Hitachi Zosen, JFE, Thermoselect, Kobelco, Mitsui, Nippon Steel Engineering, Plasco Energy Group and Takuma (Arena, 2012). Most of the gasification systems in operation are atmospheric pressure and require fuel pre-treatment, such as separation or shredding (Malkow, 2004). Combustion of the syngas in an adjoining chamber is the most common method of energy recovery. However, a rare example of a system in which clean syngas is extracted from the system is the Thermoselect process. In this process as-received waste is compacted using a hydraulic press and pushed into an indirectly heated degassing channel at 600°C. The degassed waste then enters a high-temperature pyrolysis (i.e. oxygen-free) zone at 800°C, followed by high-temperature (1200–2000°C) gasification with oxygen of the pyrolysis products. The syngas product is then cooled and cleaned and may then be used for external applications (Consonni and Vigano, 2012; Malkow, 2004). The production of clean syngas is an advantage to this system; however, there are energy losses involved with rapidly cooling the hot syngas and pre-heating the MSW in the degassing chamber (Themelis, 2007).

More often the syngas is combusted internally to produce heat or electricity from a steam cycle. For example, the Ebara gasifier is an atmospheric pressure, low-temperature fluidized bed reactor (Arena, 2012). Shredded MSW is gasified in suspension with oxygen resulting in a fluidized bed reactor, and the produced syngas is combusted in a higher temperature cyclone furnace (Consonni and Vigano, 2012; Suzuki, 2007). The JFE direct-melting process utilizes a high-temperature system where oxygen gases flow from top to bottom (i.e. down-draft) through a packed bed of refuse-derived fuel (RDF).

Another example of a gasifier that does not require pre-treatment of MSW is the Direct Melting System of Nippon Steel Engineering. This is an atmospheric pressure, oxygen-enriched fixed bed down-draft gasifier. MSW is directly deposited into the gasification furnace along with solid carbon (coke) and limestone that act as a reducing agent and viscosity regulator, respectively (Tanigaki, 2012). The syngas is transferred to a downstream chamber for complete combustion and energy recovery. The Energos process also does not require pre-treatment of MSW or fuel additives. This system is an atmospheric pressure, high-temperature (900°C) air gasifier with a moving grate reactor design. The syngas is produced in a gasification stage and then combusted in a second stage, called the gas-phase oxidation phase (Alamo et al., 2012). The process produces syngas with approximately half the oxygen required for complete combustion and with a gross calorific value of 4.34 MJ Nm⁻³ (Alamo et al., 2012; Consonni and Vigano, 2012).

The Covanta Low Emissions Energy Recovery Gasification (CLEERGAS®) process has been operated for over two years at a capacity of 330 tonnes day⁻¹ of MSW by modifying one of the three units of the Tulsa, Oklahoma, WTE facility. This is the largest of the gasifier systems currently in operation and produces 40 metric tonnes (88,500 pounds) per hour of high-pressure (40 bar (670 psia); 346°C (656 °F)) process steam. The CLEERGAS process in
Tulsa consists of partial combustion (estimated at about 45%) and gasification of as-received MSW on a moving grate in the bottom half of the combustion chamber followed by full combustion of the syngas in the upper part of the chamber by injecting additional air. The design utilizes a conventional combustion grate and feed system yet stages the air to achieve gasification conditions in a targeted section of the boiler. The average NO\textsubscript{x} emissions vary between 60 and 90 mg Nm\textsuperscript{-3}, with values as low as 45 mg Nm\textsuperscript{-3}, and CO emissions are approximately 18 mg Nm\textsuperscript{-3}. This work will present an analysis of the CLEERGAS process, including material balances, determination of the composition and heating value of the syngas and estimation of the chemical and thermal efficiency of the gasification stage and of the overall process determined by steam output, overall air input, boiler temperature and enthalpy of syngas.

**Experimental methods**

In order to test the CLEERGAS process at an industrial scale, Covanta modified one of the three units of their Tulsa, Oklahoma, WTE plant. Boilers 1 and 2 of this plant are conventional combustion chambers using under-fire and over-fire air injection. Boiler 3 was retrofitted by Covanta R&D to operate in a two-stage mode: the lower stage, extending to a few metres above the grate, is operated at a sub-stoichiometric air-to-fuel ratio that results in the drying of the MSW and the generation of syngas. This syngas is then combusted fully by the injection of additional air in the upper part of the chamber (Figure 1(a)).

During the observed operation period, the MSW supplied by trucks was stored in a conventional below-ground waste storage pit and supplied to the bins of the three boilers via overhead crane delivery. Observations made from the crane-control deck confirmed that the supply of feed to the CLEERGAS® unit (Boiler 3) was identical to that provided to the conventional units (Boilers 1 and 2). There was no pre-sorting, special waste selection, processing or special attention of any kind to the material fed into the gasification boiler. Also, a tour of the entire facility confirmed that the operations of the Tulsa facility are typical of conventional WTE operations.

A water-cooled probe and an Agilent/Inficon micro gas chromatograph (GC) were used to analyse gas samples obtained from two locations in Boiler 3. Figure 1(b) shows the two ports where flue gas was extracted using a water-cooled probe and transferred to the on-site GC used for chemical species identification. Port B was located at the bottom of the boiler, directly above the gasification zone, while port A was near the top of the boiler, above the zone where secondary air was injected to combust the syngas.

Because the air-to-fuel ratio is a critical parameter in combustion and gasification systems, the equivalence ratio (\(\phi\)) is used throughout this work to compare conditions throughout the boiler. The equivalence ratio is defined as the ratio of actual oxygen in the process to the oxygen required stoichiometrically for full combustion. Therefore, an equivalence ratio of less than one indicates that the process is deficient in air, promoting gasification, while a ratio greater than one indicates that the process is operating in excess air, promoting complete combustion.

**Results**

**Analysis of gas sampling at port A (gasification stage)**

Sampling port B was just above the waste bed and at the level of the lower “bullnose”, a protrusion into the furnace boiler that deflects the gas flow, as shown in Figure 1(b). The section of the...
furnace between the grate and this port is considered to be the gasification zone and includes both the primary air flow under the bed and the secondary air injected above the bed. The total airflow is controlled to be below the stoichiometric amount required for complete combustion, giving an equivalence ratio of approximately 0.6.

Figure 2 shows two datasets of gas concentration profiles obtained through port B, as a function of distance from the furnace wall. The concentrations labelled “#1” indicate a previous dataset (Storm Technologies, Inc. North Carolina, USA), while concentrations labelled #2 were measured by the authors. Figure 2 shows that the maximum gas concentrations were at the centreline of the furnace, 2.5 metres (8 feet) from the wall. The gas contained 12.8% H$_2$, 11.4% CO and 3.7% CH$_4$, that is, a H$_2$/CO ratio of 1.1. Further from the centreline, closer to the sides of the boiler, the syngas and CH$_4$ concentrations decrease, indicating a lesser extent of gasification. This is likely due to air bypass at the walls of the boiler, resulting in complete combustion closer to the sides. This air bypass is commonly observed where the boiler waterwall section interfaces with the grate section below. Since the grate is designed to move (to mix the waste) and is cooled by air upon operation the relative position of the boiler waterwall and the side-end of the grate can change, leading to some air bypass through that gap.

The later dataset obtained included H$_2$ and CO concentrations as well as CO$_2$ and O$_2$ concentrations in the boiler. The goal during the testing was to obtain samples across the area of the boiler, but due to access limitations, only 0.625 metre (2 feet) and 1.25 metre (4 feet) penetrations were obtained. These data points are also shown in Figure 2 at 3.65 and 4.27 metres (12 and 14 feet) into the boiler. The H$_2$ and CO concentrations decreased closer to the boiler wall, consistent with the earlier dataset. As expected, O$_2$ concentration was higher closer to the boiler wall, indicating higher O$_2$ content that would favour complete combustion over gasification at the edges of the boiler. Finally, CO$_2$ concentration remains steady at 7.04 ± 0.08% at the 3.65 and 4.27 metre positions into the boiler.

Figure 3 shows the product gases as a function of time at the 4.27 metre (14 foot) position from the boiler wall. This test set consisted of inserting the probe approximately 0.610 metres (2 feet) into the side wall of port B and taking samples every 3 minutes. The total test set took approximately 25 minutes. This time differential sequence provides insight into the fluctuations occurring within the gasification zone. These fluctuations are due to mixing, heterogeneity of the waste and air flow modifications. Figure 4 shows the concentration profiles of CO$_2$, CO and H$_2$ from this dataset as a function of O$_2$ concentration.

Figures 3 and 4 show the trade-off between O$_2$, CO$_2$, H$_2$ and CO. At low O$_2$ values (0–11 minutes in Figure 3), CO$_2$, CO and H$_2$ values are higher and vice versa for the 14–23 minute time range. The timeframe reported (23 minutes) is representative of the type of fluctuation observed at this location near the wall. Nitrogen, methane and hydrocarbons were measured directly using the GC. The CO$_2$ variation is directly matched by O$_2$ variation as expected in this part of the boiler. Figure 4 shows the concentration profiles of CO$_2$, CO and H$_2$ from this dataset as a function of O$_2$ concentration.

Higher concentrations of CO and H$_2$ were measured in the early stages of the test. As O$_2$ concentration increased, CO$_2$ concentrations decreased, which is consistent with gasification conditions when air is utilized. Throughout the test set, the H$_2$/CO ratio is approximately 0.59, which is very close to a typically desired ratio of 0.5 for many chemical synthesis processes, such as Fischer–Tropsch systems producing liquid fuels. This data shows that reaction is occurring and the presence of H$_2$ and CO show that the waste is being partially gasified. The low concentration of H$_2$ and CO relative to CO$_2$ is due to the proximity of the boiler wall. The probe had a maximum penetration distance into the boiler from...
the sidewall of approximately 1.22 metres (4 feet) of the overall (16 feet); therefore, a larger than expected amount of O₂ was observed. This O₂ is likely from air bypass near the wall of the boiler or air intrusion from the outside and is consistent with the higher oxygen and lower syngas concentrations for these measurements. This also highlights the importance of airtight construction when erecting large-scale gasification systems. The variation in H₂ and CO concentrations at relatively constant O₂ concentrations is due to mixing at the boiler wall.

Figure 5 shows a similar test set with an extension attached to the probe to 1.22 metre (4 feet) penetration into the boiler from the same port B, corresponding to the 3.65 metre (12 foot) position in Figure 2. Again a series of samples were taken at a fixed probe position over a time period of about 23 minutes (approximately 3 minutes per sample). O₂, CO₂, CO, H₂ and N₂ concentrations are shown as a function of time. Figure 6 shows the concentration profiles of CO₂, CO and H₂ from this dataset as a function of O₂ concentration. Here again, the CO concentration was slightly higher than the H₂, resulting in a H₂/CO ratio of 0.83. Also, similar to the 4.27 metre (14 foot) position, as O₂ concentration increased, on average, H₂, CO and CO₂ concentrations decreased, indicating reduced partial oxidation of the MSW.
Table 1 summarizes the results in Figures 3–6, showing average values and standard deviations for O₂, N₂, CO, H₂, CH₄ and CO₂ at two and four feet from the boiler wall, corresponding to 3.65 and 4.27 metre (12 and 14 foot) positions in Figure 2. It should be noted the GC was capable of measuring down to parts per million mole fraction reliably, thus the many decimal places for methane.

In addition to the CO₂, CO and H₂ produced in the lower level of the boiler, smaller amounts of hydrocarbons were also measured. Because gasification occurs in a lean-oxygen atmosphere...
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(equivalence ratio less than one), higher order hydrocarbons (HOHCs) that would be combusted in an oxygen-rich combustion atmosphere remain either unreacted in the gas phase or are aerosolized and can create issues downstream if not reacted or removed. Table 2 shows the range of HOHCs that were present in the gasification regime of Boiler 3, grouped from C2 to C9. The largest concentration of HOHC was of nonanes, between 0.6% and 2.0%. Two, three, seven and eight carbon species were the next most prominent HOHC, of the order of magnitude of 100 ppm. Finally, four, five and six carbon species were at the lowest concentration (about 100 ppm). The presence of these HOHCs again confirms that gasification is occurring in Boiler 3 and points to the vigilance that must be maintained during operation of such a system. The equivalence ratio and temperature associated with gasification create an environment conducive to the release of HOHCs from the MSW feed. Some of these species remain in the gas phase, while others form particulates and lodge onto the boiler wall, which are responsible for the smooth tar (highly recalcitrant carbonaceous material) layers on the inner wall of the boiler in the port B region. Neither the tar nor these species are present in the upper level of the boiler, as expected, as the oxygen-rich combustion environment is capable of oxidizing the HOHCs into CO2 and H2O.

Upper boiler gas analysis

Gas analysis from the upper section of the boiler, where complete combustion was targeted, resulted in the values shown in Figures 7 and 8 and Table 3. Figure 7 shows an analysis of the temporal data at 1.8 metre (6 foot) penetration horizontally into the boiler and commensurate changes in CO2. The concentrations are quite constant due to the good mixing conditions of the secondary air injection. The data showed the expected trade-off between CO2 and O2: as CO2 is produced, O2 is consumed, as shown in Figure 8. The major species present in the upper section of the boiler are inert N2, unreacted O2, CO2 and H2O. CO is present at the ppm level. This confirms that complete combustion of syngas occurs in the upper part of the gasification-combustion chamber.

Table 3 summarizes the results for the gas species in the upper boiler, showing average values and standard deviations for O2, N2, CO, H2, CH4 and CO2 at 2.4, 3.05, 3.65 and 4.27 metre (8, 10, 12, 14 foot) positions in the boiler. The N2, O2 and CO2 values do not show much variation, indicating that the upper complete oxidation zone of the boiler is more homogeneous. Furthermore, the HOHCs observed in the lower section of the boiler were not observed in the upper section, indicating that they are completely combusted in the upper section.

Material balances

Material balances were conducted based on the gas measurements discussed above. This was done because the scale of the unit (330 tonnes day−1) does not enable a representative sample to be taken. The waste is transferred from collection trucks to a holding pit where it is then crane-fed to the top of the gasification boiler

![Table 2. The higher order hydrocarbon species present in the lower level of boiler 3.](image)

<table>
<thead>
<tr>
<th>Species</th>
<th>Concentration (± 50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>1620 ppm</td>
</tr>
<tr>
<td>C3</td>
<td>1730 ppm</td>
</tr>
<tr>
<td>C4</td>
<td>15 ppm</td>
</tr>
<tr>
<td>C5</td>
<td>110 ppm</td>
</tr>
<tr>
<td>C6</td>
<td>50 ppm</td>
</tr>
<tr>
<td>C7</td>
<td>2850 ppm</td>
</tr>
<tr>
<td>C8</td>
<td>990 ppm</td>
</tr>
<tr>
<td>C9</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

![Figure 7. Upper level boiler species concentrations at the 1.8 metre (6 foot) location. N2 is on the secondary axis.](image)
untreated. The amounts of MSW and air supplied to the plant were provided by Covanta. The molecular formula of the MSW was determined using the overall combustion reaction with added air and assumed moisture content of the waste at 20%:

$$\text{C}_x\text{H}_y\text{O}_z + \beta\text{O}_2 \rightarrow \gamma\text{CO}_2 + \delta\text{H}_2\text{O (g)}$$

along with the following simultaneous equations:

$$y = 2\delta$$
$$z + 2\beta = 2\gamma + \delta$$
$$x = \gamma$$

Additional constraints in this analysis were that the composite chemical should match the higher heating value for typical MSW and the C/H, C/O and H/O molar ratios should match as closely as possible to measured values. In this case the ratios from the calculations were C/H = 0.41, C/O = 0.31 and H/O = 0.76. The calculation resulted in a molecular formula of \(\text{C}_6\text{H}_{10}\text{O}_4\), which is close to the formula \(\text{C}_6\text{H}_{10}\text{O}_4\) developed by Themelis et al. (2002). In that study, the chemical thermodynamics of the MSW combustion reaction were modelled by representing the composite combustible MSW by an established hydrocarbon compound. It is interesting to note that on the basis of the above formula and the assumption that the Tulsa MSW contains 30% carbon, which is typical of US MSW received at WTE plants (Bahor et al., 2009), the heating value of this MSW is calculated to be 11 MJ kg\(^{-1}\), comparable to the 10.5 MJ kg\(^{-1}\) provided by Covanta, which is typical of US MSW according to previous studies (Themelis et al., 2013).

For the gas mixtures present in the lower and upper portion of the boiler, shown in Tables 1 and 3, respectively, \(\text{H}_2\text{O}\) concentration, adiabatic temperature, equivalence ratio, heating value and atomic molar ratios were calculated. These values are provided in Table 4. It should be noted the location of port B only allowed for a short probe to be inserted into the boiler; therefore, the locations reported for port A enable direct comparisons with the port B location and connection to Table 3. The \(\text{H}_2\text{O}\) concentration was calculated because water vapour in the sample gas was condensed prior to introduction into the GC, thus dry samples were taken. The temperature shown is the estimated adiabatic temperature inside the chamber. The equivalence ratio is defined as the O\(_2\) concentration injected into the boiler in comparison to the stoichiometric concentration required for complete combustion. Values less than one indicate low O\(_2\) atmospheres that favour gasification, while higher values favour complete combustion.

The equivalence ratio results are highly significant because they demonstrated that full combustion was achieved in the pilot unit with only 20% excess air versus the conventional operation.
CO and H2 measured by the Earth Engineering Center (EEC) at 11.4% and 12.8%, respectively. The actual concentrations of lower CO and H2 percentages than theoretically expected. This oxidizes a large amount of the syngas in the region and yields an already low syngas environment. As a result, this air fully bypasses the MSW/grate, creating an oxygen-rich atmosphere in boiler for comparison. At the edge of the boiler, primary air were 2.3% and 1.0%, respectively, 1.22 metres (4 feet) into the and CO2 (7 mol%) present in the "syngas" stream. A correspond-
ances. For every tonne of MSW processed, 1.00 tonne of CO and
values ranging between 1.13 and 1.24 or between 13% and 24%
where excess air is of the order of 80–100%. Port A, which is at
Based on the calculated formula of MSW and the feed rate of
This corresponds well to the data taken by Storm at the boiler cen-
theoretical maximum values of CO and H2 that could be produced can be calculated using C and H balances. For every tonne of MSW processed, 1.00 tonne of CO and 0.88 tonnes of H2 can be produced theoretically. Assuming that the mass flow rate in the lower level of the chamber is equal to that in the upper level, this corresponds to maximum theoretical concentrations of 13.0% and 10.1% for CO and H2, respectively. This compares well to the data taken by Storm from Figure 8) results in a syngas heating value of 4098 kJ per normal cubic metre near the centreline of the gasification chamber. These are typical heating values of syngas produced via air gasification.
Importantly, the particulate matter (PM) or dust measurements in-situ NOx formation, it is important to maintain a reducing environment immediately above the waste bed. Goh et al. (2003) demonstrated this effect via modelling and suggested that the waste bed should have a char portion to promote NOx reduction. Also, EEC researchers Frank and Castaldi (2011) have shown via computational fluid dynamics (CFD) coupled to detailed chemical kinetic modelling that it is imperative to provide sufficient time for the fuel-bound nitrogen to form N2, which then passes through the secondary air injection stage as an inert gas. Therefore, the avoidance of NOx formation immediately

<table>
<thead>
<tr>
<th>Location</th>
<th>H2O (%)</th>
<th>T ad (K)</th>
<th>φ</th>
<th>Syngas HV kJ m−3</th>
<th>C/H</th>
<th>C/O</th>
<th>H/O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port B, 0.610 m</td>
<td>15.40</td>
<td>1540</td>
<td>1.08a</td>
<td>616.29</td>
<td>0.26</td>
<td>0.22</td>
<td>0.85</td>
</tr>
<tr>
<td>Port B, 1.22 m</td>
<td>16.04</td>
<td>1540</td>
<td>1.09a</td>
<td>616.27</td>
<td>0.27</td>
<td>0.25</td>
<td>0.95</td>
</tr>
<tr>
<td>Port A, 0.610 m</td>
<td>15.82</td>
<td>1375</td>
<td>1.22</td>
<td>N/A</td>
<td>0.19</td>
<td>0.14</td>
<td>0.76</td>
</tr>
<tr>
<td>Port A, 1.22 m</td>
<td>15.87</td>
<td>1447</td>
<td>1.16</td>
<td>N/A</td>
<td>0.21</td>
<td>0.16</td>
<td>0.79</td>
</tr>
<tr>
<td>Port A, 1.83 m</td>
<td>16.56</td>
<td>1485</td>
<td>1.13</td>
<td>N/A</td>
<td>0.22</td>
<td>0.19</td>
<td>0.85</td>
</tr>
<tr>
<td>Port A, 2.44 m</td>
<td>15.73</td>
<td>1353</td>
<td>1.24</td>
<td>N/A</td>
<td>0.17</td>
<td>0.13</td>
<td>0.76</td>
</tr>
</tbody>
</table>

*aφ is slightly above one due to the proximity of the sample near the boiler wall.

**Emissions impact**

The operation of Boiler 3 in a gasification mode was shown to have a positive effect on emissions, resulting in a lower air pollution control (APC) system load downstream. In particular, the NOx production was significantly lower due to the reducing environment just above the waste bed. The NOx emissions (at 7% O2) during the testing from Boiler 3 were reported by Covanta to be 60–90 ng N m−3, which is nearly 40% below normal operation with normal CO emission approximately 18 ng N m−3. Importantly, the particulate matter (PM) or dust measurements were approximately 10% of the total ash generated, which is significantly less than normal excess air operation. This is consistent with the overall airflow reduction of 38% reported by Covanta during gasification. The under-grate air is controlled to be substoichiometric in relation to the amount of waste on the grate, resulting in complete oxygen utilization and leaving partially oxidized products (CO and H2), lighter hydrocarbons (CH4, C2H4, etc.) and lower concentration of nitrogen oxides. These emission results are achieved with an estimated overall boiler temperature increase of 400 K, leading to an estimated overall thermal efficiency improvement of approximately 5%. In contrast, a conventional WTE boiler maintains an oxidizing environment through and above the waste bed, which does not allow in-situ NOx reduction.

The main conditions that contribute to NOx formation in WTE boilers are intimate mixing between the gases emanating from the bed and the air flow introduced to the furnace off-gases in the waste and the chemical composition in the gas phase immediately above the bed. While intimate mixing of the air within the fuel bed is desired from a combustion perspective, it is undesirable from a NOx formation perspective. Since most of the NOx is formed from fuel-bound nitrogen, it is important to maintain a reducing environment immediately above the waste bed. Goh et al. (2003) demonstrated this effect via modelling and suggested that the waste bed should have a char portion to promote NOx reduction. Also, EEC researchers Frank and Castaldi (2011) have shown via computational fluid dynamics (CFD) coupled to detailed chemical kinetic modelling that it is imperative to provide sufficient time for the fuel-bound nitrogen to form N2, which then passes through the secondary air injection stage as an inert gas. Therefore, the avoidance of NOx formation immediately
above the waste bed from fuel-bound nitrogen is one of the most critical steps that can be taken to reduce overall NO\textsubscript{x} formation in WTE boilers.

Conclusions

The CLEERGAS\textsuperscript{®} process has been tested extensively on an industrial scale (330 tonnes day\textsuperscript{-1}). The process consists of two stages: the lower stage, extending to just above the grate, is operated at a sub-stoichiometric air-to-fuel ratio that results in the generation of syngas. The syngas produced in the lower part of the chamber is then combusted fully by injecting additional air in the upper part of the chamber. Gasification in the lower part of the unit and subsequent combustion of the syngas in the upper part resulted in full combustion of as-received MSW at an excess air input of only 20\%, versus conventional WTE grate combustion units where 80–100\% excess air is typically used. Another important attribute of the CLEERGAS\textsuperscript{®} process is that gasification takes place on a moving grate, a technology that has been tested, proven and used in over 600 existing WTE plants around the world.

In the prototype of the process, now under design by Covanta Energy, the amount of air infiltration in the gasification chamber will be reduced and the conditions for combustion of the syngas in the separate gas combustion unit will be improved. Therefore, it is expected that the amount of excess air required in the prototype will be substantially lower than in conventional grate combustion WTE plants. Lower excess air will result in higher thermal efficiency of the process and, most importantly, in lower capital and operating costs per tonne of MSW processed. The two-stage process of gasification followed by syngas combustion also enables better control of NO\textsubscript{x} generation by properly designing the air injection to the syngas combustion chamber.

Acknowledgements

The cooperation of Covanta Energy and the Tulsa, Oklahoma, WTE plant in providing data and hosting the researchers during their collection of operating data and measuring gas compositions in the gasification-combustion chamber are gratefully acknowledged.

Declaration of conflicting interests

None declared.

Funding

This work was supported by the EEC of Columbia University and City College of New York.

References


