



## Modeling and comparative assessment of municipal solid waste gasification for energy production

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### ABSTRACT

Gasification is the thermochemical conversion of organic feedstocks mainly into combustible syngas (CO and H<sub>2</sub>) along with other constituents. It has been widely used to convert coal into gaseous energy carriers but only has been recently looked at as a process for producing energy from biomass. This study explores the potential of gasification for energy production and treatment of municipal solid waste (MSW). It relies on adapting the theory governing the chemistry and kinetics of the gasification process to the use of MSW as a feedstock to the process. It also relies on an equilibrium kinetics and thermodynamics solver tool (Gasify<sup>®</sup>) in the process of modeling gasification of MSW. The effect of process temperature variation on gasifying MSW was explored and the results were compared to incineration as an alternative to gasification of MSW. Also, the assessment was performed comparatively for gasification of MSW in the United Arab Emirates, USA, and Thailand, presenting a spectrum of socioeconomic settings with varying MSW compositions in order to explore the effect of MSW composition variance on the products of gasification. All in all, this study provides an insight into the potential of gasification for the treatment of MSW and as a waste to energy alternative to incineration.

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### 1. Introduction

Municipal solid waste (MSW) is a very heterogeneous resource. Nevertheless, separation of MSW into waste categories can increase the homogeneity of the waste streams. It also allows an optimization of waste reuse, recycle, and treatment and yields the greatest benefit depending on possible treatment options for each category. Therefore, an ideal categorization of separate waste streams lies in their potential waste treatment. Based on that, MSW can be broadly divided into the following categories or streams: metals, paper, plastics, textiles, wood, food wastes, yard wastes, and glass. Those streams are quite different and their proportions in the total MSW generated vary depending on socio-economic and geographical factors as well as governmental policies (Parizeau et al., 2006; Alavi Moghadam et al., 2008; Bandara et al., 2007; Al-Khatib et al., 2007; Arafat et al., 2007).

Gasification is the process of converting organic compounds into a mixture of gaseous species that is dominated by carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), hydrogen (H<sub>2</sub>), and methane (CH<sub>4</sub>). Other chemical products are also formed in the process of gasification but their concentrations are mostly negligible. The primary benefit attributed to gasification is the ability to convert biomass into an energy carrier. This is apparent since hydrogen and

methane are among the primary products. This conversion is achieved at high temperatures and in the presence of limited oxygen (Higman and van der Burgt, 2008). Gasification has a significant potential as a waste treatment option for municipal solid waste (MSW). Of the MSW categories mentioned earlier, metals and glass are largely inorganic and thus cannot be gasified. On the other hand, the remaining waste streams are organic and have a gasification potential.

Gasification is a readily available technology with a worldwide capacity of 122,106 thermal MW, as of 2010 (Worldwide Gasification Database, 2010). The biggest share of gasification application is in the coal industry, as shown in Fig. 1, where gasification is employed to produce cleaner fuels. Biomass and waste gasification constitute only 0.33% of the total worldwide gasification capacity (Worldwide Gasification Database, 2010), a tiny portion of the current gasification market. However, this can be thought of as an untapped market with tremendous potential. In recent year, attention to gasification as a potentially viable technology for energy recovery from waste has increased (Lombardi et al., 2012; Tanigaki et al., 2012; Consonni and Viganò, 2012). A municipally supported integrated waste management plan with provisions for waste-to-energy can substantially increase the demand for gasification to treat the waste. This is especially the case since gasification has several advantages over incineration. The products from gasification have many energy and industrial uses, gasification is potentially more efficient than incineration, is potentially operated at

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### Nomenclature

|                     |   |                    |  |
|---------------------|---|--------------------|--|
| CGE                 | cold gas efficiency                                 | $P_i$              | normalized partial pressure of component ( $i$ ) |
| $C_p$               | heat capacity                                       | $P_{\text{Total}}$ | total pressure                                   |
| $\Delta G^0$        | the standard Gibbs free energy of formation         | $R$                | universal gas constant                           |
| $H_f^0$             | enthalpy of formation of a product or a reactant    | $T$                | gasification temperature                         |
| HHV                 | higher heating value                                | $\Delta T$         | change in temperature                            |
| $\Delta H_T^0$      | change in the enthalpy due to change in temperature | $x_i$              | stoichiometric ratio of component ( $i$ )        |
| $\Delta H_{v,H_2O}$ | heat of vaporization of water                       | $x_{\text{Total}}$ | the total moles of gaseous products              |
| $K_i$               | equilibrium reaction constant for reaction $i$      |                    |  |
| LHV                 | lower heating value                                 |                    |  |
| $m$                 | air flow rate to the gasifier                       |                    |  |

lower temperature, and finally, fewer pollutants are volatilized in gasification than in incineration (Arena, 2012).

Most of the gasification studies found in the literature focus on evaluating gasification of specific MSW from a certain locality under very specific conditions. For example, Caton et al. (2010) studied the gasification of food waste from the US Naval Academy, while Zhao et al. (2010) studied the gasification of a local MSW mixture. Our study elucidates the potential of gasification for both waste treatment and energy production. It does so by developing an easy to use methodology to compare the gasification potential of different MSW streams. This method is centered on a developed model that predicts the products of gasification, in the form of chemical species that are ultimately quantified into energy carriers and pollutants. The novelty of this study is that the developed methodology allows for the quick assessment of gasification for any MSW feedstock for either a standalone evaluation or for comparison to other possible waste treatment technologies. The results of this study are also reported on a stream basis (e.g., the gasification potential of the paper stream in MSW) along with that of the MSW as a mixture. This allows others to quickly combine the reported results based on their MSW composition to obtain a quick insight into the potential of gasification in a given situation and how it compares to other waste treatment technologies. This will help in creating a clearer perspective on how gasification fairs in comparison to other waste treatment options (recycling and incineration for instance). The effects of gasification conditions and MSW composition (illustrated through MSW examples of three countries) on gasification process performance for MSW treatment are also analyzed.

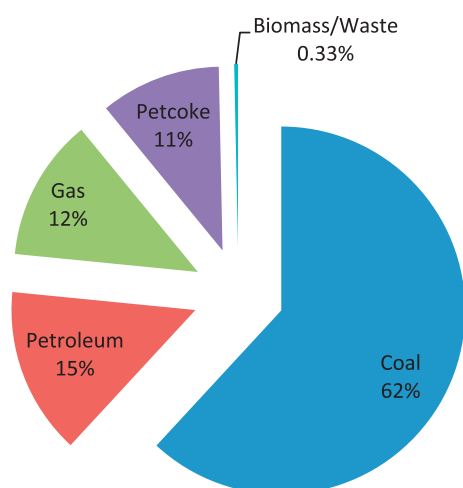


Fig. 1. Global gasification capacity by industry as a fraction of total thermal energy produced (Worldwide Gasification Database, 2010).

### 1.1. Gasification potential in the United Arab Emirates

The Center for Waste Management in the emirate of Abu Dhabi (the largest and capital Emirate in the United Arab Emirates (UAE)) estimates that the Emirate of Abu Dhabi generated 5.9 million tons of waste between the years 2007 and 2008. About 97% of that waste ended up in dumpsites in the desert without biogas collection systems, energy recovery, or recycling programs (Dumble, 2010). In 2009, the UAE MSW generation rate was 532 kg per capita per year (Dumble, 2010). That same year, the OECD (Organization for Economic Cooperation and Development) member country with the highest MSW generation rate was Denmark at a rate of 830 kg per capita per year. On the other hand, generation rate for Japan (another OECD member country) was only 380 kg per capita per year (OECD Factbook, 2011), 70% that of UAE. Hence, there is a huge energy potential entrapped in MSW in UAE. On average, one ton of MSW can generate around 600 kW h of electricity through energy recovery or waste to energy technologies, including gasification (Patel, 2003). The Emirate of Abu Dhabi has recently set an ambitious target of 90% diversion of waste from dumpsites by 2013 (Dumble, 2010). Therefore, there is currently a spur of waste infrastructure development in Abu Dhabi and the UAE at large, aimed at building an integrated solid waste management system. Gasification of MSW is one key candidate technology for this purpose.

The aim of this study is to evaluate gasification as a waste-to-energy technology for energy recovery from MSW, and to compare it to incineration. The study assesses, theoretically, the potential of gasification as a waste-to-energy pathway for different waste streams, and also for the MSW bulk stream. Applications of gasification to MSW in the UAE is taken as a case study and is compared to the United States and Thailand, providing a spectrum of three regions with varying socio-economic and, therefore, MSW profiles.

An assessment of the potential of gasification can only be made after modeling the products of gasification and their concentrations at different operating conditions. In this study, we attempted to do so for MSW by first dividing MSW into representative categories, representing those categories and their gasification chemically, and finally predicting the relative concentrations of process products using a computer package with a built-in Gibb's energy minimization model. Energy and efficiency calculations were then conducted based on these product predictions. This work relies on thermodynamic models, scientific literature, and published experimental results; bringing those resources together in a novel approach. It attempts to generalize the findings; thus, increasing their applicability to other countries.

## 2. Methodology

To fully understand the condition of MSW and its gasification potential, a set of chemical and physical waste characterization

tests must be undertaken, mainly proximate and ultimate tests. In the specific case of MSW, the proximate analysis is structured to find the moisture content, fixed organic matter, volatile organic matter, and amount of ash content in MSW. On the other hand, the ultimate analysis is structured to determine the chemical composition of an MSW compound and the chemical formula that represents that composition (Niessen, 2010). The information from those tests is used in modeling the gasification process, since the yields of energy and waste conversion depend on the chemical structure of the feedstock (that is, waste stream). The ultimate analysis of different waste streams is presented in Table 1, which was obtained from a study that was conducted for the US Department of Health, Education and Welfare and reported in Niessen (2010), in addition to a second study presented in Themelis et al. (2002). The advantage of using the results in (Niessen, 2010) stems from the breadth and the depth of the study, which was a very thorough and meticulous study that considered a multitude of aspects, streams, and conditions for different waste streams. The results in Niessen (2010) were reported as a percentage of total mass and those figures were converted here to a chemical formula as shown in Table 1. Results of the proximate analysis are presented in Table 2 (Niessen, 2010; Themelis et al., 2002). The results will not be exactly the same for different countries since MSW is a heterogeneous resource but a review of published results showed only slight variations (Niessen, 2010; Themelis et al., 2002). Having said that, the heterogeneous nature of waste forbids the production of universal results and thorough local tests will have to be conducted at the design stage of a gasification waste to energy plant. The same problem arises with the gasification of coal, which is also a heterogeneous resource (Niessen, 2010).

In the second step, those chemical formulas were then used as input to a software solver package with a built-in gasification model. The package is the MATLAB-based solver, Gasify<sup>®</sup> (V2.01), developed by Marten J. van der Burgt and Christopher Higman from Higman Consulting (Germany). The solver calculates the molar concentrations of CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub>, C, N<sub>2</sub>, NH<sub>3</sub>, and HCN, as the main gasifier products. However, the developers of Gasify<sup>®</sup> strongly recommend that the user be thoroughly familiar with the thermodynamics of the gasification process on hand, as the Gasify<sup>®</sup> solver relies on inputting process conditions which can only be determined based on such understanding of process thermodynamics. Attempting to use the software (which mainly functions as a black box tool) without this thermodynamics familiarity often leads to model divergence. Moreover, understanding process thermodynamics is key to interpreting the solver output. It is important to mention here that the solver merely is a database of the equations involved in gasification and it allows for a quick solution of those equations. The user of Gasify is required to input the reacting MSW components, specify their properties (such as the higher heating value), input the reactor conditions (temperature and air flow rate) and select which equilibrium equations should the solver use. For this, the user should be aware of the nuances of the gasification process, the required inputs for a solution to be converged to, the relevant equations for the case at hand,

**Table 1**  
Ultimate analysis of MSW streams as mass percentage of carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and ash and the resulting chemical formula (Niessen, 2010; Themelis et al., 2002).

| Category    | %C    | %H   | %O    | %N   | %Ash | Chemical formula  |
|-------------|-------|------|-------|------|------|---|
| Paper       | 43.41 | 5.82 | 44.32 | 0.25 | 6.0  | C <sub>3.6</sub> H <sub>5.8</sub> O <sub>2.8</sub> N <sub>0.02</sub>  |
| Plastics    | 60.0  | 7.2  | 22.8  | 0    | 10.0 | C <sub>5.0</sub> H <sub>7.1</sub> O <sub>1.4</sub>                    |
| Textiles    | 55.0  | 6.6  | 31.2  | 4.6  | 2.4  | CH <sub>1.7</sub> O <sub>0.7</sub> N <sub>0.04</sub>                  |
| Wood        | 49.4  | 6.1  | 43.7  | 0.1  | 0.6  | C <sub>4.1</sub> H <sub>6.1</sub> O <sub>2.7</sub> N <sub>0.007</sub> |
| Food wastes | 44.99 | 6.43 | 28.76 | 3.3  | 16.0 | C <sub>3.7</sub> H <sub>6.4</sub> O <sub>1.8</sub> N <sub>0.2</sub>   |
| Yard wastes | 40.31 | 5.64 | 39.0  | 2.0  | 13.0 | C <sub>3.4</sub> H <sub>5.6</sub> O <sub>2.4</sub> N <sub>0.1</sub>   |

and the nature of each equation (linear or nonlinear, and divergent or convergent for the given case). Hence, it was inevitably essential for us to build the thermodynamic model for the gasification process, which will be described briefly in the next section. Full details of the model can be found in Jijakli (2012).

Another software package, NASA's Chemical Equilibrium with Applications tool (CEA), was also considered for modeling the gasification process. It was found that its applicability was limited to a set of reactants that included fuels mostly and not waste streams or MSW. Also, provisions for inputting different streams in CEA were absent. Hence, CEA was not considered further.

Based on the modeling of gasification process, gasifier products for each MSW stream were determined and energy efficiency analysis was conducted using typical MSW composition data previously published for UAE, which was also compared to USA and Thailand. Parallel calculations were also made for incineration for comparison. Three sets of data were used to determine the waste composition as fractions of waste streams in the three countries to contrast the variability of the gasification potential based on economic development (Dumble, 2010; USEPA, 2010; Thamavithyaa and Dutt, 2008).

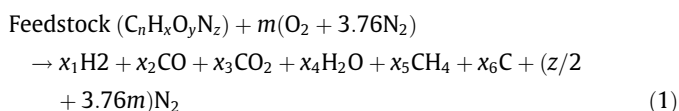
### 3. Thermodynamics and modeling procedure of MSW gasification

Gasification is the process of converting biomass primarily into syngas. This is accomplished at high temperatures and in the controlled presence of oxygen, which is the major difference between gasification and incineration. Incineration utilizes an abundant supply of oxygen to combust the waste stream and the products are mainly CO<sub>2</sub> and H<sub>2</sub>O. On the other hand, gasification utilizes a limited and controlled amount of oxygen that will result in a certain control over the process and the chemical reactions that proceed (Arena, 2012). This leads to the controlled production of chemical species, primarily syngas.

Gasification products are synthesized through a complex chemical mechanism that involves a phase transition (from solid to gas) and gaseous reactions. Most of the complexity in the chemistry behind gasification arises from the phase transition from solid to gas (Liu et al., 2010). However, this complex chemistry can be presented in a simplistic manner that sums the entire gasification process into three major processes. First, residual moisture, if any, evaporates. This is followed by the second process: pyrolysis. In pyrolysis, volatiles are freed from the solid phase and are able to react among each other and with the char to form new species. Finally, those complex char-gas and gas-gas reaction yield to the controlling reactions that, eventually, form the final products of gasification (Liu et al., 2010).

Pyrolysis depends on operating conditions such as temperature, pressure, and residence time (Liu et al., 2010). In pyrolysis, a temperature increase supplies enough energy to break down complex compounds in the feedstock into simpler species. This occurs in the absence of oxygen and is the initial species transformation that will eventually lead to the main gasification products. Those initial volatile species are very exothermic and their combustion provides the required heat to complete the gasification process (Liu et al., 2010). Therefore, gasification is thought of as an exothermic process generally.

The following general chemical equation sums up the reactants and products involved in the gasification process using air (air = 1O<sub>2</sub> + 3.76N<sub>2</sub>):



**Table 2**

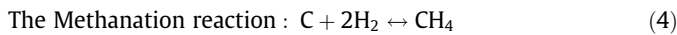
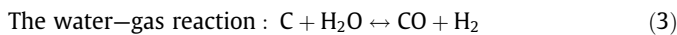
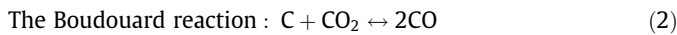
Proximate analysis of the as-received MSW streams reported as percentages by weight (Niessen, 2010; Themelis et al., 2002).

| Category    | Moisture | Volatile organic matter | Fixed organic matter | Ash   |
|-------------|----------|-------------------------|----------------------|-------|
| Paper       | 10.24    | 75.94                   | 8.44                 | 5.38  |
| Plastics    | 2.00     | 95.80                   | 2.00                 | 0.20  |
| Textiles    | 10.00    | 66.00                   | 6.50                 | 17.50 |
| Wood        | 12.00    | 75.05                   | 12.41                | 0.54  |
| Food wastes | 72.00    | 20.26                   | 3.26                 | 4.48  |
| Yard wastes | 62.00    | 26.74                   | 6.32                 | 4.94  |

As Eq. (1) suggests, the feedstock (any organic substances in the MSW) is converted in the presence of air into six primary products. Those products include two energy carriers ( $H_2$  and  $CH_4$ ), pollutants ( $CO$  and  $CO_2$ ), water vapor ( $H_2O$ ), free carbon ( $C$ ) and nitrogen gas ( $N_2$ ). Free carbon represents the fraction of carbon in the feedstock that remains unconverted after the gasification process. This fraction depends on operational conditions and the chemical structure of the feedstock. Nitrogen gas ( $N_2$ ) is abundantly present in air (3.76 times more than oxygen) and is assumed to remain unreacted in this chemical representation. Moreover, nitrogen in the feedstock can either be assumed to be ultimately converted to  $N_2$  (Niessen, 2010) (as presented in this section for simplicity) or it can be assumed to convert to  $NH_3$  or  $HCN$  (Higman and van der Burgt, 2008). Since nitrogen conversion to non- $N_2$  species (i.e.,  $NH_3$  or  $HCN$ ) is usually minute in quantity, empirical relations are used to perform the estimations for these species in Gasify<sup>®</sup> (Higman and van der Burgt, 2008).

The stoichiometric amounts involved in the reaction (Eq. (1)) are symbolized by  $m$ ,  $x_1$ ,  $x_2$ ,  $x_3$ ,  $x_4$ ,  $x_5$ , and  $x_6$ , while  $n$ ,  $x$ ,  $y$  and  $z$  represent the atomic ratios of carbon, hydrogen, oxygen, and nitrogen in the feedstock, respectively (see Table 1 for examples of this presentation). The stoichiometric amounts ( $m$ ,  $x_1$ ,  $x_2$ ,  $x_3$ ,  $x_4$ ,  $x_5$ , and  $x_6$ ) are the seven unknowns in this chemical representation of gasification to be solved for. Reaction temperature and ( $m$ ) are interrelated (the amount of supplied air controls the temperature via its cooling effect). Seven independent equations are needed to solve for the unknowns. Three mass balances for carbon, hydrogen, and oxygen constitute three equations. Three more equations come from chemical equilibrium formulations, and the last one from an overall energy balance.

Gasification is a complex chemical process that is composed of many chemical reactions. Those reactions primarily involve the transformation of the feedstock into an intermediate chemical species followed by a transformation of that intermediate into a final product. For simplicity, three equilibrium reactions are mainly dominant in the gasification process (Higman and van der Burgt, 2008):



The total moles of gaseous products,  $x_{\text{Total}}$ , is defined as:

$$x_{\text{Total}} = x_1 + x_2 + x_3 + x_4 + x_5 + \left(\frac{z}{2} + 3.76m\right) \quad (5)$$

It is needed to convert the equilibrium constants from a partial pressure representation to a molar representation of gaseous species reaction equilibrium (Syed et al., 2012). For the Boudouard reaction, the equilibrium constant ( $K_{\text{Boudouard}}$ ) is as follows (where  $P$  represents the normalized partial pressure and  $x$  represents number of moles):

$$K_{\text{Boudouard}} = \frac{P_2^2}{P_3} = \frac{x_2^2/x_{\text{Total}}^2}{x_3/x_{\text{Total}}} = \frac{x_2^2}{x_3 x_{\text{Total}}} \quad (6)$$

$P_{\text{Total}}$  is the total pressure in the system which can be assumed to be 1 atm (Gonzalo-Tirado et al., 2012). The chemical equilibrium Eqs. (2) and (3) (Boudouard and water gas reactions) can be combined to give the CO shift reaction (Higman and van der Burgt, 2008) with its respective chemical equilibrium constant ( $K_{\text{CO Shift}}$ ):



$$K_{\text{CO Shift}} = \frac{x_5 x_1}{x_2 x_4} \quad (8)$$

Finally, the methanation reactions (Eq. (4)) will give another equilibrium constant equation ( $K_{\text{Methanation}}$ ) (Zainal et al., 2001; Jarungthammachote and Dutta, 2007):

$$K_{\text{Methanation}} = \frac{x_5 x_{\text{Total}}}{x_1^2} \quad (9)$$

The equilibrium constants ( $K_{\text{Boudouard}}$ ,  $K_{\text{CO Shift}}$ ,  $K_{\text{Methanation}}$ ) can be calculated using the following equation (Ebbing and Gammon, 2009) for any equilibrium constant ( $i$ ):

$$K_i = e^{-\frac{\Delta G^0}{RT}} \quad (10)$$

where  $R$  is the universal gas constant and  $T$  is the reaction temperature. The  $\Delta G^0$  term in Eq. (10) is the standard free energy of formation, tabulated in various references (Ebbing and Gammon, 2009). Those tabulated values are usually listed at standard temperature and pressure (25 °C and 1 atm) and must be corrected for the gasification temperature.

Energy conservation in chemical reactions can be represented by the conservation of enthalpy. Namely, the enthalpy of the reactants is equivalent to the enthalpy of products. Based on this simple concept, an energy balance can be utilized to derive the seventh equation required for the calculation of the gasification molar concentrations. Starting with a general enthalpy balance equation, the overall gasification equation (Eq. (1)) is utilized to expand the equation for this specific case of gasification as follows:

$$\sum cH_{f,\text{reactants}}^0 = \sum dH_{f,\text{products}}^0 + \Delta H_T^0 \quad (11)$$

where  $c$  and  $d$  are the number of moles,  $H_f^0$  is the enthalpy of formation of the products or reactants, and  $\Delta H_T^0$  is the change in the enthalpy due to change in temperature. The  $\Delta H_T^0$  change in enthalpy is a function of the heat capacity ( $C_p$ ) along with the change in temperature ( $\Delta T$ ) (Melgar et al., 2007). Incorporating these, and Eq. (1) into Eq. (11) yields:

$$\begin{aligned} H_{\text{feedstock}}^0 + mH_{O_2}^0 + 3.76mH_{N_2}^0 = & x_1(H_{H_2}^0 + C_{p,H_2}\Delta T) + x_2(H_{CO}^0 \\ & + C_{p,CO}\Delta T) + x_3(H_{CO_2}^0 \\ & + C_{p,CO_2}\Delta T) + x_4(H_{H_2O}^0 \\ & + C_{p,H_2O}\Delta T) + x_5(H_{CH_4}^0 \\ & + H_{p,CH_4}\Delta T) + x_6(H_C^0 \\ & + C_{p,C}\Delta T) \\ & + \left(\frac{z}{2} + 3.76m\right)(H_{N_2}^0 \\ & + C_{p,N_2}\Delta T) \end{aligned} \quad (12)$$



One thing to note in Eq. (12), is that the heat released is assumed to be zero ( $Q = 0$  kJ/mol), meaning the reactor is adiabatic. Hence, the gasifier temperature will depend on the heat released during the reaction, which will be totally consumed internally in causing the reactor temperature to change. This issue will be visited later. The enthalpy of the feedstock ( $H_{\text{feedstock}}^0$ ) is a function of the higher heating value (HHV) and the composition of the feedstock, and can be calculated by (Syed et al., 2012):

$$H_{\text{feedstock}}^0 \text{ (kJ mol)} = \text{HHV} - \frac{x}{2} 285,830 - 393,546 \quad (13)$$

where  $x$  is the number of hydrogen atoms in the feedstock. There are two ways of presenting the heating value (the amount of heat released as a result of combustion or gasification) of a substance. One is the higher heating value (HHV) and the other is the lower heating value (LHV). The choice of HHV or LHV depends on what happens to the produced steam. Condensing the steam leads to a greater release of energy and a larger heating value termed the HHV. If the steam is not condensed, then the heating value does not account for the extra energy released from steam condensation and the heating value is reported as the LHV. HHV is estimated by (Syed et al., 2012):

$$\text{HHV (MJ kg)} = (0.3491 * \%C) + (1.1783 * \%H) - (0.1043 * \%O) \quad (14)$$

where %C, %H, and %O are the mass percentages of carbon, hydrogen, and oxygen in the waste stream, respectively. The LHV can be calculated from the HHV using the following relationship (Davis and Cornwell, 2008):

$$\text{LHV} = \text{HHV} - [(\Delta H_{v,\text{H}_2\text{O}})(9\%H)] \quad (15)$$

where  $\Delta H_{v,\text{H}_2\text{O}}$  is the heat of vaporization of water, approximately 2420 kJ/kg, and %H is the mass percentage of hydrogen in the organic compound. The choice of HHV or LHV for the evaluation of gasification depends on plant operations and suggested energy cycle. Eqs. (14) and (15) were also used to estimate the thermal energy potential from incinerating each waste stream. Finally, the heat capacity values inputted in Eq. (12) can be calculated as a function of temperature ( $T$ ) using an empirical formula in Turns (2011).

In this simplistic presentation, there are now seven equations; three mass balances, three chemical equilibrium constants (Eqs. (6), (8), and (9)), one energy balance (Eq. (12)) and seven unknowns to solve for ( $m$ ,  $x_1$ ,  $x_2$ ,  $x_3$ ,  $x_4$ ,  $x_5$ ,  $x_6$ ). These equations can be solved for each of the six gasifiable MSW categories considered here and solved for the seven unknowns at different temperatures, which the basis of calculation in the Gasify<sup>®</sup> software.

Process control is key to gasification with two parameters to be controlled: air flow and temperature. Those parameters dictate the quantities of each product from gasification and are interrelated. The heat required to drive the gasification process actually comes from the process itself. As the feedstock combusts and initial products are formed, heat is also released. This heat drives the gasification process further and since gasification depends on the air supply, temperature can also be controlled by controlling the air flow into the gasifier (Higman and van der Burgt, 2008). Since the gasifier was assumed to be adiabatic in the above presentation, the gasifier temperature will depend on air flow rate. The heat released during the reaction will be totally consumed internally, directly affecting the temperature of the gasifier contents. On the other hand, in order for the solver software (Gasify<sup>®</sup>) to calculate the gasifier output composition, the user must input the gasifier temperature. Therefore, an iterative solution process will start by fixing  $m$  and assuming a value for the unknown temperature ( $T$ ). The solution is then iterated (as summarized in Fig. 2) until a  $T$  value that corresponds to  $m$  converges. The air flow was chosen in

the range which led to a temperature range from 600 to 1800 °C. This temperature range was reported in Liu et al. (2010) to be the most ubiquitous.

## 4. Results and discussion

In the following discussion, incineration is first discussed as a baseline scenario for MSW, against which gasification is later bench-marked. To illustrate the sensitivity of both processes, and our analysis, to MSW composition, analyses were conducted and compared for MSW having a published composition for UAE, USA and Thailand (a spectrum of three regions with varying socio-economic profiles). This also helped generalize our findings. The MSW composition in the three mentioned countries is shown in Table 3 (Dumble, 2010; USEPA, 2010; Thamavithyaa and Duttab, 2008).

### 4.1. MSW incineration

The HHV and LHV values of the six MSW categories considered were first calculated (Table 4). The values presented in Table 4 are theoretical maximum energy values. The actual net energy that can be obtained from incineration depends on the energy usage (heat or electricity) and the efficiency of the employed energy cycles. Conventional incinerators solely producing electricity have a lumped efficiency of around 22% (AZN, 2012), which also takes into account the energy consumed in the incineration process itself. Using 22% as the efficiency value, the efficiency adjusted LHV energy values are also presented in Table 4 to reflect electricity production projection from an incineration plant for each MSW stream. It can be noticed from Table 4 that different MSW streams have different heating values. Plastic and textile have the highest heating values, while yard waste has the lowest.

An advantage of incineration is its applicability to all the considered waste streams (except metal and glass). In such a case, incineration might be applied as a treatment of MSW as a bulk and not as separate component streams. This will make the energy

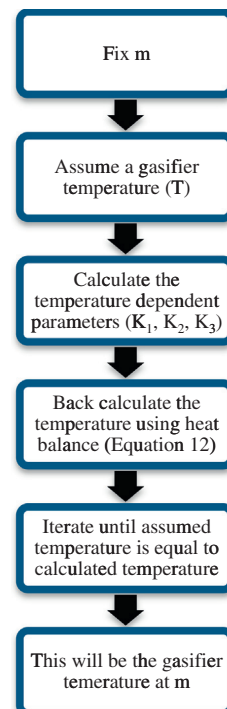


Fig. 2. Iterative solution procedure for the calculation of the gasification temperature.

**Table 3**  
MSW composition from three countries (as fraction of 1 kg of MSW).

| Component  | UAE <sup>a</sup> | USA <sup>b</sup> | Thailand <sup>c</sup> |
|------------|------------------|------------------|-----------------------|
| Paper      | 0.22             | 0.34             | 0.23                  |
| Plastics   | 0.14             | 0.15             | 0.05                  |
| Textiles   | 0.03             | 0.10             | 0.02                  |
| Wood       | 0.17             | 0.08             | 0.01                  |
| Food waste | 0.22             | 0.17             | 0.56                  |
| Yard waste | 0.22             | 0.16             | 0.13                  |

<sup>a</sup> Dumble (2010).

<sup>b</sup> USEPA (2010).

<sup>c</sup> Thamavithyaa and Duttab (2008).

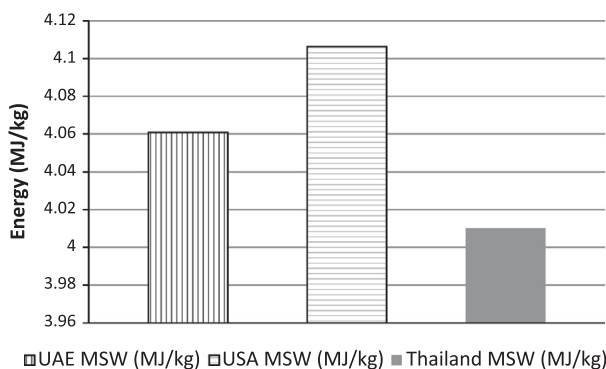
**Table 4**  
HHV and LHV values and potential electrical energy output from incineration of MSW components.

| MSW category | HHV (MJ/kmol) | LHV (MJ/kmol) | Efficiency-adjusted electric energy output by incineration (MJ/kmol) |
|--------------|---------------|---------------|--|
| Paper        | 1634.6        | 1515.4        | 333.4  |
| Plastics     | 2434.7        | 2293.5        | 504.6  |
| Textiles     | 2315.4        | 2175.1        | 478.5  |
| Wood         | 1975.6        | 1843.5        | 405.6  |
| Food wastes  | 1703.7        | 1586.1        | 348.9  |
| Yard wastes  | 1488.6        | 1341.7        | 295.2  |

potential of incineration sensitive to the composition of the MSW (make up from individual streams) as can be seen in Fig. 3. The variation in the amount of energy produced per kg of mixed MSW, observed in Fig. 3, is due to the difference in MSW composition in the three countries, as shown in Table 3. The latter shows a general decrease in organic waste (food waste and yard waste), as the country's level of development increases (Dumble, 2010; USEPA, 2010; Thamavithyaa and Duttab, 2008). From Table 3, it can be seen that the generation of plastics and textiles (wastes with high LHV values) is highest in the USA while the generation of food and yard wastes (wastes with low LHV values) is the lowest. The opposite is true for Thailand, and UAE is somewhere in between. It is interesting to see, however, that the variations in efficiency-adjusted energy for MSW from the three countries (Fig. 10, discussed later) are only within 2.5% of each other. This is due to the fact that other MSW components, having their own heating values, also vary among these countries, dampening the overall effect on total energy produced.

#### 4.2. MSW gasification products

As detailed above, gasify<sup>®</sup> was used to numerically solve for gasification products for the six MSW categories (food waste, yard

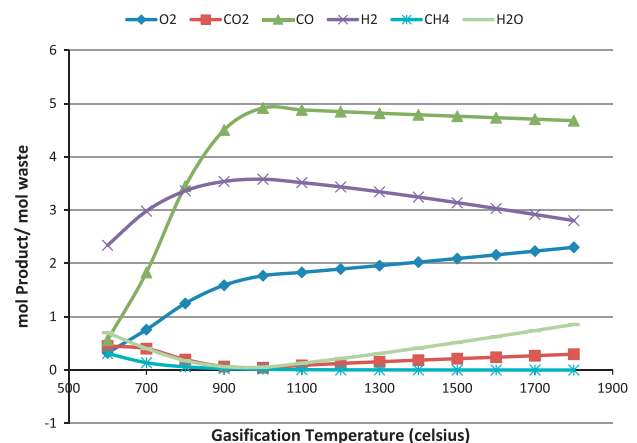


**Fig. 3.** Efficiency adjusted energy from the incineration of 1 kg of MSW in the UAE, USA, and Thailand.

waste, paper, textiles, wood, plastic). The temperature range modeled was from 800 to 1800 °C. The gasifier pressure was assumed to be atmospheric at all times (Gonzalo-Tirado et al., 2012). Generally, an increase in pressure decreases the yield of H<sub>2</sub> and CO while increasing the yield of CO<sub>2</sub> and CH<sub>4</sub>. However, this change in yield is not significant enough (Higman and van der Burgt, 2008), so the effect of pressure was not investigated. The change in temperature term ( $\Delta T$ ) required for the energy balance equation was taken as the difference between the gasification temperature (800–1800 °C) and an MSW feedstock “storage” temperature of 25 °C. This term signifies the difference in the feedstock’s temperature before gasification and while gasification is under way. The assumption of 25 °C was based on the observation that most gasifiers are housed within a facility, where the temperature would not dramatically change across the year.

The solution by Gasify<sup>®</sup> yielded a very close to zero presence of free carbon ( $x_C$ ). The gasifier product results are presented for the gasification of plastic waste, as an example, at different temperatures in Fig. 4. The observable trend is not consistent for all products and shows a strong dependency on temperature. The trend seems to become more consistent as temperature increases; in this case, particularly at temperatures greater than 1000 °C. A valid and consistent observation from the results in Fig. 4 is that, as the temperature increases, combustion becomes more complete. Therefore, the amount of combustibles (H<sub>2</sub>, CH<sub>4</sub>) produced decreases, while the amount of O<sub>2</sub>, H<sub>2</sub>O and CO<sub>2</sub> increases. As H<sub>2</sub> and CH<sub>4</sub> are the main products of interest in gasification, a careful optimization of gasification temperature is needed to prevent their conversion to CO<sub>2</sub> and H<sub>2</sub>O via combustion. Previous experimental studies, conducted on waste tires (Portofino et al., 2013), have also concluded a significant effect of temperature on gasification, with optimal gasification occurring between 800 and 1000 °C. Also, the amount of nitrogen species (N<sub>2</sub>, NH<sub>3</sub>, and HCN) is zero in the case of plastics since plastics do not contain nitrogen. Similarly, these amounts were very close to zero for the other MSW streams. This is because the amount of nitrogen is relatively low in the waste streams to begin with. The results presented so far are for the specific case of plastic waste. Similar trends were also observed for the remaining five MSW categories, although not shown here.

The yield of chemical species as products depends on the three equilibrium reactions discussed in Section 3; the Boudouard reaction (Eq. (2)), the water gas reaction (Eq. (3)) and the methanation reaction (Eq. (4)). Those three reactions are governed by three equilibrium constants ( $K_1$  for the Boudouard reaction,  $K_2$  for the water gas reaction, and  $K_3$  for the methanation reaction), which are functions of temperature. A quick analysis of their evolution



**Fig. 4.** Molar concentration of gasification products for plastic waste.

as temperature changes shows that  $K_1$  decreases while  $K_2$  and  $K_3$  increase as temperature increases. As obvious from the Boudouard, water gas, and methanation reactions, as  $K_1$  decreases, the yield of CO decreases while the yield of  $\text{CO}_2$  increases. As  $K_2$  increases, the yield of  $\text{CO}_2$  and  $\text{H}_2$  increases, and as  $K_3$  increases, the yield of  $\text{CH}_4$  increases. Taken independently, those three equilibrium reactions do not fully explain the trends observed throughout the results of solving the gasification equilibrium model for plastic waste. However, even this simplistic system of three equilibrium equations is not independent and displays an overlap between the reactions' products and reactants. The result is a coupling of chemical equations that cannot be easily interpreted to develop a trend without solving for the product yields. Moreover, the effect of temperature on the reaction rate and equilibrium constants will lead to a change in product concentrations and further complexity when considering the coupled reactions and the temperature corrections. Therefore, the three equations must be considered jointly along with any factors that can influence the yield of products in gasification.

On the other hand, experimental results can be used to verify the trends observed. An experiment conducted for the gasification of bulk MSW were reported in Zhao et al. (2010) and used here as a reference. The results from that experiment were compared to the results obtained from the gasification solver (Gasify<sup>®</sup>) after it was applied to the same bulk MSW composition in Zhao et al. (2010) and under their reported operation conditions. This comparison shows that the model becomes closer to the experimental results as the temperature increases and this can be shown in Fig. 5. An explanation to this behavior is the underlying assumption of complete gasification in the model as seen in Eq. (1). Eq. (1) lacks tars (complex hydrocarbons) which are intermediates to gasification products that persist at lower temperatures. As the temperature of gasification increases, conversion becomes more complete and the persistence of tars less apparent. That means that the assumption of complete gasification becomes more valid. Other experimental results were presented in Thamavithyaa and Duttab (2008), Luo et al. (2010), He et al. (2009a), and Xiao et al. (2007). However, those publications do not fully report the parameters required for the solver and therefore could not be used to verify our model.

If the gasification model was to be applied to MSW as a bulk as opposed to separate streams, clear variations arise due to the different MSW composition (fraction of each stream to the total MSW stream) in different countries. The results of such an application are shown in Fig. 6. The USA MSW resulted in the largest yield of products (combustible gases and pollutants) followed by the UAE then Thailand. Thai MSW generates the highest amount of  $\text{H}_2\text{O}$  because food waste and yard waste tend to have high moisture content. A final observation is that the amount of  $\text{O}_2$  (or air) required for the gasification of USA MSW is highest. This is because of the high conversion due to the higher presence of wastes with higher LHV. Moreover, the results (energy and molar concentration) of gasifying the different waste streams can be combined to study the potential of mixing a few waste streams as an input to the gasification process. If no significant reacting between the different waste streams is assumed, then a simple adding of the gasification outputs of the individual MSW streams can offer an approximate insight into the gasification potential of other waste stream combinations.

#### 4.3. Energy and efficiency analysis

The results of the gasification product analysis presented in Section 4.2 can also be interpreted from an energy efficiency view point. The energy that can be extracted from the gasification of MSW is initially in the form of combustible gases, namely  $\text{H}_2$  and

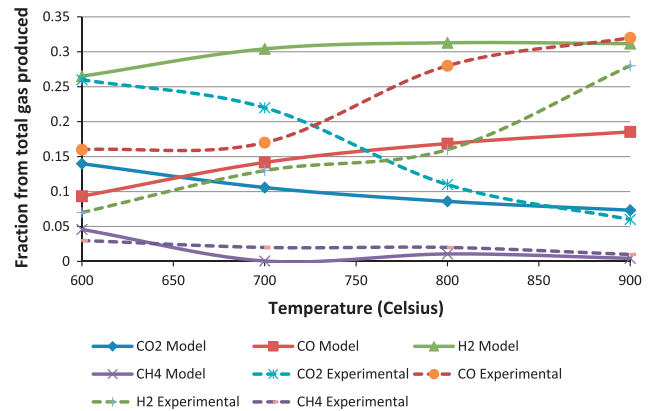


Fig. 5. Comparison between experimental and model gasification results under the conditions reported in Zhao et al. (2010).

$\text{CH}_4$ , which can be combusted for thermal energy production. The total energy output increases as long as the amount of those combustible gases increases. However, the overall energy (combination of all combustible gases) released from plastic and paper wastes increases then decreases as seen in Fig. 7. This signifies an energy advantage with operating at a narrow temperature range that ensures the maximization of the yield of combustible gases. The same applies to Fig. 8, which shows the LHV (from combustion of all combustible products) from the gasification of a UAE, USA, and Thailand MSW mix. One interesting trend to note in Fig. 8 is the significant reduction in energy yield as the amount of food waste and yard waste (wet organics) increases in the MSW, which is the case for Thailand. Also, the optimal temperature for maximum energy production is slightly different for the different country MSW mixes.

It is also interesting to look at the efficiency of conversion from MSW feedstock to final gasification products. This efficiency can be expressed as the cold gas efficiency (CGE), defined as follows (Melgar et al., 2007):

$$\text{CGE} = \frac{\text{Heating Value of Products (J)}}{\text{Heating Value of feedstock (J)}} \quad (16)$$

The heating value could be the lower (LHV) or the higher (HHV) heating value, but the usage of either should be consistent for the products and the feedstock in Eq. (16). The CGE examines the efficiency of converting the feedstock into a different product through normalizing the heating value of the conversion product to the heating value of the feedstock. Through that, CGE examines how

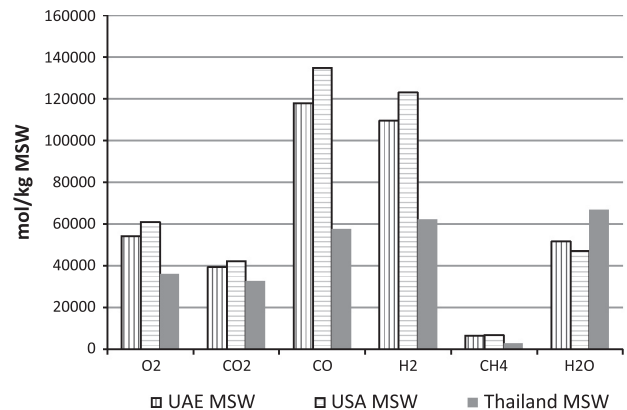


Fig. 6. Major gasification products (in mol product/kg MSW) for bulk MSW generated in the UAE, USA, and Thailand.

much of the heating value of the feedstock has been wasted whilst converting the feedstock into a different product. The results of the CGE analysis for various MSW components are summarized in Fig. 9. From Fig. 9, it can be seen that the most efficient energy conversion from MSW feedstock to product is possible for plastic waste. The primary reason is that plastic waste has the highest conversion to combustible gases and therefore the highest LHV. The least efficient MSW feedstock turns out to be food waste which has a low conversion rate and ultimately the lowest LHV.

Another important consideration when assessing the efficiency of gasification pertains to the efficiency of the end use of the gasification products. If the gasification products are combusted to generate electricity then the efficiency is related to the energy cycle used. A steam cycle energy recovery system will have an efficiency of around 23%; an ignition engine will have an efficiency of over 25%; while a gas turbine will have efficiency around 40% (Belgiorno et al., 2003). A gas turbine does not require pretreatment of the gaseous products and the reported efficiency of that cycle does not consider pretreatment. On the other hand, the mentioned efficiencies of the ignition engine and steam cycle are lowered to account for the required pretreatment of the gaseous products before they can be employed in those energy cycles (Belgiorno et al., 2003). Again, those efficiency values consider the energy consumed in the gasification process and; therefore, a separate analysis into the energy consumed by the process is unnecessary.

Finally, the energy that results from the gasification of 1 kg of bulk MSW is presented in Fig. 10 for UAE, USA, and Thailand. Taking electrical efficiency as the evaluation criteria, the results in Fig. 10 have been adjusted to reflect the real and usable energy output as mentioned above. The net electrical efficiency from a gasification pathway is assumed to be around 20% (Arena, 2012). Fig. 10 shows that gasification produces the highest energy when applied to bulk MSW generated in the USA. This is because USA's MSW has the highest fraction of plastics (waste stream with highest yield of combustible gases) and lowest fraction of food and yard wastes (waste streams with lowest yield of combustible gases). The USA is followed by UAE and finally Thailand, the country with the highest generation of food waste and yard waste, component with the lowest CGE. Another interesting observation is that, while country-to-country energy variations were small for incineration (Fig. 3), the differences are much more significant for gasification (Fig. 10).

4.4. Alternative gasification processes

One point worth making here is the physical significance of the model presented above. When solving the model for a given waste

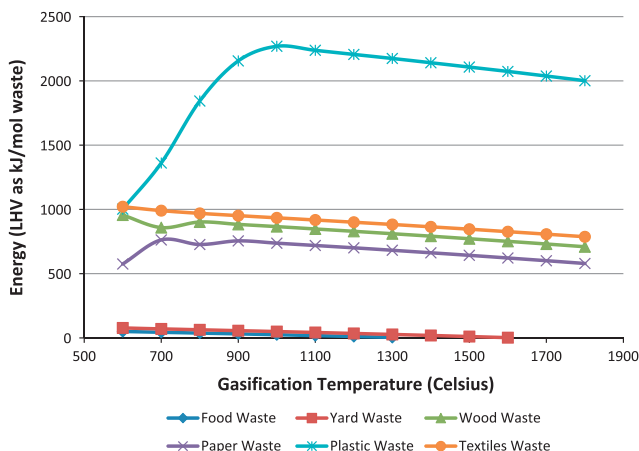


Fig. 7. Lower heating value (LHV) from combusting the products of waste gasification of different MSW streams.

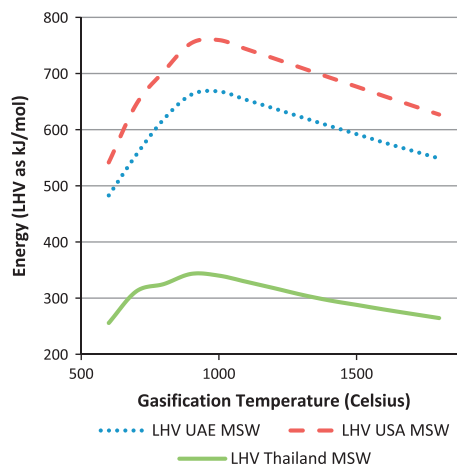


Fig. 8. Lower heating value (LHV) from combusting the products of waste gasification of MSW from UAE, USA, and Thailand.

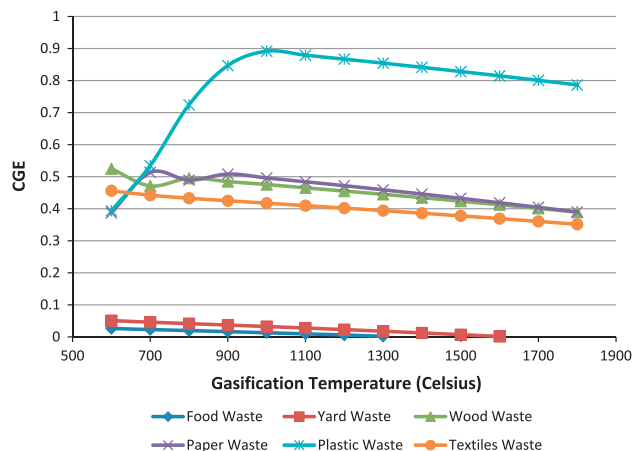


Fig. 9. Cold gas efficiency (CGE) of the six gasifiable streams in MSW.

composition and gasification temperature, the flow of air was kept constant while temperature was varied through changing the stoichiometric ratio. This approach can also be substituted by solving for the air flow rate and holding the gasification temperature constant. In this alternative approach, the air flow will vary for different temperatures and stoichiometric ratios of gasification products. Those two approaches represent the two different methods for controlling the gasification process in real gasifiers; either

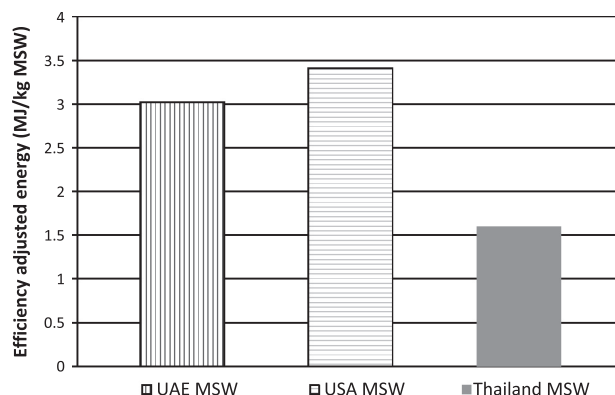


Fig. 10. Efficiency adjusted energy from the gasification of 1 kg of MSW in the UAE, USA, and Thailand.



the amount of air flowing into the gasifier is varied to fix the temperature or the temperature within the gasifier is allowed to vary.

In addition, the underlying assumption in the model in Section 3 is that air is the source of oxygen for oxidation, while actually oxygen is the required species for gasification. Therefore, an alternative would be to pump pure oxygen into the gasifier instead of air, which will reduce the pumping requirements and almost double the energy obtained from the gasification products (Saft, 2007). However, the separation of oxygen from air requires more energy than the savings achieved in the pumping requirements from such substitution which makes the use of pure oxygen useless in most cases. As for the overall efficiency of the gasification process in general, as the oxygen increases in the intake, the feedstock-to-gas conversion efficiency increases and the ratio of O<sub>2</sub> to syngas decreases (Higman and van der Burgt, 2008). This signifies an increase in performance efficiency with increasing the oxygen purity of the intake.

A third alteration would be to introduce steam into the gasifier intake as a temperature moderator in addition to air or oxygen. In general, superheated steam within a temperature range of 300–400 °C is used to avoid condensation of the steam in the gasifier. An intrinsic advantage of using steam is that it further increases the amount of H<sub>2</sub> gas produced while reducing the amount of CO produced (Belgiorno et al., 2003; He et al., 2009b; Wu and Williams, 2010). However, superheated steam is a valuable resource in other uses (electricity generation, potable water production, etc.) and its use in gasification must be weighed against its alternative uses.

#### 4.5. Gasification versus incineration

As discussed earlier, gasification has distinct advantages over incineration. It produces a multi-use product, operates at lower temperatures, is generally more efficient than incineration and volatilizes less pollutants than when waste is incinerated (Arena, 2012). However, the energy potential from MSW incineration can be higher than that from gasification, as can be seen by comparing Figs. 3 and 10. This means that, energy-wise, incineration produces more energy. To use the products of gasification for electricity generation, the flue gas must be pretreated first and that consumes energy and resources leading to a drop in the efficiency of gasification. Therefore, currently and from an energy perspective, incineration surpasses gasification. However, gasification still has the advantage of producing a multi-use product (H<sub>2</sub> and CH<sub>4</sub>) and when pretreatment is not considered, its efficiency is sometimes higher than that of incineration. Overall, it is highly recommended to evaluate the optimal waste to energy technology on a case by case basis due to the multitude of considerations that should be evaluated.

Cost is another important consideration in the evaluation of waste-to-energy technologies. The total cost of incineration is estimated at \$115,000 per ton of waste per day (Klein and Themelis, 2003), which includes the entire capital cost amortized on the basis of plant capacity (tons/day). On the other hand, the cost of gasification was estimated to be between \$86,000 and \$97,000 per ton of waste per day, which makes it a cheaper treatment option than incineration (Klein and Themelis, 2003).

## 5. Conclusions

In this work, we modeled gasification as an alternative process to incineration for energy recovery from MSW. Both processes were modeled for bulk MSW as well as segregated MSW streams. Our model was tested using experimental gasification data from the literature and was found to reasonably match the trends of that

data. We showed that different MSW streams have different heating values, with plastic and textile wastes having both highest heating values and conversion rate, while yard waste having the least. Consequently, the amount of energy produced per kg of mixed MSW, via either process (incineration or gasification), was shown to depend on the relative composition of the MSW. In more affluent countries, with smaller fractions of food and yard wastes and higher fractions of plastic and textile in the MSW, higher energy can be recovered from the waste. On the other hand, developing countries can expect to generate more of the undesired water during gasification, thanks to food yard wastes with higher moisture content.

The gasification products were also shown to be strong functions of temperature. As the gasification temperature increases, combustion becomes more complete. Therefore, the amount of combustibles (H<sub>2</sub>, CH<sub>4</sub>) produced by gasification decreases, while the amount of O<sub>2</sub>, H<sub>2</sub>O and CO<sub>2</sub> increases. The yield of these different chemical species in the gasification reaction was shown to be the outcome of three inter-linked equilibrium chemical reactions; the Boudouard reaction, the water gas reaction, and the methanation reaction. Our results show that an energy advantage can be achieved by operating at a narrow temperature range, which ensures the maximization of the yield of combustible gases.

Overall, our results show that incineration of a given MSW mixture will produce more energy than gasification. To use the products of gasification for electricity generation, the gasification product gas must be pretreated first, leading to a drop in efficiency. However, gasification still has the advantage of producing a multi-use product (H<sub>2</sub> and CH<sub>4</sub>) and when pretreatment is not considered, its efficiency is sometimes higher than that of incineration.

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