

Validation of the Plasma Resource Recovery System (PRRS) Simulations

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ABSTRACT

The Plasma Resource Recovery System (PRRS) converts waste into electrical energy, metal, and vitreous slag in two stages. Unsorted waste is fed into a graphite arc reactor. The organic portion is gasified to synthesis gas (syngas) while the inorganic portion melts and is tapped separately as metal ingots and vitrified slag, which could be usable as construction material.

The syngas, generated from the reactor, is polished using an air plasma torch removing long chain hydrocarbons and tars, and then cleaned of particulates, heavy metals and acid gases. The clean syngas (typical composition of 24% CO, 6% CO₂, 15% H₂ and balance N₂) can be fed into an internal combustion engine to produce energy.

PyroGenesis Canada Inc. (PGC) operates a PRRS prototype facility in Montreal, Canada. PGC is currently scaling-up the system to treat 10.5 metric tonnes per day (TPD) of Municipal Solid Waste (MSW), Hazardous Waste and Biomedical Waste for an application in the United States. Towards this scale-up, a computer process simulation model was developed to establish a basis for the mass and energy balance. Simulation results were validated on the prototype installation.

Process simulation results indicate that, for 0.12 kg/s (10.5 metric tonnes per day, TPD) of MSW fed, 0.22 Standard Cubic Meter per Second (465.7 Standard Cubic Feed per Minute, scfm) of dry syngas would be produced. The results show that a 15% increase in the moisture content from 30 to 45% would result in a 3.5% reduction in the heating value of the dry syngas, and a 10% increase in the inorganic content from 20 to 30% would result in a 1.8% reduction in the heating value of the dry syngas.

The prototype and the simulation model results, as well as the scale-up system, are discussed in this paper.

INTRODUCTION

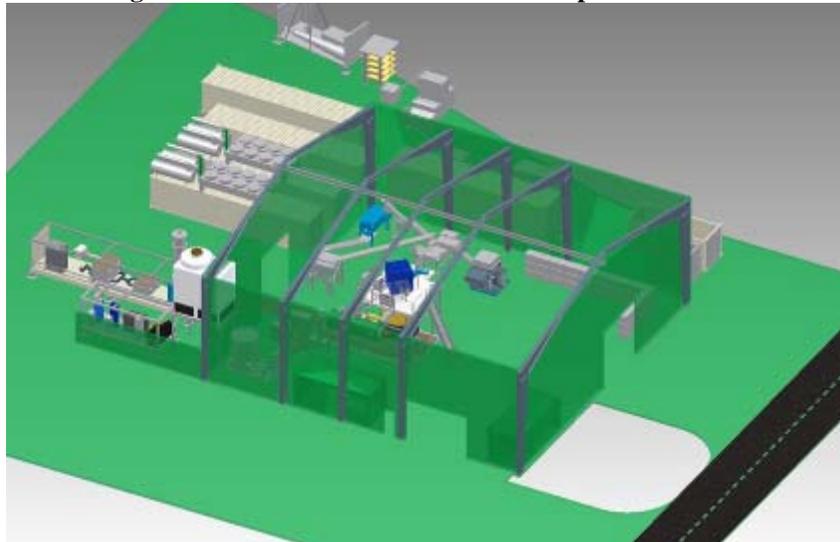
Energy recovery from Municipal Solid Waste (MSW) has gained a huge momentum over the past twenty years. Using thermal plasma technology to recover energy from the waste and convert hazardous waste into inert usable materials has become prominent over the past decade¹. Due to the advantages of the thermal plasma technology, such as high energy densities, high temperatures, and high heat transfer rates, it has become a viable option of waste treatment^{1, 2 and 3}. Over the past decade, many commercial systems using thermal plasma technology have been successful commissioned and are being operated^{1, and 4}.

PyroGenesis Canada Inc., (PGC) has developed and patented a two-stage plasma gasification and vitrification system, the 'Plasma Resource Recovery System (PRRS), to treat unsorted MSW, Hazardous Waste and Biomedical Waste. PGC has a 0.5 to 2 TPD prototype PRRS at its Montreal facility and is currently scaling-up the PRRS to a 10.5 TPD transportable (i.e., skid mounted on standard ISO containers) system for an application in the United States. Figure 1 and Figure 2 show pictures of the PRRS prototype facility and a 3D model of the 10.5 TPD transportable PRRS, respectively.

Figure 1 PRRS Prototype Facility



Figure 2 3D Model of the 10.5 TPD Transportable PRRS



Towards this scale up, a computer simulation model was developed to establish the mass and energy balance of the production system and the key simulation predictions were validated using test results from the PRRS prototype system.

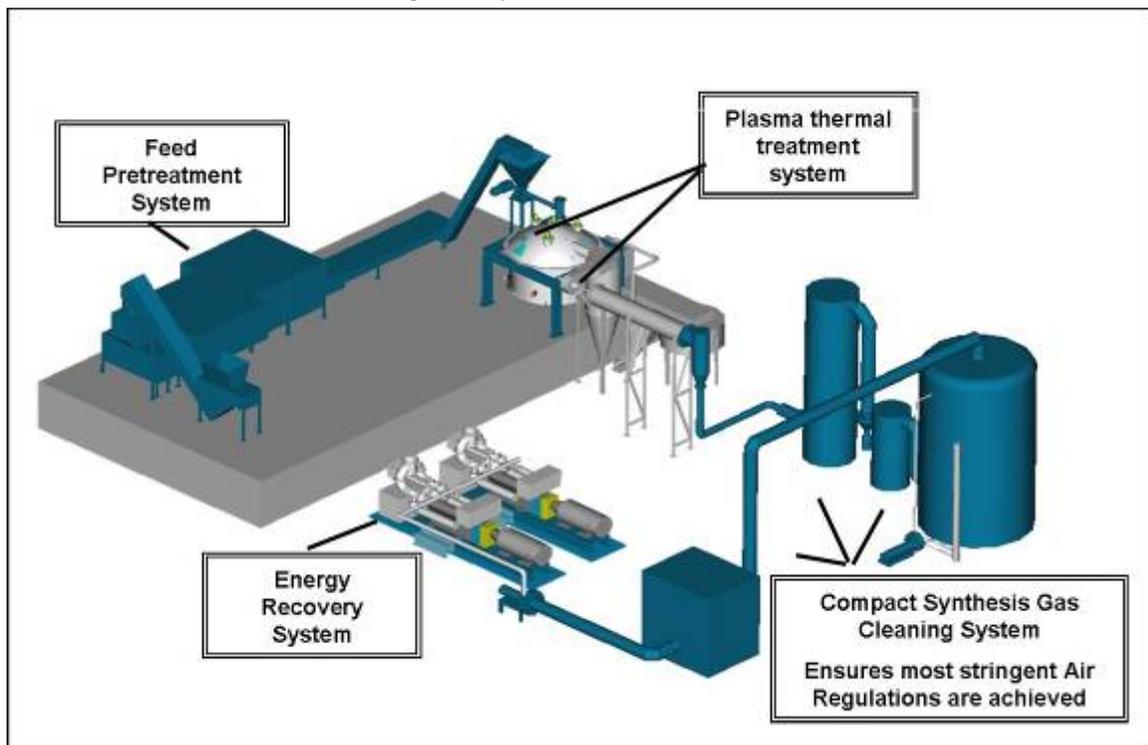
DESCRIPTION OF THE PROCESS

PGC's two-stage gasification and vitrification process uses thermal plasma technology to convert the organic fraction of waste into a clean fuel and the inorganic fraction into a stable and inert slag. The clean gaseous fuel (or synthesis gas) is used for the production of electricity and the inert slag (glass) can be used for construction applications or converted into other added value products, like decorative molded floor or counter tops.

This novel process consists of four main sub-systems (Figure 3):

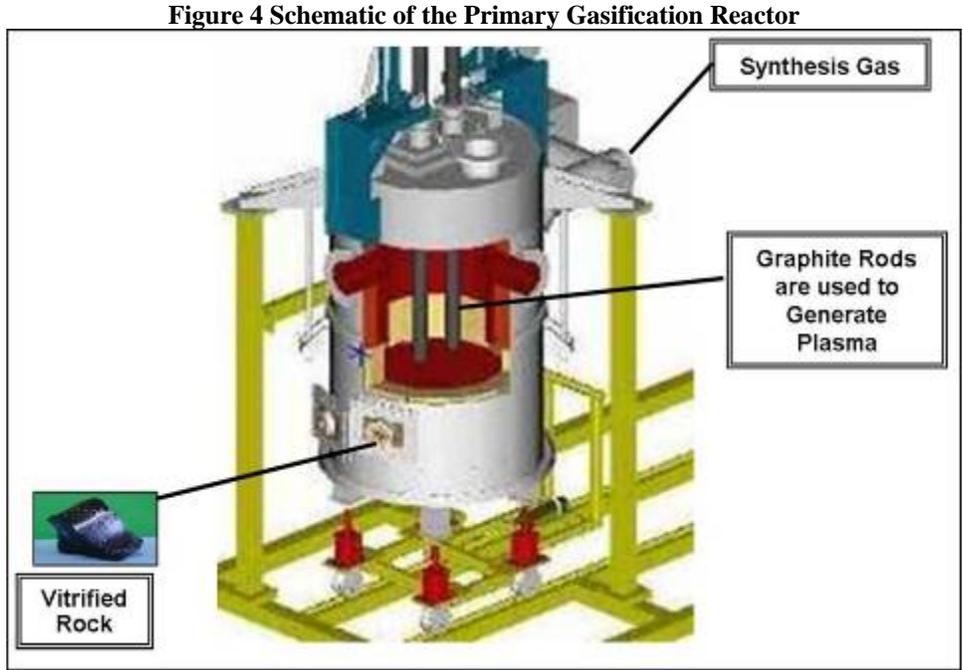
- Waste preparation and feeding system
- Plasma thermal treatment system
- Synthesis gas cleaning system
- Energy Recovery system

Figure 3 System Overview



Unsorted MSW is first fed to a shredder, where it is reduced into small pieces, roughly 2" in length. The shredded waste is then fed continuously to the primary gasification reactor through an airlock. Figure 4 shows a schematic representation of the primary gasification reactor. In the patented primary gasification plasma reactor, that has a design similar to a DC electric arc reactor, the organic fraction of the waste is converted into a useable fuel.

The inorganic portion of the waste (metals, glass, ash, etc.) melts in the plasma reactor and is recovered periodically as a molten metal phase and a molten inert slag (glass) phase. Plasma arcs are generated in the reactor using graphite electrodes. The temperature of the molten pool in the reactor is maintained above 1550°C.



The molten metal is recovered periodically and cooled as ingots for recycling. The molten slag is also removed periodically and either granulated, when collected in water, or casted in moulds, depending on the required end use of the vitrified slag. This slag, shown in Figure 5, is a highly stable material which can be used for construction or other commercial uses. In a previous study^{5 and 6}, the leaching rate of elements from the slag has been shown to be several orders of magnitude below the US EPA regulations⁷.

Figure 5 Vitrified Slag



The gasified organic portion of the waste exits the primary gasification plasma reactor as a dirty synthesis gas, composed primarily of CO and H₂, but also containing a certain amount of carbon soot, acid gases, moisture, partially decomposed hydrocarbons,

particulate matter and trace metals. The dirty synthesis gas is then fed through a secondary gasifier, fired by a plasma torch, where a 5000°C plasma plume breaks apart any complex hydrocarbons using a combination of heat and chemical energy. This polishing step ensures that all complex organic molecules and soot particles are converted into CO and H₂.

The synthesis gas exiting the secondary gasifier is immediately quenched with water from 1100°C to less than 100°C, in less than half a second. This quenching process freezes the thermodynamic equilibrium of the hot syngas, and avoids the reformation of dioxins, furans or other complex molecules.

The synthesis gas is then cleaned in multiple stages, to make it a suitable fuel for an internal combustion engine. The synthesis gas cleaning system allows for the removal of contaminants such as any acidic HCl, dust particles, sulfur and volatile heavy metals.

The whole PRRS is kept under negative pressure using an induced draft (ID) fan.

The clean synthesis gas can be fed to an internal combustion syngas engine for the production of electricity (planned for the 10.5 TPD production facility). Since the synthesis gas is cleaned before it is used as a fuel in the engine, there are no precursors to the formation of secondary pollutants such as dioxins and furans, and clean emissions will be ensured.

APPROACH

For a 10.5 TPD commercial PRRS system, a complete computer process simulation model with as many as 100 process streams was developed. An average MSW composition, as provided by the client and detailed using references from literature^{8 and 9} was used as an input for the model. A complete process flow diagram establishing the basis for the mass and energy balance was developed. All the process utility requirements such as compressed air, compressed nitrogen, cooling water and fresh water required for the production plant were calculated using this model.

To validate the model, critical key results were compared with the PRRS prototype unit. Tests were conducted with surrogate MSW in the 0.5-2 TPD prototype system at PGC's Montreal facility. Except for the energy recovery system, all other unit operations are similar to the developed model.

Overall mass balance and the composition of the syngas predicted by the model were compared with results from the pilot tests. The flow of the syngas was measured using a standard pitot tube and the composition of the syngas was measured using 'Infrared/Paramagnetic Multi Component Analyzer, Digital 600 NDIR/O₂. The gas analyzer was hooked up directly on the pilot system and gave online digital measurements of the syngas. Point gas samples were also analyzed using a Burrell Gas Analysis Apparatus.

Using the validated computer model, a sensitivity analysis of the process was performed. The impact of variation in the feed MSW composition on the composition and heating value of the syngas produced was studied using the model. Variation in two important

feed parameters such as the moisture content and the inorganic content of the feed were also studied.

RESULTS AND DISCUSSION

Simulation of the process

The computer model developed was based on the Gibbs free energy minimization principles at the reactor operating conditions. The model was used to estimate the energy and utility requirements for each of the unit operations and compositions of the process stream after each unit operation.

The model predicts that for a targeted feed rate of 0.12 kg/s (10.5 TPD) of MSW, 0.22 Sm³/s (465.7 scfm) of dry syngas will be produced. Table 1 below gives the predicted composition of the syngas and its heating value available after the syngas cleaning system to convert it into electricity.

Table 1 Predicted Syngas Composition (dry volume %) and Heating Value

CO (%)	H ₂ (%)	CO ₂ (%)	N ₂ (% by balance)	HHV (MJ/dry Nm ³)
22.2	19.4	6.7	51.7	5.3

Model Validation with Pilot Studies

To validate the model, pilot tests with surrogate MSW were conducted. Critical parameters such as: the overall mass balance of the system and the composition of the syngas after the syngas cleaning system were compared.

Gasification - Synthesis Gas production and Composition

Volumetric flow rate of the dry syngas produced was chosen as the parameter to compare to in order validate the model. Table 2 gives the comparison of the pilot results versus the model prediction. As shown in the table, for a 30 ± 2 kg/hr of MSW feed rate, 0.017 ± 0.003 sm³/s (37 ± 7 scfm) of dry syngas was measured. That is, for every kg of MSW fed, 2.12 ± 0.2 sm³ (75 ± 12 Standard Cubic Feet, scf) of dry syngas was produced. This number compares well to the model prediction of 1.81 sm³ (64 scf) of dry syngas produced for every kg of MSW fed.

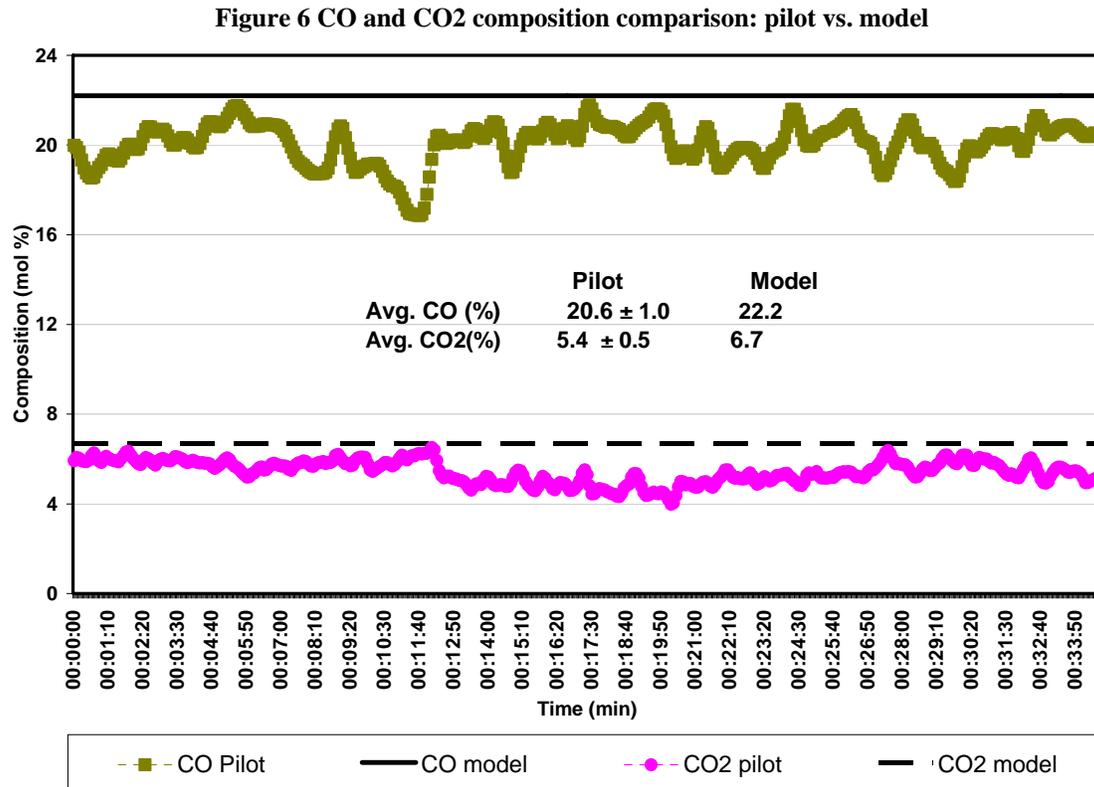
Table 2 Mass balance comparison of pilot results vs. model prediction

Parameter	Pilot	Model
Feed rate, kg/hr	30 ± 2	437.5
Dry syngas produced, sm ³ /s(scfm)	0.017 ± 0.003 (37 ± 7)	0.22 (465.7)
Ratio, sm ³ /kg (scf/ kg)	2.12 ± 0.2 (75 ± 12)	1.81 (64)

The dry composition of the syngas, particularly the CO and CO₂ concentrations were measured after the syngas cleaning system during the pilot tests. These compositions were compared to the values predicted by the model. A reliable H₂ measurement was not available during this study and as such was not included in the comparison. Point analysis

of the gas using Burrell gas analysis apparatus agreed well with the online gas composition measured by the digital gas analyzer.

Figure 6 shows the comparison of the CO and CO₂ composition measured during the pilot studies over a 30 minutes operation. The comparison indicates that the dry compositions of CO and CO₂ measured were stable and match closely the values predicted by the model. The model predicts slightly (~1%) higher values than the measured values. This difference is mainly attributed to the slight variation in the MSW surrogate composition used in the pilot testing vs. the model and the measuring accuracy of the CO/CO₂ analyzer.



Sensitivity Analysis

To further understand the model predictions and to develop an operating window for the production system, a sensitivity analysis of the model was conducted. Variations in two feed parameters were studied: the moisture content and the inorganic content of the MSW feed composition.

Effect of Feed Moisture Content on syngas quality

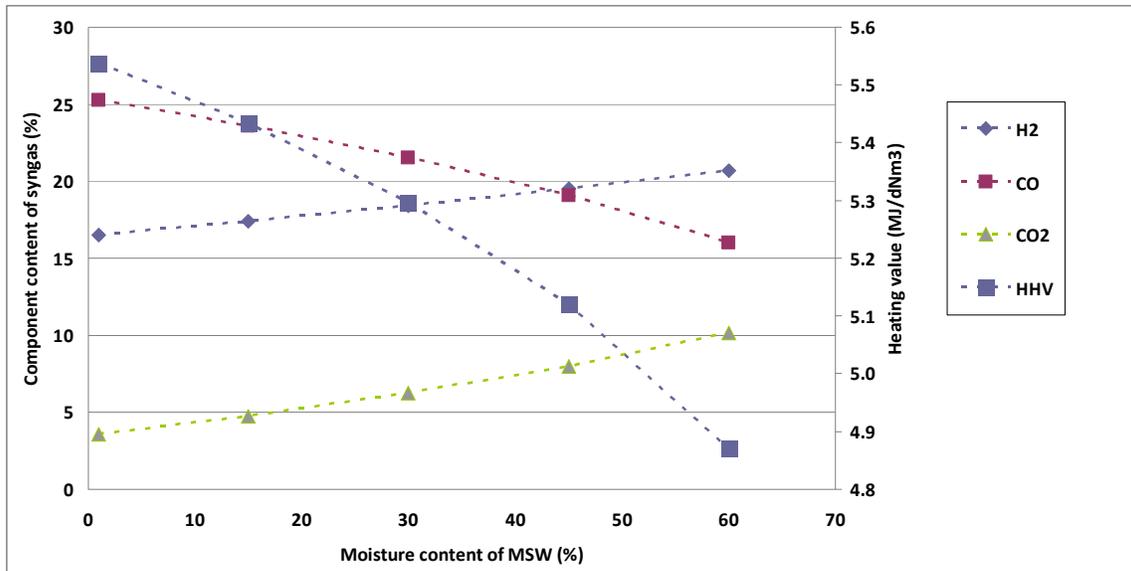
Since the moisture content of the unsorted MSW can vary significantly from day to day depending on the source of the waste, understanding its effect is critical for the successful operation of the system.

Figure 7 demonstrates the effect of varying the MSW feed moisture content on the composition and on the heating value of the syngas produced. In Figure 7, the x-axis

represents feed moisture content, the primary y-axis shows the composition and the secondary y-axis represents the heating value of the syngas per dry normal cubic meter of syngas produced.

As shown in Figure 7, the model predicts that when the moisture content of the MSW increases, the % H₂ content is expected to increase, whereas as the % CO content will be reduced because of the water gas shift reaction^{9 and 10}. However, the predicted produced amounts of H₂ and CO will be reduced. Increased moisture content in the feed means reduced gasifiable organic content. Also, as the moisture content increases, the heating value of the syngas also will be reduced as expected. The sensitivity analysis shows that, a 15% increase in the moisture content from 30 to 45% would result in a 3.5% reduction in the heating value of the dry syngas.

Figure 7 Effect of Variation in Moisture Content in MSW on Composition and Heating Value of Syngas



Effect of Feed Inorganic Content

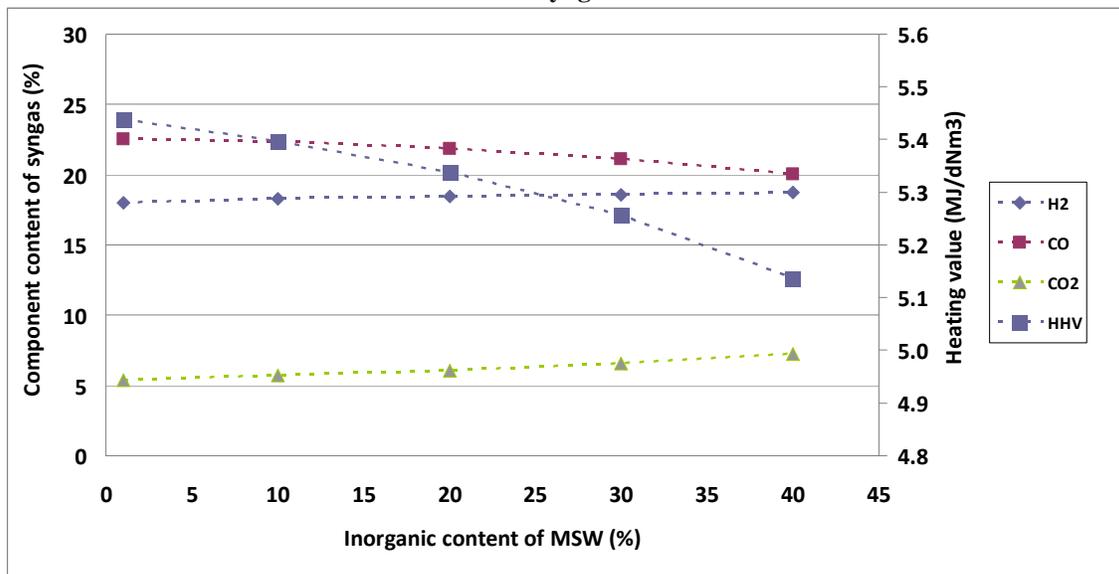
Figure 8 shows the effect of variation in the feed inorganic content on the composition and heating value of the syngas produced. Similar to Figure 7, the x-axis represents feed inorganic content, the primary y-axis shows the composition and the secondary y-axis represents the heating value.

As can be seen from Figure 8, the model predicts that the variation in inorganic content has a similar effect on the heating value of the syngas. However, the effect on the syngas composition % composition is much less pronounced than what has been predicted from the variation in moisture content.

An increase in inorganic content in the MSW means lower gasifiable organic content and less syngas production rate. The model predicts that a 10% increase in the inorganic

content from 20 to 30% would result in a 1.8% reduction in the heating value of the dry syngas.

Figure 8 Effect of Variation in Inorganic Content in MSW on Composition and Heating Value of Syngas



CONCLUSION

A computer process simulation model was successfully developed for the plasma gasification and vitrification of MSW. The model developed was validated by comparing the key prediction parameters such as the syngas generation rates and syngas composition of the system with pilot test results. The model predictions agree closely with the results obtained from the pilot tests. Sensitivity analysis on the production system was performed on the validated computer model. Variation in feed moisture content and feed inorganic content were studied. The results show that a 15% increase in the moisture content from 30 to 45% is expected to result in a 3.5% reduction in the heating value of the dry syngas, and a 10% increase in the inorganic content from 20 to 30% would result in a 1.8% reduction in the heating value of the dry syngas. This detailed mass and energy balance process simulation model is being used as the basis for carrying out the detailed design of the scaled up production 10.5 TPD PRRS.

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