PYROLYTIC GASIFICATION OF POST-CONSUMER POLYOLEFINS TO GENERATE CLEAN-BURNING FUELS

A Thesis presented

by

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Abstract
Utilization of post-consumer waste plastics as fuels is of technological interest since their energy contents (heating values) are comparable to those of premium fuels. Pyrolytic gasification of these solid polymers yields a mixture of predominately gaseous hydrocarbons and hydrogen. This gaseous fuel mixture can then be suitably blended with air and burned in premixed flames. Such flames are much less polluting than diffusion flames, which would have been generated had the polymers been burned in their solid state. In this work an apparatus was designed and built to continuously process polymers, in pelletized form, and to pyrolytically gasify them at temperatures in the range of 800-900 ºC in N₂ or CO₂-containing environments. Subsequently, the gaseous pyrolyzates were mixed with air, ignited and burned in a Bunsen-type burner. Polyethylene fueled-flames had a violet/blue tint, whereas polypropylene-fueled flames were blue with an orange surround. Both flames were fairly-steady and nearly-stoichiometric, generating effluents with low CO/CO₂ ratios. The combustion reactions released heat in a small water boiler coupled to a miniature steam engine, which produced electricity illustrating the feasibility of “clean” power generation from waste plastics. As pyrolysis of polyolefins requires a nominal heat input that amounts to only a minuscule fraction of the heat released during their combustion, large-scale implementation of this technique is deemed to be technologically viable and economically favorable.
Acknowledgment

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1.1 Introduction

As their resources are finite, it is expected that fossil fuels will become scarce and costly at some point in the future. To ensure energy sustainability, it is thus imperative not only to improve the efficiency of energy use but also, to identify and develop technologies for harnessing alternative energy sources. Readily-available alternative fuels can be found in municipal/industrial recycling and waste streams. Nearly 5% of the yearly US petroleum consumption is used to produce plastics, amounting to approximately 30 million tons [1]. In most applications, plastics are discarded upon-use. A small fraction (7%) of the discarded plastics are recycled [2], however, as plastics are degraded upon usage, there are limited markets for the recycled materials. In fact, most post-consumer plastics end up in landfills or generate ubiquitous litter. As they are non-biodegradable, they generate a long-term solid waste issue. Direct combustion of post-consumer plastics in waste incinerators releases their stored internal energy (heating value), which is comparable to those of premium fuels [3]. However, conventional direct combustion leads to diffusion flames, forming around the devolatilizing solid plastics, which generate large amounts of health-hazardous soot, poly-cyclic aromatic hydrocarbons (PAH) and other pollutants.

Figure 1.1- Direct combustion of post-consumer plastics generates acrid smoke containing condensed-phase and gas-phase hazardous pollutants.
An alternative indirect combustion technique was followed in this work, which called for a two step process: pyrolytic gasification of the solid polymers, followed by premixed combustion of the gaseous pyrolyzates with air. Such conditions afford effective mixing of gaseous fuel compounds with oxygen and can generate low emissions of pollutants [4-7]. In fact, Goncalves et al. [6] reported that indirect homogeneous combustion of PE pyrolyzates released 10 times lower polycyclic aromatic hydrocarbons (PAH) and particulates than direct combustion of the same polymer, at similar furnace operating conditions.

Indirect combustion of the plastics (pyrolytic gasification followed by combustion of the pyrolyzate gases) is technically attractive, as Jinno et al. [8,9] reported values for the heat of pyrolysis of PE and that of PP that are well-under 1 MJ/kg. Even after accounting for the higher temperatures encountered in pyrolytic gasification herein than those in the aforementioned work, the heat of pyrolysis of polyolefins is less than 2 MJ/kg, see Appendix 1. Comparing this value to the heating values (energy contents) of polyolefins, which are in range of 44 - 46 MJ/kg, it becomes evident that only a small fraction of the heat released during combustion will be needed to be fed back to pyrolytically gasify them. Therefore, a gaseous fuel stream may be produced from waste polymeric feedstocks by implementing a heat integration, where only a small penalty in energy, and thus in the operating cost of a power plant, will be encountered in running the gasifier. Based on this principle, this study developed and tested a process that accepts post-consumer plastics and releases their internal energy through environmentally-benign indirect combustion [4-7]. The feasibility of this process has been proven using polyolefins, the most voluminous commercial plastics.

Polyolefins is the collective description for plastics types that include polyethylene - low density polyethylene (LDPE), linear low density polyethylene (LLDPE) and high density polyethylene
Polyolefins - and polypropylene (PP). Polyolefins are polymers produced from simple olefins (also called alkenes with the general formula C\text{\textsubscript{n}}H\text{\textsubscript{2n}}) as monomers. They are produced from oil or natural gas by polymerization, where short chains of chemicals (monomers) are joined in the presence of a catalyst to make long chains (polymers). Polyolefins are solid thermoplastics that can be processed in two ways – by film extrusion or molding. Because of their versatility, low cost, inertness and excellent chemical resistance, polyolefins are the most popular plastics in use today. Together they account for nearly half of Europe’s total generation of 24 million tones and USA’s generation of 30 million tons of all plastics each year [23,24] Applications include: (a) LDPE: cling film, stretch film, industrial packaging film, carrier bags, agricultural film, milk carton coatings, electrical cable coating, heavy duty industrial bags, stretch film, industrial packaging film, thin walled containers, and heavy-duty, medium- and small bags. (b) HDPE: crates and boxes, bottles (for food products, detergents, cosmetics), food containers, toys, petrol tanks, industrial wrapping and film, pipes and house ware. (c) PP: food packaging, including yoghurt, margarine pots, sweet and snack wrappers, microwave-proof containers, carpet fibers, garden furniture, medical packaging and appliances, luggage, kitchen appliances, and pipes.

Polyethylene (PE), either as high-density (HDPE) or low-density (LDPE), starts decomposing at 290\textdegree C by scission of weak links and progressively by scission of tertiary carbon bonds or ordinary carbon bonds in the beta position to tertiary carbons [10]. Extensive weight loss is not observed until 370\textdegree C is reached. The main products of its decomposition are: an oil/wax product dominated by alkenes, alkynes, and alkadienes; a gas consisting mainly of alkanes and alkenes; and negligible char [4,19]. The monomer precursor ethylene (ethene) is only one of many constituents of the volatile primary products. For instance, there is also formation of aromatic species such as benzene and toluene. As the temperature of pyrolysis increases, gaseous products
are favored. Extensive work by Conesa and co-workers [7,11] examined the effects of the polyethylene type, the effects of polymer branching, the effects of batch versus continuous operation, as well as the effects of the influence of the heating rate on the decomposition yields. They found variations in both the yields and the composition of the pyrolyzates, with branched PE yielding 91.8% gas with a higher aromatic content, and less branched PE yielding 97.5% gas with lower aromatic content, both at 800°C. These results are in good agreement with those of Scott et al. [14] and Kaminsky [12]. Westerhout et al. [13] found that, at 800°C, the product contains more methane than ethylene and low amounts of aromatics and, most importantly, they determined that the type of pyrolyzed PE, i.e., LDPE or HDPE, had no significant influence on the product spectrum produced. The effect of the residence time and the temperature of pyrolysis on the products distribution were studied by Mastral et al. [15] in two free-fall reactors, placed in series. Their experiments showed that up to 700°C the main products obtained were waxes and oil fractions; and that the gas yield increased as the temperature increased. The generation of aromatics was reported to be significant at 800°C and showed an increasing trend with temperature and residence time. The main compounds in the gas fraction were hydrogen, methane and acetylene at temperatures up to 1000°C. Longer residence times led to a more intense cracking of the aliphatic fractions, and the methane and ethylene yields increased significantly.

Polypropylene (PP), having every other carbon in the main chain as a tertiary carbon is prone to attack [10]; this lowers the stability of PP as compared to PE. Polypropylene starts decomposing at 230°C by chain scission and chain transfer reactions [10]; volatilization becomes significant above 300°C.
Exploratory experiments were conducted in the laboratory to observe the decomposition behavior of common polymers [25]. To conduct these experiments, pellets were placed in a stainless steel crucible and were heated by a Bunsen burner flame. A thermocouple was placed in the fixed bed of particles to monitor temperature, see Fig. 1.2. As the temperature of the bed increased the plastic pellets softened and melted. Polystyrene melted readily in the neighborhood of 250 °C, polyethylene at a little higher temperature, and polypropylene at yet a higher temperature. At 300 °C all three plastics were found in a liquefied molten state.

![Polyethylene](image1.png)
![Polypropylene](image2.png)
![Polystyrene](image3.png)

*Figure 1.2- Melting of different plastics (PE, PP and PS) on a stainless steel plate [25]*
High temperature pyrolysis of PE and PP generates a mix of light hydrocarbon gases, including methane, ethylene, propylene, butylene, etc. [6,11,13,17,18] and hydrogen [26]. This experimental study aims at demonstrating that a high-energy-content gaseous fuel can be produced from post-consumer polyolefin feedstocks and can be burned in an environmentally-benign manner, akin to natural gas, for power generation, process heat or other energy-related applications. A laboratory-scale system was designed and constructed to pyrolytically gasify pelletized polymers, at steady-state steady-flow conditions, and to generate a combustible gaseous fuel and burn it in a miniature steam engine to generate electricity. An energy balance analysis was performed to assess the net thermal energy output of such process, per unit mass of waste plastics input to the system. Pyrolytic gasification took place in both N₂ and CO₂ carrier gases. The reason being that, whereas N₂ has to be purposely procured through a cryogenic process and is thus costly, a mixture of N₂ and CO₂ gases can be readily obtained at no cost by taping to the exhaust effluent of a combustion process. In fact a slipstream of the effluent of the very same combustion process can be used to supply the pyrolyzer. There may be other additional benefits to using CO₂ as the work of Yamada et al. (16) has shown in the catalysis-aided reforming of the pyrolyzates of PE to CO and H₂ at 950 °C.
CHAPTER TWO

(Experimental Apparatus)

2.1 Experimental Apparatus

A laboratory-scale pyrolytic gasifier system has been designed and constructed to accept granulated plastics, and sequentially liquefy and gasify them. The gaseous pyrolyzates are then mixed with air and burned in a nominally-premixed burner. For demonstration purposes, the burner is also coupled with a miniature steam generator and steam engine setup to produce electricity (Wilesco D18). The pyrolytic gasifier is shown in Figure 2. Its major components are a feedstock storing and feeding system and a heating chamber. The feeding system incorporates a reservoir with a hopper where pelletized polymers are stored, an electric motor, and an auger/feeding box. Pellets are gravity-fed from the reservoir through the hopper. The variable-speed electric motor (Leeson Corp. model 985.613F, 8.7 N-m peak torque, 0 – 94 RPM, continuous duty) drives the horizontally-oriented auger which carries the pellets from the feeding box to a vertical purge chamber leading to the furnace. The rotating auger uses a sealed bearing to minimize leakage from the system and, thus, maintain the pressure of the inert carrier gas.

The furnace chamber is defined by a stainless steel tube, whose dimensions are designed to provide sufficient space for the expansion of a targeted flow rate of polymers upon gasification. The furnace is heated by electrical resistance elements (ATS Series 3110), rated at 1.43 kW. The furnace is connected to a proportional integral derivative (PID) loop temperature controller (ATS Series XT16). This is a feedback controller and it computes the error value based on the difference between the measured variable and a desired set-point; subsequently, it minimizes the
error by varying the inputs. This allows for precise and reliable regulation of system temperature at any desired set point. The speed of the electric motor that drives the polymer feeding system is adjusted to obtain the desired mass flow rate of plastic pellets. The direct-drive motor and screw-type auger system provide a linear relationship between feeding rate and motor speed (RPM).

Asymmetrically-perforated disks have been inserted at several vertical locations in the tubular furnace to intercept the falling polymer pellets and facilitate their sequential melting and gasification. In this manner the particles gasify in the radiation cavity of the furnace, instead of settling at its cooler bottom. In addition to this feature, the gas exit tube in the chamber is elevated from the bottom, to prevent its plugging by settling tars, and it is protected by a conical roof to prevent impingement of any falling molten polymer ligaments. Furthermore, the system is fitted with two relief valves, to avoid over-pressuring.

The most leak-prone connections in the system are flanges inserted between the gasification and the purging chambers. High-temperature gaskets (THERMA-PUR style 4122 corrugated metal gasket, manufactured by Garlock Sealing Technologies) have been used for sealing the flanges. The system was tested by pressurization, the pressure was turned off and the gradient of the pressure drop with time is shown in Fig. 2.1. The flange bolts were tightened to 45 N-m (400 in-lb) and the set pressure was 68.9 kPa (10 psi). The relief valves (rated at 234 kPa/34 psi) were tested at both STP and 850 °C operating conditions. Maintaining a tight seal on the system is essential to minimizing the amount of carrier gas and pyrolyzate gas losses through overboard leakage.
Figure 2.1- Laboratory-scale pyrolytic gasification apparatus designed and constructed for the needs of this study: (a) two dimensional schematic detailing the apparatus architecture and (b) photograph of the actual system.
A typical centerline gas temperature distribution in the furnace, as measured by a type-K thermocouple (Omega) is shown in Fig. 2.2. In this case, the controller set-point was set to maintain a constant wall temperature of 950 °C. Temperature measurements were taken at each of the perforated disks in the chamber in order to gauge the uniformity of the heater. The temperature gradient plateaued in the bottom-half of the chamber, where the maximum temperatures prevailed.
Figure 2.3- Gas temperature gradient at different elevations of the pyrolysis chamber at a furnace set-point of 950°C.

As mentioned before, it has been previously reported (8) that the yield of gas from pyrolysis of PE increases with temperature; it only accounts for 5.7 wt% at 500 °C, reaches a maximum of 96.5 wt% at a $T_{\text{pyrolysis}} = 800$ °C, and slowly decreases with increasing temperature thereafter. Therefore, a gas temperature of 800 °C was chosen in this work to maximize the yield of gaseous PE pyrolyzates, while minimizing the generation of tars and oils. To account for heat losses throughout the system, the furnace controller set-point was raised to the range of 900-950 °C to ensure an average gas temperature of 800 °C in the pyrolysis chamber.
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### 2.2 Characteristic of Polyolefin Feedstocks

The two polyolefin polymer feedstock materials used in this study were low density polyethylene (LDPE) with a chemical formula of \((C_2H_4)_n\), and polypropylene (PP) with a chemical formula of \((C_3H_6)_n\). High density polyethylene (HDPE) was not included in this study since it has been previously reported to decompose in a fashion similar to that of LDPE [11]. Commercially available post-consumer plastics in pelletized form were obtained by a local supplier and used in these experiments. LDPE has a density range of 0.91-0.94 g/cm\(^3\), whereas PP has a density range of 0.86-0.95 g/cm\(^3\). LDPE can be heated up to 80 °C continuously and 95 °C for a short time. PP has a melting point range from 130 to 171 °C. PP also has crystallinity between LDPE and HDPE. One gram quantities of the LDPE and PP polymers used in this study are shown in Fig. 2.4.
2.3 Experimental Procedure

In each experiment, the pelletized polymers were loaded into the hopper and the feeding system was sealed. The carrier gas is N$_2$ or CO$_2$ at a flowrate of 1 lpm. These gases were used to purge the air out of the system and to ensure oxygen-free pyrolysis. Thereafter, the polymer pellets were introduced to the system at a targeted feeding rate. Typical plots of the feeding mass of pellets with time are shown in Fig. 2.5. To obtain this data, the feeding system was detached from the pyrolysis apparatus and was setup in a bench top style experiment, with a calibrated mass balance (Mettler AE50) positioned to catch and measure the output. The hopper was loaded with plastic pellets and the drive motor was run at constant speed, with manual data readings taken every 5 seconds. The plots shown in Fig. 2.5. demonstrate fairly linear overall rates of pellets in the broad neighborhood of 1 g/min.
Figure 2.5- Feeding characteristics of low density polyethylene (LDPE) polypropylene (PP) pellets used in this work.
In all subsequent experiments the feeding rate of solid pelletized polymers in the furnace was set at 1 g/min, based on experimentally-determined repeatable steady-state operation of the feeder. This value also matched the capacities of two nominally premixed-flame burners used in this work, a Bunsen burner and a rectangular burner (measuring 2 x 14 cm) supplied with the miniature steam engine (Wilesco D18). In this regard, the capabilities of both burners were tested using bottled ethylene gas (which has been identified as a major pyrolyzate of the polyolefins). Since the ratio of the volume of solid polymer to the volume of gaseous ethylene pyrolyzate is inversely proportional to the ratio of their respective densities (e.g., $\rho_{\text{solid PE}}=940$ kg/m$^3$ and $\rho_{\text{ethylene}} = 1.178$ kg/m$^3$), the equivalent mass flowrate of ethylene gas to match the mass flowrate of the 1g/min of polymer pellets was determined to be 830 cm$^3$/min. This flowrate of ethylene produced steady flames of appropriate intensity for the operation of the miniature engine.

Additional experiments were also conducted to explore the effect of the carrier gas ($N_2$) on the flammability and stability of the flames. The motivation being, that reduced inert gas flowrates are economically advantageous. Experiments were conducted at the aforementioned ethylene gas flow rate of 0.83 lpm and inert nitrogen flowrates varying by a threefold. These experiments, in agreement to other pertinent experiments elsewhere [20], showed that the addition of various amounts of nitrogen inert gas did not significantly affect the flammability of the ethylene gas in the nominally-premixed burners used herein [21].

The pyrolytic gasification chamber contained five perforated steel plates, placed at different axial locations in the furnace tube. The free-falling plastic pellets were intercepted by these plates they heated up and, as they melted, molten mass dripped through the plates, changing state to liquid and then ultimately to gas subsequently, the effluent pyrolyzate gases (nominally 0.83 lpm),
mixed with the carrier gas (1 lpm), and then travelled through the exhaust pipe and entered the burner.

A brief series of experiments was conducted to visualize the behavior of molten polymers through the perforated plates. To accomplish this, a quantity of pellets was placed in a stainless steel crucible whose bottom was perforated with several holes, see Fig. 2.6. A thermocouple was placed in the fixed bed of particles to monitor temperature. The crucible was then heated by an electric tape to temperatures approaching 300 °C. As the temperature of the bed increased the plastic pellets softened, melted, liquefied and dripped through the holes. As these experiments were conducted under a fume hood at STP conditions, the dripping re-solidified. However, inside the hot environment of the pyrolytic gasifier, it is expected that the drippings will gasify.

Figure 2.6- Demonstration of melting and dripping of polyolefins through the perforated plates used in the pyrolytic gasifier. [25]
CHAPTER THREE
(Results and Discussion)

3.1 Results and Discussion

Typical compositions of the pyrolyzates of PE and PP obtained herein are shown in Table 1, when nitrogen was used as the inert carrier gas. Chemical speciation was conducted with gas chromatography, using a Hewlett Packard 6890 A instrument with flame-ionization and thermal conductivity detectors. In the case of PE the major pyrolyzates include methane (25.45%), ethane (5.55%), ethylene (31.38%), propylene (7.02%), butadiene (3%), ethylacetylene (1.6%) benzene (4.44%) and hydrogen (21.61%). Mass balances revealed over 95% of the polymer mass was accounted for in the detected gaseous pyrolyzates. Ethylene has the highest mole fraction in the pyrolyzate gas mixture, which is consistent with the results obtained elsewhere (Goncalves et al. [6], Conesa et al. [11], Westerhout[13], Sawaguchi et al. [17,18], etc.). However, the mole fraction of methane was higher. In the case of PP the major pyrolyzates include methane (33.37%), ethane (4.77%), ethylene (23.61%), propylene (7.59%), benzene (4.44%) and hydrogen (19.53%). These results differ from results obtained elsewhere [13,17 and18], where propylene was found to have the highest mole fraction. However those studies were conducted at 750 °C. Although primary pyrolysis of polyolefins tends to favor their monomers, it has been reported that higher pyrolysis temperatures [13] and/or longer residence times [27] lead to higher yields of methane at the expense of ethylene and propylene.
<table>
<thead>
<tr>
<th>Pyrolyzate Gases</th>
<th>PP CO2 Carrier</th>
<th>PP N2 Carrier</th>
<th>PE CO2 Carrier</th>
<th>PE N2 Carrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>15.48%</td>
<td>19.53%</td>
<td>14.02%</td>
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<tr>
<td>O-xylene</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

Table 3.1 - The composition of the effluent of pyrolytic gasification of PE and PP at 800 °C gas temperature.
Figure 3.1. Comparison plot for the effluent of pyrolytic gasification of PE and PP at 900°C.

Nominally-premixed flames generated from continuous feeding of polyethylene and polypropylene in the apparatus, are shown in the photographs of Fig. 3.2, using the Bunsen burner. In Fig 3.2(a), a flame of natural gas is shown for comparison purposes. Figs 3.2(b) and 3.2(c) show flames of PE and PP, respectively in nitrogen carrier gas. At the estimated nearly-stoichiometric conditions of this work, the natural gas and the PE flames had violet/blue tints, whereas the PP flame was blue with a faint orange surround.
3.2 Numerical Simulation

A 2D-model has been developed to assess the gas velocity profile and gas temperature distribution in the furnace using ANSYS-Fluent. Based on the velocity profile, a residence time of the pyrolyzates in the heated zone of the furnace was estimated, based on the assumption that the pellets were intercepted by the perforated plates and melted and devolatilized therein. The k-ε model was used for simulating the velocity profile. In this simulation nitrogen was used as the carrier gas at a flowrate of 1 lpm and, in a simplification, the pyrolyzate gases were considered to consist only of one compound: ethylene, which is a major component of polyolefin decomposition. The mass flow rate of ethylene was set at 0.83 lpm. The temperature distribution in the furnace was solved based on the DTRM radiation model, and it was assumed that the source of radiation was the hot wall of the tubular furnace, which was maintained at a temperature of 950 °C (1223 K).

Predicted temperature profiles in the furnace are shown in Fig. 3.3., and are in good agreement with the experimental results presented in Fig. 2.3., which were obtained with a bare
thermocouple placed along the centerline of the furnace. These results confirm that the temperatures present in the axial and radial directions of the heated section of the furnace are sufficient for maximum pyrolytic gasification (850 °C or 1123 K) yield from the polymer pellets. In Fig. 3.3., the velocity vectors inside the pyrolysis chamber are also shown. High velocities at the holes of the perforated plates are predicted, and are expected to enhance the polymer devolatilization rates. This ANSYS model also predicted a high velocity at the exit of the pyrolysis chamber, which suggests that the chosen carrier gas flow rate is sufficient to force the polymer pyrolyzates through the bottom of the chamber, with no potential for recirculation back up towards the feeding system.

Figure 3.3-Results of numerical analysis (using ANSYS-Fluent) where gas velocity vectors and contours of static temperature are shown in the pyrolysis chamber.
3.3 Combustion Effluent Analysis

Once the feeding system was developed and fine-tuned to provide a continuous flame, a number of experiments were performed to quantify the affects of different temperatures and carrier gasses on the levels of CO and CO$_2$ present in the combustion product gases. The gases were monitored by sampling the effluent of the flames and channeling the slipstream to a *California Analytical Instruments* dual CO-CO$_2$ analyzer, model 200. Given the nature of the burners used, it was not easy to accurately determine the equivalence ratio of their nominally-premixed flames based on the amounts of reactants. Hence, the equivalence ratio was estimated based on the measured CO and CO$_2$ combustion products. To achieve this, the partial pressures of the combustion products of pyrolyzate gasses were calculated using the chemical equilibrium code STANJAN (22). For this calculation, the pyrolyzate gas mixture composition, documented in Table 1, was input to the code as reactants (along with the respective carrier gas), and the molar amounts of the major combustion products (O$_2$, N$_2$, CO, CO$_2$, H$_2$O, NO, NO$_2$) were computed. The calculation was run over several iterations, with the O$_2$ mole fraction in the reactants altered to produce a range of CO$_2$/CO ratios. These ratios are plotted against the experimentally-measured results for comparison purposes in Figure 3.4. It should be mentioned that data points were obtained at two set-point temperatures of the pyrolytic gasification furnace: 900 and 950 °C. Experiments were run for 20 min and were repeated at in triplicate; average mole fractions and standard deviations are shown in Figure 3.4. For comparison purposes, experimental data obtained burning natural gas is also included in Fig. 3.4.

Based on the predictions of the chemical equilibrium code STANJAN, it can be inferred that in most cases combustion took place in the broad neighborhood of stoichiometry, perhaps mildly
fuel-lean. Moreover, there was some scatter in the emissions data which may be attributed to some unsteadiness in the pellet feeding and devolatilization as well as to mild fluctuations of the air supply to the Bunsen burner under the operating fume hood. Surprisingly, similar fluctuations in the emissions data were also observed for the case of the natural gas flames, suggesting that the latter mechanism was a significant contributor to this scatter. It may also be observed from these figures that all fuels resulted in comparable CO$_2$/CO ratios, under the conditions of this work, confirming the effectiveness of combustion of the gaseous pyrolyzates of post-consumer polyolefins is akin to that of natural gas.

Figure 3.4- Experimentally-determined CO$_2$/CO vs. equivalence ratio at various furnace set-point temperatures, with N$_2$ as the carrier gas.
Furthermore, Fig. 3.4. shows that the furnace set-point temperature in the range of 900°C to 950°C had a beneficial influence on the relative CO₂/CO post-flame emissions of the fuels: it increased this ratio, which is indicative of more complete combustion. This may be attributed to more effective pyrolysis of the polymer to lighter hydrocarbon species [7, 11-14].

### 3.4 Replacement of Nitrogen Background Gas with Carbon Dioxide

Substitution of background N₂ gas with CO₂ was very well tolerated by the flame, producing no discernible differences. As expected, since CO₂ is added to the pyrolytic gasifier input, the amount of CO₂ in the effluent is also higher than in experiments where N₂ was used as the carrier inert gas. Small variations in CO concentrations may be attributed to fluctuations in the polymer pellet feeding rate. The implication of substitution the nitrogen background inert gas with carbon dioxide in the pyrolytic gasifier may prove to be important in the economics of an industrial-scale application. The use of N₂ as a carrier gas requires the procurement, maintenance, and servicing of on-site N₂ gas storage. This is costly, takes up space, and diverts valuable resources to maintaining such a system. CO₂ is a byproduct of combustion, and devising a system to capture the CO₂ as produced from combustion gasses to be used as a carrier gas in the system will present significant cost and resource savings, as the CO₂ is produced with no additional cost and diminishing the supply of it is not a factor, as with storing bottled N₂ on site.

<table>
<thead>
<tr>
<th></th>
<th>CO₂ carrier gas</th>
<th>N₂ carrier gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>T&lt;sub&gt;set point&lt;/sub&gt; = 900 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂%</td>
<td>14.2 ± 1.04</td>
<td>11.1±0.7</td>
</tr>
<tr>
<td>CO%</td>
<td>0.6±0.1</td>
<td>1.5 ±0.5</td>
</tr>
</tbody>
</table>

Table 3.2- Average mole fractions of carbon dioxide and carbon monoxide in the combustion effluent of PE, along with computed standard deviations.
3.5 Conversion of Post-Consumer Plastics to Electricity Proof of concept

A technical goal of this project has been to produce a continuous flame with sufficient energy to run the miniature steam engine and produce DC electricity through a generator and to eventually turn on a light bulb, shown in Fig. 3.4. As mentioned before, a polymer mass feeding rate of 1 g/min generated a flame that was more than sufficient to generate steam and run the miniature steam engine at a high speed. The flame burned with bright bluish colors, see Fig. 3.2. The steam engine system was able to sustain a boiler pressure of 1 bar and operate consistently at 1800 RPM for duration of an experiment, which was set to 20 minutes. This operational speed was sufficient to use the on board generator to produce a small electric current to illuminate the miniature light bulb. This demonstrated the concept that waste plastics can be used to produce gaseous fuels with high energy content and, in turn, can reliably generate useful work in the form of electricity, see Fig. 3.5.

Figure 3.5- The miniature steam engine in action powered by combustion of pyrolyzates of post-consumer polyethylene in a small burner. The coupled electricity generator powers the light bulb.

3.6 Economic Considerations

Market prices for recycled post-consumer plastics in 2012 are in the range of 0.05-0.5 $/kg, depending on cleanliness, sorting, separation, pelletization, etc. Given that the energy content of
polyolefins is in the neighborhood of 45 MJ/kg, then the specific price range of recycled plastics per energy content is in the range of 1-11 $/GJ. This is analogous to the specific price range of natural gas, which in the past 10 years fluctuated between 2-14 $/GJ. Hence, for recycled plastics to have a competitive advantage as a fuel their price should stay as low as possible, preferably as close as possible to the lowest price, i.e., in the vicinity of 1 $/GJ. Therefore, it is recommended that a power plant is built in the vicinity of a recycling center, to avoid transportation costs and other handling costs and maximize profits.

A simple economic model is constructed in Appendix 3 detailing the profit calculations for a sample setup. Some general assumptions were made on manning (2 eight-hour shifts per day) and maintenance costs of $600/day as well as efficiency for the electrical power generation. The running costs are assumed to be $50/hr for labor with 16 hours per day of runtime. To add an extra measure of conservatism to the estimate, an overall system uptime of 75% is assumed. The system would need to process in excess of 638 kg/hr in order to turn a profit. The chart below details the results of the model being run for the cases of 100 – 1000 kg/hr feed rate. The feed rate was varied and the resulting outputs for both income and expenditures are calculated on a per kg and per day basis. The net income per kg of plastic is constant, and the running costs are spread out among the feed rate, thusly resulting in a diminishing running cost per kg as feed rate increases. As mentioned above, the break-even point is 638 kg/hr. At higher feed rates than this, the running cost becomes spread more evenly and the per kg running costs become less than the per kg income.
3.7 Self-Sustaining Power Plant Efficiency Calculations

The corresponding efficiency, $\eta_s$, defined as the ratio of energy output from the aforementioned process to the energy content of the feedstock, could be in the order of 90%, after a careful energy balancing with minimization of heat losses (see Appendix 2). A self-contained power plant running on these alternative fuels would accept waste plastics from a recycling plant, and would be completely self-sufficient in crushing and prepping the plastic for pyrolytic gasification. Having plastic shredders and associated equipment on-site will cut down on transportation costs for these materials. Based on simplified calculations, the recycled plastics in U.S alone can provide about 1,434 GWh of electricity annually. This will be sufficient to supply the needs of more than 125,000 households.

<table>
<thead>
<tr>
<th>Feed Rate (kg/hr)</th>
<th>Income (per day)</th>
<th>Income (per kg)</th>
<th>Expenditures (per day)</th>
<th>Expenditures (per kg)</th>
<th>Net Cashflow (per day)</th>
<th>Net Cashflow (per kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>$272</td>
<td>$0.227</td>
<td>$1,284</td>
<td>$1.070</td>
<td>$1,012</td>
<td>$0.843</td>
</tr>
<tr>
<td>200</td>
<td>$544</td>
<td>$0.227</td>
<td>$1,368</td>
<td>$0.570</td>
<td>$824</td>
<td>$0.345</td>
</tr>
<tr>
<td>300</td>
<td>$817</td>
<td>$0.227</td>
<td>$1,452</td>
<td>$0.403</td>
<td>$635</td>
<td>$0.176</td>
</tr>
<tr>
<td>400</td>
<td>$1,089</td>
<td>$0.227</td>
<td>$1,536</td>
<td>$0.320</td>
<td>$447</td>
<td>$0.093</td>
</tr>
<tr>
<td>500</td>
<td>$1,361</td>
<td>$0.227</td>
<td>$1,620</td>
<td>$0.270</td>
<td>$259</td>
<td>$0.043</td>
</tr>
<tr>
<td>600</td>
<td>$1,633</td>
<td>$0.227</td>
<td>$1,704</td>
<td>$0.237</td>
<td>$71</td>
<td>$0.010</td>
</tr>
<tr>
<td>700</td>
<td>$1,906</td>
<td>$0.227</td>
<td>$1,788</td>
<td>$0.213</td>
<td>$118</td>
<td>$0.014</td>
</tr>
<tr>
<td>800</td>
<td>$2,178</td>
<td>$0.227</td>
<td>$1,872</td>
<td>$0.195</td>
<td>$306</td>
<td>$0.032</td>
</tr>
<tr>
<td>900</td>
<td>$2,450</td>
<td>$0.227</td>
<td>$1,956</td>
<td>$0.181</td>
<td>$494</td>
<td>$0.046</td>
</tr>
<tr>
<td>1000</td>
<td>$2,722</td>
<td>$0.227</td>
<td>$2,040</td>
<td>$0.170</td>
<td>$682</td>
<td>$0.057</td>
</tr>
</tbody>
</table>

Table 3.3 - List of expenses for scaling up the system.
3.8 Future Considerations

As we know CO₂ is a product of combustion and it is also known that when we mix the light hydrocarbons with air, we are going to have N₂ in the products too. Both CO₂ and N₂ can be captured and then recirculated back in the system to be used as a carrier gas. This recirculating has some advantages like avoiding the cost of buying Nitrogen as a carrier gas and not having problems for the storage. Scaling up the system can be another future consideration for this project. A system that can pyrolyze more plastic and also produce more electricity.
APPENDIX I

Required amount of polymer feedstock to operate the Pyrolytic Gasifier

without external heating

Applying the energy balance for the system determines the amount of polyethylene required. The input is the amount of pellets required to heat the system from room temperature to 950°C. Pyrolysis energy (EPyrolysis) is the amount of energy required to gasify the pellets. Heat Loss energy (EH.L) is the heat loss from the system to ambient and all other unforeseen wastes. Feed energy (EFeed) corresponds to the amount of gas required to heat the pyrolysis chamber to 950°C multiplied by its energy content. The energy balance equation is shown in equation 1.

\[ E_{\text{in}} = E_{\text{Pyrolysis}} + E_{\text{H.L}} + E_{\text{Feed}} \]  

Equation (1)

**Calculation of E_{\text{Pyrolysis}}**

The energy required for pyrolysis of polyethylene at 455°C has been reported by Gupta and co-workers to be 254 kJ/kg [3]. At the higher temperature of 950°C the corresponding energy requirement per unit mass of feedstock (Q_{\text{Pyrolysis}}) is calculated in equation (2).

\[ E_{\text{pyrolysis}} = C_p \Delta T \dot{m} \]  

Equation (2)

Performing the interpolation to calculate specific heat at \( T=975K \) is shown in equations (3 – 5).

\[ T_{\text{avg}} = \frac{455+950}{2} + 273 = 975 \text{ K} \]  

Equation (3)
\begin{equation}
\frac{C_p - 3.088}{T_{avg} - 850} = \frac{3.18 - 3.088}{900 - 850} \quad \text{Equation (4)}
\end{equation}

\begin{equation}
C_{p975} = 3.318 \frac{\text{kJ}}{\text{kg K}} \quad \text{Equation (5)}
\end{equation}

Using the calculated $C_p$ from equation (5) and substituting into equation (1) yields the following pyrolysis energy:

\begin{equation}
E_{\text{pyrolysis}} = 254 + 3.318 \times (950 - 455) = 1896 \frac{\text{kJ}}{\text{kg}} \quad \text{Equation (6)}
\end{equation}

For the purposes of this work, $Q_{\text{pyrolysis}}$ is rounded up to 2 MJ/kg.

**Calculation of $E_{HL}$**

Two primary sources of losses in the system is heat transfer from the pyrolysis chamber to ambient through the insulation, and energy required to raise the temperature of the Nitrogen carrier gas.

\begin{equation}
E_{HL} = \dot{E}_{\text{ins}} + \dot{E}_{N_2} \quad \text{Equation (7)}
\end{equation}

The conductive heat loss is calculated using the relationship in equation (8).

\begin{equation}
\dot{E}_{\text{ins}} = \frac{KA\Delta T}{Thk} \quad \text{Equation (8)}
\end{equation}

The geometry of the heater and insulation is evaluated via figure A1 and equations (9 – 10).
Substituting equations (9 – 11) into equation yields the following result:

\[
\dot{E}_{\text{ins}} = \frac{kA\Delta T}{\text{Thk}} = \frac{0.05 \left( \frac{\text{W}}{\text{mK}} \right) 0.15(\text{m}^2)(950-25)(\text{K})}{0.2(\text{m})} = 35 \left( \frac{\text{J}}{\text{s}} \right)
\]  
Equation (12)

The relationship to solve for energy required to heat up the Nitrogen carrier gas in the pyrolyzer is calculated with the relationship in equation (13).

\[
\dot{E}_{\text{N}_2} = \frac{c_p\rho q\Delta T}{3600}
\]  
Equation (13)

Substituting in known values for specific heat, gas density, flow rate, and temperature yields the following (equation 14):

\[
\dot{E}_{\text{N}_2} = \frac{1040 \left( \frac{\text{J}}{\text{kgK}} \right) 1.2 \left( \frac{\text{g}}{\text{lit}} \right) 0.25 \left( \frac{\text{lit}}{\text{min}} \right) (2030 - 25)(\text{K})}{3600} \frac{\text{kg}}{1000\text{g}} = 0.17 \left( \frac{\text{J}}{\text{min}} \right)
\]
Or \(0.003\left(\frac{1}{s}\right)\)  

The value of \(\dot{E}_{N_2}\) is several orders of magnitude less than \(\dot{E}_{\text{Ins}}\) and thusly is determined to be negligible. The following relationship is then assumed for \(\dot{E}_{\text{HLL}}\) (from equation 7):

\[
\dot{E}_{\text{HLL}} = \dot{E}_{\text{Ins}}
\]

Equation (15)

Figure A1. Schematic Picture of Insulation Thickness and Length (Units: inch)

Multiplying the total heat loss by a factor of 2 to consider all unpredicted and other unknown losses yields the following value:

\[
\dot{E}_{\text{HLL}} = 35 \times 2 = 70\left(\frac{1}{s}\right)
\]

Equation (16)
To calculate the overall heat loss in the system, values from equations (6, 16) are used with the thermal balance equation (1) to perform the following calculation:

Substituting in the energy balance equation;

\[ m \times 46300 = \dot{m} \times Q_{\text{pyrolysis}} + E_{\text{HL}} + 1430 \quad \text{Equation (17)} \]

\[ \dot{m} = 0.0337 \frac{g}{s} = 2 \frac{g}{\text{min}} \]

This calculation shows that 2 g/min pellets are required to heat this laboratory-scale pyrolyzer to 950°C. This amount of plastics is required for the system to just break even energy-wise. This amount of plastics mass flow rate (2 g/min) generates enough energy to sustain its own operation, i.e., it will be energy self-sufficient. It will take plastics mass feed rates higher than 2 g/min to start generating gaseous fuel for net power generation, i.e., for external applications.
APPENDIX II

Calculation of Self-Sustaining Power Plant Efficiency $\eta_s$

The self-sustaining efficiency, $\eta_s$, is defined as the ratio between the energy output and the amount of plastic feedstocks necessary to heat and pyrolyzer the feedstocks to the optimal pyrolysis temperature.

$$\eta_s = \frac{E_{\text{out}}}{E_{\text{In}}} = \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{In}}} = \frac{\overline{E}_{\text{out}}}{\overline{E}_{\text{In}}}$$  \hspace{1cm} \text{Equation (18)}

Wherein $E_{\text{out}}$ is the energy output of the proposed self-sustaining waste-to-energy process.

In the aforementioned process, a small fraction of the energy released by combustion of plastic pyrolyzates, denoted as $E_{\text{In}}$ herein, is fed-back to pyrolyze the solid plastics feedstock and to overcome the energy loss of the system. There is unavoidable energy losses involved in this process, and is denoted as $E_{\text{Loss}}$ herein. The $\dot{E}$ represents $E$ per unit time, and $\overline{E}$ refers to $E$ per unit mass. A simplified energy balance can therefore be obtained as equations (19 – 21):

$$E_{\text{out}} = E_{\text{in}} - E_{\text{Pyrolysis}} - E_{\text{Loss}}$$  \hspace{1cm} \text{Equation (19)}

$$\frac{\dot{E}_{\text{out}}}{\text{kg of PE}} = \frac{E_{\text{in}}}{\text{kg of PE}} - \frac{E_{\text{Pyrolysis}}}{\text{kg of PE}} - \frac{E_{\text{Loss}}}{\text{kg of PE}}$$  \hspace{1cm} \text{Equation (20)}

$$\overline{E}_{\text{out}} = \overline{E}_{\text{in}} - \overline{E}_{\text{Pyrolysis}} - \overline{E}_{\text{Loss}}$$  \hspace{1cm} \text{Equation (21)}

Using polyethylene (PE) as an example, where the energy content of PE is $\overline{E}_{\text{in}}=46,300 \text{ kJ/kg}$, where the energy needed to pyrolyse PE at its maximum rate ($455^\circ C$) and to heat it up to desired temperature ($800^\circ C$) is:

$$\overline{E}_{\text{Pyrolysis@800°C}} = \overline{E}_{\text{Pyrolysis@455°C}} + C_p \times \Delta T$$  \hspace{1cm} \text{Equation (22)}
\( C_p \) is the heating capacity of materials, and its value of ethylene was used herein as a surrogate due to the fact that ethylene is the monomer of PE and the major component in the PE pyrolyzates. Although \( C_p \) of ethylene varies and increases along with the temperature, we assume it increases linearly with the temperature and a conservative simplification use the highest value available. Thus,

\[
T_{ave} = \frac{T_i + T_f}{2} = \frac{455 + 800}{2} = 627.5^\circ C \approx 900 \text{ K}
\]

\( C_{p@900K} = 3.18 \frac{\text{kJ}}{\text{kg} \cdot ^\circ \text{C}}, \) and Equation (22) yields

\[
\bar{E}_{\text{Pyrolysis@800^\circ C}} = 254 + 3.18 \times (800-455) \text{kJ/kg} = 1,352 \text{ kJ/kg};
\]

In this study, the energy loss is simplified to be due to the heat loss during the pyrolysis process. Assuming the heat loss occurs across a cylindrical surface, see Fig. A1 where the dimensions were marked (inch).

The insulation material was assumed to be calcium silicate with a thermal conductivity coefficient of \( k=0.05 \text{ W/mK}. \)

Therefore,

\[
\bar{E}_{\text{Loss}} = \frac{t \times \dot{Q}_{\text{Insulation}}}{\text{kg of PE}} = \frac{t \times kA\Delta T}{d \times \text{kg of PE}} \quad \text{Equation (23)}
\]

Where \( \dot{Q}_{\text{Ins}} \) is the heat loss through the insulation per second,

\[
\dot{Q}_{\text{Ins}} = \frac{kA\Delta T}{d} \quad \text{Equation (24)}
\]
A was defined as the outer surface area of insulation and L as the insulation thickness. ΔT is temperature difference between heater and ambient. The thickness of insulation is shown in Figure A1.

\[ d = 12 - 3.75 = 8.25'' = 0.2 \text{ m} \]

\[ A = 2\pi r L = 2\pi (6'' \times 6'') = 0.15 \text{ m}^2 \]

\[ \Delta T = 800 - 25 = 775 \text{ °C} \]

Therefore, Equation (23) yields the following value for heat loss:

\[
\bar{E}_{\text{Loss}} = \frac{\text{t} \times 0.05 \left(\frac{\text{W}}{\text{m} \cdot \text{K}}\right) 0.15 (\text{m}^2) 775 (\text{K}) \times 2}{0.2 (\text{m})} \approx 0.06 \text{ t kWh/kg;}
\]

In this study, the time needed to feed one kilogram of polyethylene, denoted as \( t \) herein, is

\[ t = \frac{1000 \text{ g}}{1 \text{ g/min}} = 1000 \text{ minutes} = 60000 \text{ seconds} , \]

Based on Equation (17)

\[
\eta_s = \frac{46300 - 1352 - 0.06 \times t}{46300} = \frac{46300 - 1352 - 0.06 \times 60 \times \frac{1000}{\text{m}}}{46300}
\]

\[ = \frac{41348}{46300} \approx 89.3\% \quad \text{Equation (26)} \]

As shown in Equation (9), for the apparatus used in this study, there is a relation between the self-sustaining efficiency, \( \eta_s \), and the mass feeding rate, \( \dot{m} \), as shown in Fig. A2. Higher feeding rate leads to less duration for pyrolyzating the same amount of feedstock, thus higher efficiency. The ideal efficiency can be as high as 96%, as the feeding rate is larger than 4 g/min.
Self-Sustaining Efficiency $\eta_s$

$$
\eta_s = \frac{46,300 - 1,352 - 0.06 \times 60 \times \frac{1000}{\dot{m}}}{46,300}
$$

Figure A2. Relation Between the Self-Sustaining Efficiency $\eta_s$ and the Feeding Rate $\dot{m}$ (g/min).
APPENDIX III

Thermocouple temperature measurement correction for radiation effects.

The temperature at different elevations of the pyrolysis chamber was measured with a bare thermocouple. These readings need to be corrected to exclude the furnace wall radiation effects. This correction is based on an energy balance on the thermocouple bead.

\[ \rho C_p V \frac{dT_b}{dt} = \dot{Q}_{convection} + \dot{Q}_{radiation} \quad \text{Equation (27)} \]

It is assumed that the bead of the thermocouple is in thermal equilibrium with its surroundings (steady state). A k-type OMEGA thermocouple was used for these measurements and the diameter of the bead was measured to be 500 µm. By considering steady state conditions, equation (27) equation changes to below:

\[ \dot{Q}_{convection} + \dot{Q}_{radiation} = 0 \quad \text{Equation (28)} \]

Convection and radiation terms are determined from:

\[ \dot{Q}_{convection} = h \times A_b \times (T_{gas} - T_b) \quad \text{Equation (29)} \]
\[ \dot{Q}_{radiation} = \varepsilon_b \times \sigma \times A_b \times (T_{wall}^4 - T_b^4) \quad \text{Equation (30)} \]
Where \( A_b \) is the area of the bead and \( T_{gas} \) and \( T_b \) are temperatures of the gas and bead respectively. Heat transfer coefficient \( h \) can be calculated from equations (31 – 32) by considering the bead to be a spherical object.

\[
Nu = \frac{h \times D}{k} = 2 + \frac{0.589 \times Ra_D^{1/4}}{9 \left[ 1 + \left( \frac{0.469}{Pr} \right)^{16} \right]^{4/9}}
\]

Equation (31)

\[
Ra_D = \frac{g \times \beta \times (T_b - T_{gas}) \times D^3}{v^2} \times Pr
\]

Equation (32)

Equation 31 is showing the Nusselt number which shows the ratio of the convection to conduction heat interaction across the fluid layer. Equation 32 is Rayleigh number which is dimensionless and it is being used for calculating natural convection heat interaction. \( Pr \) is also another dimensionless number which depicts the velocity and thermal boundary layers thicknesses relatively.

The Nusselt number calculated is valid for \( Ra_D < 10^{11} \) and \( Pr > 0.7 \).

Finally, equation (28) becomes:

\[
h \times \left( T_{gas} - T_b \right) + \epsilon_b \times \sigma \times \left( T_{wall}^4 - T_b^4 \right) = 0
\]

Equation (33)

It needs to be mentioned that for obtaining convection coefficient we need to have the thermal conductivity of the gas. For calculating thermal conductivity there are relations that can be used and since these relations are based on gas temperature, it is needed to first assume a number for gas temperature and then by trial and error zero the equation (33). Finally, relations that were used for obtaining the properties of air have errors since they have been all derived empirically and this means that corrected gas temperatures can be even lower.
<table>
<thead>
<tr>
<th>Measured Temperature with Thermocouple (°C) (°C)</th>
<th>Corrected Gas Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>390</td>
<td>371</td>
</tr>
<tr>
<td>610</td>
<td>598</td>
</tr>
<tr>
<td>650</td>
<td>639</td>
</tr>
<tr>
<td>690</td>
<td>681</td>
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<tr>
<td>790</td>
<td>784</td>
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<tr>
<td>830</td>
<td>825</td>
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<tr>
<td>840</td>
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<td>855</td>
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<td>855</td>
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</table>

Table A2.1- Comparison between corrected and uncorrected temperature readings.
## APPENDIX IV

### Economic Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer Fed</td>
<td>kg/hour</td>
<td>1000</td>
</tr>
<tr>
<td>Carrier gas required</td>
<td>L per kg of polymer</td>
<td>250</td>
</tr>
<tr>
<td>Carrier Gas Feed [Nitrogen]</td>
<td>L/hour</td>
<td>250000</td>
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<tr>
<td>Hours/Shift</td>
<td>Hours</td>
<td>8</td>
</tr>
<tr>
<td>Shifts/Day</td>
<td>Quantity</td>
<td>2</td>
</tr>
<tr>
<td>Uptime</td>
<td>75%</td>
<td>0.75</td>
</tr>
<tr>
<td>Hours/Day</td>
<td>Hours</td>
<td>12</td>
</tr>
<tr>
<td>Maintenance Rate</td>
<td>$/hour</td>
<td>50</td>
</tr>
<tr>
<td>Daily Maintenance Cost</td>
<td>$/day</td>
<td>600</td>
</tr>
<tr>
<td>Labor Rate</td>
<td>$/hour</td>
<td>50</td>
</tr>
<tr>
<td>Daily Labor Cost</td>
<td>$/day</td>
<td>600</td>
</tr>
<tr>
<td>Daily Polymer Feed</td>
<td>kg/day</td>
<td>12000</td>
</tr>
<tr>
<td>Daily Carrier Gas Use</td>
<td>L/day</td>
<td>3000000</td>
</tr>
<tr>
<td>Energy Content LDPE</td>
<td>kJ/kg</td>
<td>46300</td>
</tr>
<tr>
<td>Pyrolysis Energy LDPE</td>
<td>kJ/kg (10% of total energy content, per appendix 2 calculations)</td>
<td>4630</td>
</tr>
<tr>
<td>Energy Input</td>
<td>kJ/day</td>
<td>555600000</td>
</tr>
<tr>
<td>Energy used to Pyrolyze</td>
<td>kJ/day (10% of total input)</td>
<td>55560000</td>
</tr>
<tr>
<td>Energy Available for Recovery</td>
<td>kJ/day</td>
<td>500040000</td>
</tr>
<tr>
<td>Wholesale Energy Price</td>
<td>New England, (<a href="http://www.eia.gov/electricity/wholesale/">http://www.eia.gov/electricity/wholesale/</a>), $/kWh</td>
<td>0.056</td>
</tr>
<tr>
<td>Recovered Energy Efficiency Factor</td>
<td>35%, typical Rankine cycle power plant</td>
<td>0.35</td>
</tr>
<tr>
<td>Recovered Energy</td>
<td>kJ/day</td>
<td>175014000</td>
</tr>
<tr>
<td>Recovered Energy</td>
<td>kWh/day</td>
<td>48615</td>
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<tr>
<td>Recovered Energy Value Per Day</td>
<td>$/day</td>
<td>2722.44</td>
</tr>
<tr>
<td>Cost of Carrier Gas</td>
<td>$/unit</td>
<td>0.00028</td>
</tr>
<tr>
<td>Daily Cost of Carrier Gas</td>
<td>$/day</td>
<td>840</td>
</tr>
</tbody>
</table>

Table A2.2-Costs for scaling up the system.
REFERENCES


The world factbook Country Comparison Oil – consumption. ISSN 1553-8133, 2012.


