
A Thesis presented

by

Saber Talebi Anaraki

to

The Department of Mechanical and Industrial Engineering

In partial fulfillment of graduation requirements in

Master of Science

in

Mechanical Engineering

In the field of

Thermofluids

Northeastern University
Boston, Massachusetts

July 2012
Abstract

The amounts of waste plastics discarded in developed countries are increasing drastically, and most are not recycled. The small fractions of the post-consumer plastics which are recycled find few new uses as their quality is degraded; they cannot be reused in their original applications. However, the high energy density of plastics, similar to that of premium fuels, combined with the dwindling reserves of fossil fuels make a compelling argument for releasing their internal energy through combustion, converting it to thermal energy and, eventually, to electricity through a heat engine. To minimize the emission of pollutants this energy conversion is done in two steps, first the solid waste plastics undergo pyrolytic gasification and, subsequently, the pyrolyzates (a mixture of hydrocarbons and hydrogen) are blended with air and are burned “cleanly” in a miniature power plant. This plant consists of a steam boiler, a steam engine and an electricity generator.
Acknowledgment

I would like to express my appreciation and gratitude to my academic advisor, Dr. Yiannis A. Levendis. His advice, guidance, and viewpoints always helped me to solve problems by approaching them from a different angle. Besides, I would like to thank Chuanwei Zhuo (PhD candidate), his experience in the lab helped kept the project on track. The Northeastern University machinist Jonathan Doughty was a tremendous help and he taught me a lot about machining. Finally, I want to thank my parents for all of their kindness and emotional support that they have given me during my entire life.
## CONTENTS

Abstract ............................................................................................................. 4

Acknowledgment ............................................................................................. 5

Contents ............................................................................................................. 6

Appendixes ....................................................................................................... 9

List of Figures .................................................................................................. 10

Chapter 1 (Introduction) .................................................................................. 12

1.1 Introduction ............................................................................................... 12

1.2 Reviews on the Properties of Plastics ...................................................... 13

1.3 Reaction of Plastics .................................................................................... 16

1.3.1 Pyrolysis ............................................................................................... 16

1.3.2 Thermal Decomposition of Waste Plastics .......................................... 18

1.3.3 Pyrolysis of Waste Plastics .................................................................... 22

1.3.4 Pyrolysis of Low Density Polyethylene ................................................ 22

Chapter 2 (Design and Development of Experimental Facilities) .............. 24

2.1 General Design .......................................................................................... 24
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2 Construction</td>
<td>26</td>
</tr>
<tr>
<td>2.2.1 Pyrolyser</td>
<td>27</td>
</tr>
<tr>
<td>2.2.2 Purging Chamber (Manual Feeding Process)</td>
<td>28</td>
</tr>
<tr>
<td>2.2.3 Feeding Chamber (Steady state Feeding)</td>
<td>29</td>
</tr>
<tr>
<td>2.3 Assembly</td>
<td>30</td>
</tr>
<tr>
<td>2.4 Pre-Testing</td>
<td>32</td>
</tr>
<tr>
<td>2.4.1 Temperature Gradient</td>
<td>33</td>
</tr>
<tr>
<td>2.4.2 Leak Test</td>
<td>36</td>
</tr>
<tr>
<td>2.4.3 Laboratory Scale Steam Engine</td>
<td>37</td>
</tr>
<tr>
<td>2.4.4 Plastics Feeding Rate</td>
<td>39</td>
</tr>
<tr>
<td>Chapter 3 (Results and Discussion)</td>
<td>40</td>
</tr>
<tr>
<td>3.1 Pyrolyser Testing Result</td>
<td>40</td>
</tr>
<tr>
<td>3.2 Results</td>
<td>41</td>
</tr>
<tr>
<td>3.3 Required Plastic to Start-up the System without Heater</td>
<td>43</td>
</tr>
<tr>
<td>Appendix I</td>
<td>48</td>
</tr>
<tr>
<td>Appendix II</td>
<td>50</td>
</tr>
<tr>
<td>Appendix III</td>
<td>54</td>
</tr>
</tbody>
</table>
Appendixes

Appendix I
Calculation of the feed-rate of low density polyethylene (LDPE) required maintaining miniature steam engine operation

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

Appendix III
Recycling Center-Based Waste-to-Energy Conversion

Appendix IV
Nitrogen Dilution
List of Figures

Chapter 1

F-1.1  Nomenclature of Recyclable Plastics  13
F-1.2  Simplified Depiction of Pyrolysis Chemistry  16
F-1.3  The Main Pyrolysis Products of PE  23

Chapter 2

F-2.1  Schematic of Experimental Prototype  25
F-2.2  Machine Shop of Mechanical and Industrial Engineering at NEU  26
F-2.3  Pyrolyser Assembly  27
F-2.4  Manual Purging Chamber Assembly  29
F-2.5  Automated Steady State Feeding System  30
F-2.6  Feeding Part Assembly  30
F-2.7  Pyrolyser System Assembly  31
F-2.8  Gas Temperature gradient at Different Elevation of the Pyrolysis Chamber  33
F-2.9  Temperature Gradient at Different Plates of Gasification Chamber  35
F-2.10 Pressure Holding Capability of the Pyrolyser an Initial Pressure of P=10
F-2.11 Pressure Drop at T= 850°C and P= 10 Psi

F-2.12 Steam Engine Boiler

F-2.13 Rankine Cycle

Chapter 3

F-3.1 One Gram LDPE pellet

F-3.2 Produced Blue Flame by Pyrolyser

F-3.3 Steam Engine Operation and Conversion of the Chemical Energy Stored in the Plastics to the Light

F-3.4 Expansion Prototype

Appendixes

Fig. A1 Simplified Depiction of Pyrolysis Chemistry

Fig. A2 Relation Between the Self-Sustaining Efficiency $\eta_s$ and the Feeding rate

Fig. A3 Flammability and Nitrogen Dilution of Ethylene Gas

Fig. A4 Flammability of Ethylene at Different Ratio
CHAPTER ONE

(Introduction)

1.1 Introduction

Worldwide energy consumption is rapidly increasing in modern times, especially due to exponential population growth and the proliferation of electronic devices and other technological conveniences. Since fossil fuel-based resources are finite and rapidly consumed, finding replacement options for power generation is crucial. Due to increasing demand driven by both developed and developing countries, fossil fuels reserves are expected to diminish in the future.

In 2010, 99 million barrels of petroleum were consumed yearly in the entire world, out of which 19 million barrels of this amount were consumed in the US. An amount equal of 5% of the latter were used to generate 30 million tons of plastics, out of which 14 million tons were used as containers and packaging materials. A majority of these plastics were then discarded ended up in landfill as non-biodegradable wastes. Some plastics are recycled (approx. 7 wt. %), and as plastics cannot be used in the same application once they are recycled (due to contaminations and other issues), the markets and consumer applications for recycled plastics are limited. Due to the high energy density of plastics, similar to that of premium fuel, this large quantity of waste plastics has the potential of being a viable energy source.

This work introduces a method for “Clean” conversion of waste plastics to
thermal energy and, eventually, to electricity.

1.2 Reviews on the Properties of Plastics

Pure plastics are organic polymers which contain components with high molecular mass. Most of plastics have petrochemical bases and are synthetic. Generally plastics could be synthetic or semi-synthetic\(^4\).

The different chain and molecular structures of plastics form their classifications. The acrylics, polyesters, silicones, polyurethanes, and halogenated plastics are some remarkable groups of these classifications. Plastics can also be classified by the chemical process used in their synthesis such as condensation, poly-addition, and cross-linking\(^4\).

Plastics are not degradable easily, hence they are durable. Thus, eventually become a source of solid pollution. Micro pellets can be produced from plastics breakdown and become the biggest environmental threat by plastics. These small particles could be eaten by fish and birds.

As plastics are not solvable in liquids such as water they generally have low toxicity. Commercial plastic containers have been classified based on their composition. As illustrated

<table>
<thead>
<tr>
<th>Nomenclature of Recyclable Plastics [F-1.1]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PETE</strong></td>
</tr>
<tr>
<td><strong>HDPE</strong></td>
</tr>
<tr>
<td><strong>PVC</strong></td>
</tr>
<tr>
<td><strong>LDPE</strong></td>
</tr>
<tr>
<td><strong>PP</strong></td>
</tr>
<tr>
<td><strong>PS</strong></td>
</tr>
<tr>
<td><strong>Other</strong></td>
</tr>
</tbody>
</table>

Saber Talebi Anaraki
in Figure [F-1.1], a plastic container using this scheme is marked with a triangle of three "chasing arrows", which encloses a number giving the plastic type.\(^4\)

1. PET (PETE), polyethylene terephthalate
2. HDPE, high-density polyethylene
3. PVC, polyvinyl chloride
4. LDPE, low-density polyethylene
5. PP, polypropylene
6. PS, polystyrene
7. Other types of plastics

This project mainly concentrates on pyrolysis of LDPE which is the most voluminous polymer in production and finds the most consumer applications.
For categorizing different types of plastic in a large scale, an automation system is required. Plastic bottles are separable by the carved number on the bottom of them. Some parts of recyclable plastics are not proper for recycling. These restrictions create problems for automation system. However, some developments are implementing new processes of mechanical sorting to increase capacity and efficiency of plastic recycling.

Sorting the types of plastic in large scale is not only difficult but also costly. In some cases, the mixtures of plastics make the process of sorting harder and cause extra expense. On the other hand, some sorts of plastics are not recyclable. For example, polystyrene is rarely recycled because it is usually not cost effective.

Plastics can be converted as a fuel since they are usually hydrocarbon-based and can be easily broken down into a liquid and further to a gas. One kilogram of waste plastic produces a liter of hydrocarbon. Burning plastics (direct combustion) releases toxic fumes. Burning the plastic polyvinyl chloride (PVC) may also create toxic polychlorinated dioxins. Thus, it is recommended that PVC is separated out prior to feeding waste plastics to a combustor.
1.3 Plastics Reactions

1.3.1 Pyrolysis

Pyrolysis is a thermochemical decomposition of organic material at high temperatures without the participation of oxygen. As shown in the figure [F-1.2], this irreversible process involves simultaneous changes of chemical composition as well as physical phase.

Pyrolysis is a case of thermolysis, and is most commonly used for organic materials, being one of the processes involved in charring. In general, the products of pyrolysis of organic substances are gas, liquefied products, and solid residue richer in carbon content (char). Extreme pyrolysis, which leaves mostly carbon as the residue, is called carbonization.

The process is used heavily in the chemical industry to produce charcoal, and other chemicals from wood, to convert ethylene dichloride into vinyl chloride (and then PVC), to produce coke from coal, to convert biomass into syngas and bio-char, to turn waste into safely disposable substances, and for transforming medium-weight hydrocarbons from oil into lighter ones like gasoline. These specialized uses of pyrolysis may be called various names, such as dry distillation, destructive distillation, or cracking.

The main difference between pyrolysis and the other high temperature
process like combustion, hydrolysis, and gasification is the reaction in lack of oxygen, water or any other reagents. In practice, it is not possible to achieve a completely oxygen-free atmosphere. Because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs.

The term has also been applied to the decomposition of organic material in the presence of superheated water or steam (hydrous pyrolysis), for example, in the steam cracking of oil⁶.
1.3.2 Thermal Decomposition of Waste Plastics

Thermal properties of various solid waste plastics are different during all phases of thermal decomposition. For this issue one must examine the thermal destruction behavior of different components in the wastes under controlled conditions. Results are presented on the thermal decomposition characteristics of different types of polymers under controlled thermal and chemical environments. Generated compounds represent important composition of the wastes. Thermogravimetry (TGA) tests and Differential Scanning Calorimetry (DSC) tests have been conducted by others on the thermal decomposition of polyethylene, polypropylene, polystyrene, polyvinyl chloride, and cellulose in nitrogen gas. The material composition and properties, heating rate, and surrounding gas chemical environment affect the material decomposition rates under defined conditions. The composition of waste materials significantly affects the thermal decomposition behavior. Experimental results show that decomposition process shifts to higher temperatures at higher heating rates as a result of the competing effects of heat and mass transfer to the material. The results on the maximum decomposition temperature and heat of pyrolysis obtained from the thermal decomposition of surrogate wastes showed significantly different features between the aforsaid materials. Energy evolved at the early stages from certain easy to decompose materials can be used to destruct the other materials that decompose at higher temperatures or require more energy to decompose. The energy required to decompose the material is only a small
fraction of the chemical energy evolved from the material.

Conesa et al.\textsuperscript{8} reported that thermal treatment of PE at temperature of 800°C convert 97.5wt% of its mass to gas. The remaining (residue) 2.5% is a mixture of oils and tars. Similarly, Kaminsky\textsuperscript{9} pyrolyzed PE wastes in a pilot plant and reported a gaseous hydrocarbon yield of 96% at 810°C. Finally, Westerhout et al.\textsuperscript{10} recorded the range of conversions of waste plastics to gas is between 80-90%, with compositions depending on temperature. The gaseous stream of hydrocarbons may then be mixed with air and burned in furnaces operating with premixed flame burners, such as those found in natural-gas-fired boilers. Part of the heat released in the furnace may be used in a heat-exchanger/gasifier unit to gasify incoming fuel.

This study concentrated on polyethylene (PE), the most abundant waste plastics. This investigation was partly motivated by the work of Jinno et al.\textsuperscript{11,12}, who measured the heat of pyrolysis of PE to be 254 kJ/kg, and found this value to be nearly-independent of the heating rate. Comparing the heat of pyrolysis to the heating value (energy content) of this polymer, which is 46,300 kJ/kg, it becomes evident that only a rather insignificant fraction of the heat released during combustion may be needed to be fed back to pyrolyze this fuel. This illustrates that a gaseous fuel stream may be produced from such wastes by implementing favorable heat integration. Only a small penalty in energy, and thus in the operating cost of a power plant, will be encountered in running the gasifier.

The decomposition temperature of Polyethylene (PE), either as high-
density (HDPE) or low-density (LDPE), starts at 290°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\textsuperscript{13}. The weight loss is negligible until 370°C is reached. The main decomposition products are: oil/wax product dominated by alkenes, alkynes, and alkadienes; a gas consisting of mainly of alkanes and alkenes; and negligible char\textsuperscript{13,14}. The monomer precursor ethylene (ethane) 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. Gaseous products of waste plastics are favored as the temperature of pyrolysis increases. Extensive work by Conesa and co-workers\textsuperscript{8,15} examined the effects of the polyethylene type, the effects of polymer branching, the effects of batch versus continuous operation, as well as 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.\textsuperscript{16} and Kaminsky\textsuperscript{9}. Westerhout et al.\textsuperscript{10} found that, at 800°C, the product contains more methane than ethylene and low amounts of aromatics, but 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.\textsuperscript{17} 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
started 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.

Several investigations examined the direct combustion of solid pellets or
particles of polyethylene (PE), where the solid polymer was inserted in a furnace
where it was pyrolyzed and burned in air, in non-premixed (diffusion) envelope
flames. The emissions of products of incomplete combustion (PIC), such as CO,
light hydrocarbons, polycyclic aromatic hydrocarbons (PAH) and particulates
were monitored\textsuperscript{18,19,20,21,22}. Therein, efforts to minimize pollutant emissions were
made using techniques such as combustion staging, regulation of furnace
temperatures and feeding rates, installation of an afterburner and employment of
high-temperature barrier filters\textsuperscript{23,24,25}. Conditions were identified where most of
these pollutants could be curtailed.
1.3.3 Pyrolysis of Waste Plastics

Direct combustion of post-consumer plastics in waste incinerators may release their stored internal energy (ca. 46,000 kJ/kg)\textsuperscript{26}; however, conventional direct combustion leads to diffusion flames (around devolatilizing solids) and inefficient energy production. That generates large amounts of health-hazardous soot, hydrocarbons and other pollutants.

The presented method is based on waste pyrolysis, followed by indirect combustion of the generated pyrolyzates. This method right now is proven in the laboratory with a continuous flame which is sufficient to generate electricity with a model steam engine and dynamometer. This method of sequential waste plastics gasification/combustion produces much less pollutants\textsuperscript{27,28} than direct combustion.

1.3.4 Pyrolysis of Low Density Polyethylene

This project mainly focused on the gasification of low density polyethylene (LDPE); using one type of plastics keeps measurement consistent.

Based on analytical results obtained in this laboratory\textsuperscript{28}, the contents of the gasified polyethylene (PE) are shown below; [F-1.3]

Ethylene (38%),
Propylene (17%),
Methane (14%),
Hydrogen (8%),
Butadiene (5%),
Ethane (4%),
Butane (4%),
Benzene (3%),
Ethyl-acetylene (2%),
Propane (1%),
Acetylene (0.3%),
CHAPTER TWO

(Design and Development of Experimental Facilities)

2.1 General Design

The goal of this laboratory-scale experiment is to produce a continuous flame with sufficient energy to run a model steam engine and generate DC electricity through a dynamometer and, eventually, to turn on a light bulb.

A key requirement for the experimental setup is to provide a continuous flow of LDPE pellets to the system at a mass flow rate in the order of 1 g/min. [Appendix I] Also the system should be well-sealed to avoid direct combustion during the pyrolysis of the plastics.

The method of pyrolysis of waste plastics contains three major steps. First, plastics are fed to the system at a constant feeding rate. Next, the plastics are purged of air via injection of nitrogen to the system. Finally, the plastics are heated up, liquefied, and gasified to complete the process of pyrolysis.

In initial experiments batches of granulated post-consumer plastics were fed manually into the system as shown in figure [F-2.1]. Nitrogen gas was used to purge the air, and the plastics moved into the heater for gasification via gravity feed. A positive upstream pressure in the system of 5 psig was maintained to carry the pyrolysis gases through the system. Pressure relief valves are utilized as a backup in the event of an overpressure. Operating the system at high temperature
requires that not only the system should be sealed safely but also the sealing equipment and materials must be selected properly.

The size of equipment is about 4 feet high and 2 feet long. This size helps all parts of the equipment to be accessible. This project is of a laboratory scale, hence it has a limited capacity for processing waste plastics (pelletized waste post-consumer LDPE) feedrates.
2.2 Construction

The three main parts of the system have been constructed specifically for this project, which include the pyrolyser, purging chamber, and feeding system. All manufacturing has been done in the Mechanical and Industrial Engineering department’s machine shop [F-2.2]. Making the parts ourselves gave us the
advantages of low cost (availability of scrap materials, no labor charge for machine time) and flexibility – parts could be modified or manufactured immediately as needed.

2.2.1 Pyrolyser

The main part of the system is the pyrolyser, which is basically a chamber where pellets are heated, liquefied, and eventually gasified at high temperature (around 800°C). The pyrolysing chamber needed to be made from a non-reactant material as well as to be large enough to allow room for the plastics to expand and
gasify. Heat conduction and convection are the two main heat interaction methods that the pyrolyser relies on to gasify the plastics. The pyrolyser was constructed of stainless steel. By using stainless steel perforated plates inside the gasification chamber, the conduction heat transfer through the plates made the process of gasification more uniform. [F-2.3]

Perforated plates at several elevations provided sufficient contact area for the pellets to be gasified. Two exits have been set up at the bottom of the pyrolyser. One is for exhausting the pyrolyzate gas and the other one is a pressure relief valve. The tubes sit approximately one inch above the bottom of the pyrolysis chamber to ensure that any particulate matter or soot that collects in the bottom of the chamber does not clog or interfere with the pipes.

2.2.2 Purging Chamber (Manual Feeding Process)

The area between the feeding system and the pyrolyser is called the purging chamber. In this part, nitrogen gas was introduced to the system to purge the air. At the first stage of project the purging process was manual and was controllable by two butterfly valves. Plastics were fed batch-wise in to the system by hand. This step became eventually unnecessary due to installation of an automatic feeder.
The purging chamber [F-2.4] contains four parts. Pellets were fed when the bottom valve (V-2) was closed. Nitrogen gas (I-1) purged the air when top valve (V-1) and bottom valve (V-2) were closed. After about 30 seconds the bottom valve (V-2) was opened and purged pellets from the air are fed to the pyrolyser via gravity. For safety issues a pressure gauge and a safety valve have been provided on the system as an outlet of excess pressure, should the need arise (O-1).

2.2.3 Feeding chamber (Steady State Feeding)

The feeding chamber’s main goal is feeding plastics to the purge chamber at a consistent ratio. This will produce a uniform amount of exhaust gas and consequently a flame with minimal fluctuation in size and intensity.

The feeding system [F-2.5] has been made of three main parts: a reservoir with a hopper, an electrical motor, and an auger/feeding box. Pellets are fed into the reservoir and gravity fed through the hopper. The variable speed electric motor drives the auger and feeds plastics into the feeding box, through which the plastics dropped into the purge chamber. The rotating auger uses a sealed bearing to maintain nitrogen pressure and to minimize leakage from the system.
2.3 Assembly

After manufacturing and testing all individual parts, the system was assembled. [F-2.6], [F-2.7]
As shown in the pictures above [F-2.7], an electric heater was used to heat the pyrolyzer chamber. This is a Model 3110 electric resistant furnace, was made by ATS (Applied Test Systems, INC), consuming 1430 Watts power with maximum temperature of 1000˚C. All connections and frames have been assembled at Northeastern University with components purchased from McMaster Carr. The gasket between flanges is high temperature resistance and provided by Garlock Company.
2.4 Pre-Testing

Before feeding the plastics and running the entire system, it is necessary to do some component-level testing. These tests were conducted to assess the temperature gradient in the pyrolysis chamber, overall system leak-proof capability, and the feed rate as well as the reliability of the hopper/motor/drill assembly.
2.4.1 Gas Temperature Gradient

The gas temperature of the pyrolysis chamber needed to be measured to ensure the plastics are reaching the optimum temperature for pyrolysis. Shown in the graph below is the $T_{\text{gas}}$ gradient in the pyrolysis chamber. [F-2.8], [F-2.9]

Gas temperature gradient at different elevations of the pyrolysis chamber [F-2.8]
The results show that setting the temperature of the electric heater at 950°C is reasonable to provide sufficient energy to heat the incoming pellets and liquefy them to the temperature of 200°C (melting point of LDPE has been noted as 110°C - heat loss during the experiment should be considered\textsuperscript{29}). Also the temperature of chamber through the way is high enough to gasify the liquefied pellets. It means the pellets are capable to be liquefied and at the end of chamber they will be completely gasified. The high temperature inside the chamber provides enough heat to let the pellets convert from solid to gas.

In addition, the temperature gradients on the perforated plates are sufficiently high enough to satisfy the process of liquefaction and gasification. Lower plates have higher temperatures and this helps all polymer matter to be gasified before exiting through exhaust line.
Temperature gradient at different plates of the pyrolysis chamber [F-2.9]
2.4.2 Leak Test

The most leak-prone connections in the system are the flanges between the gasification and purging chamber. High temperature gasket has been used for sealing of the flanges. The gradient of pressure drop is shown below. [F-2.10]

![Pressure Drop Graph](image)

Pressure Holding Capability of the Pyrolyser with Initial Pressure of P=10 psi [F-2.10]

The flange bolts were tightened to 400 in-lb and the set pressure was 10 psi. In addition, the safety valves were tested and their relief pressure at the ambient temperature was 34 psi. The same condition has been repeated at operating temperature of 850°C. All the results are reproducible and that the connections were sufficiently sealed. [F-2.11]
2.4.3 Laboratory Scale Steam Engine

In order to prove the experiment’s result a miniature steam engine was procured. A miniature steam engine (supplied from Wilesco-D18)\textsuperscript{30} was utilized and integrated with the pyrolysis chamber. This steam engine operates on the Rankine Cycle principle [F-2.13]. As shown in [F-2.12] the assembly contains a boiler, a steam engine, a electricity generator and a light post.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Pressure_Drop.png}
\caption{Pressure Drop during the Leak Test at T= 850°C and P= 10 psi [F-2.11]}
\end{figure}
This Rankin cycle shown below is similar with the steam engine available in the laboratory. As shown, boiler, heat supply, and turbine (engine) have the same applications. The output shaft work is converted to electricity.
2.4.4 Plastics Feeding Rate

This is a method to determine the appropriate feeding rate of plastics. The steam engine was initially run on the bench using a cylinder of compressed ethylene gas. Ethylene was used due to its similarity to the LDPE pyrolyzate gas. For example, the major component of LDPE pyrolyzates was determined to be ethylene, therefore it is reasonable to use ethylene as the surrogate fuel. Once the necessary flow rate of ethylene gas was determined, the amount of plastic pellets required to pyrolyse and produce the same amount of energy was calculated to be 0.3 g/min. [See Appendix I]
CHAPTER THREE

(Results and Discussion)

3.1 Pyrolyser Test Results

Temperature controller set point was set to 950°C in purpose of reaching the appropriate heating and pyrolysis condition. The system must be kept at this temperature at least for 2 hours to ensure all parts of the system are heated to their final temperatures. Prior to adding plastics, the system is purged with 0.5 l/min for 5 minutes of nitrogen (N₂) gas to evacuate any air [Appendix I], [Appendix IV].

Next, the plastic pellets (one gram pellets spread on a paper occupy roughly about the size on a quarter [F-3.1]) are fed into the hopper and the motor was turned on. At the pyrolysis chamber the pyrolysis process of plastics occurs. The gasified plastic is then ignited in a small Bunsen burner forming a premixed flame. [F-3.2]
3.2 Results

The goal of this project is to produce a continuous flame with sufficient energy to run a miniature steam engine and generate DC electricity through a dynamometer and to eventually to turn on a light bulb. The energy released through the pyrolyzates combustion is more than sufficient to power the steam engine. The flame burns with a bright blue color [F-3.3]. The steam engine system is 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. The operational speed is sufficient to use the on board dynamometer to generate a small electric current to illuminate the miniature light bulb. This successfully proves the concept that waste plastics can be used to produce gaseous fuels with high energy content and, in turn, generate useful work in the form of electricity.

Future applications of this technology would be in the large scale production of pyrolyzate gas on-site for use in a power plant. The calculations shown in [Appendix II], and in [Appendix III] express the efficiency of this concept as applied to a traditional Rankine Cycle power plant operating on a commercial scale.
Steam Engine Operation and Conversion of the Energy Stored in the Plastics to Light [F.3.3]
3.3 Required Plastic to Start-up the System without Heater

In a commercial application the electric furnace that was used in this experimental apparatus to heat-up the pyrolyser will be replaced with a device that uses some of the gasified plastic in a burner as a source of energy input. For this design, an energy balance calculation has been done to obtain the minimum follow rate of pelletized polyethylene required to just heat the system up to 950°C. Additional follow rate of plastics will generate power output or other targeted types of energy. [F-3-4]

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 ($E_{\text{Pyrolysis}}$) is the amount of energy required to gasify the pellets. Heat Loss energy ($E_{H,L}$) is the heat loss from the system to ambient and all other unforeseen wastes. Feed energy ($E_F$) corresponds to the amount of gas required to heat the pyrolysis chamber to 950°C multiplied by its energy content. The energy balance equation has been shown below;
Expansion Prototype [F.3-4]
\[ E_{\text{in}} = E_{\text{Pyrolysis}} + E_{\text{HL}} + E_{\text{Feed}} \]

**Calculation of \( E_{\text{Pyrolysis}} \):**

The energy required for pyrolysis of polyethylene at 455°C has been reported to be 254 kJ/kg\(^2\). This amount of energy at 950°C per unit mass of feedstock can be calculated as,

\[ Q_{\text{pyrolysis}} = C_p \Delta T \]

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

Interpolating to calculate specific heat at \( T=975 \text{K} \)

\[ \frac{C_p - 3.088}{T_{\text{avg}} - 850} = \frac{3.18 - 3.088}{900 - 850} \]

\[ C_{p_{975}} = 3.318 \text{ kJ/kgK} \]

\[ Q_{\text{pyrolysis}} = 254 + 3.318 \times (950 - 455) = 1896 \text{ kJ/kg} \]

**Calculation of \( E_{\text{HL}} \):**

It has been assumed the heat loss of insulation and nitrogen flow. The number will be multiply by a factor of safety.

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

\[ \text{Thk} = 12-3.75 = 8.25'' \times (0.0254) = 0.2 \text{ m} \]

\[ A = 2\pi rL = 2\pi (6'' \times 0.0254) \times (6'' \times 0.0254) = 0.15 \text{ m}^2 \]

\[ \Delta T = 950 - 25 = 925 \text{ K} \]

The energy required to heat up the stream of inert nitrogen carrier gas in the
pyrolyzer is calculated as shown below;

\[
\dot{E}_{N_2} = \frac{C_p \rho \dot{q} \Delta T}{3600} = \frac{1040 \left( \frac{J}{\text{kg.K}} \right) 1.2 \left( \frac{g}{\text{lit}} \right) 0.25 \left( \frac{\text{lit}}{\text{min}} \right) (2030 - 25)(K) \frac{\text{kg}}{1000 \text{ g}}}{3600}
\]

\[
= 0.17 \left( \frac{J}{\text{min}} \right) = 0.003 \left( \frac{J}{s} \right)
\]

Which is negligible.

The total heat loss has been multiplied by a factor of 2 to consider all unpredicted and unknown losses.

\[
\dot{E}_{H,L} = 35 \times 2 = 70 \frac{J}{s}
\]

Heat loss is the amount of heat waste around the heater and insulation, heat.
loss due to nitrogen flow, and other unpredicted factors.

Substituting in the energy balance equation;

\[ m \times 46300 = \dot{m} \times Q_{\text{pyrolysis}} + E_{\text{H,L}} + 1430 \]

\[ \left( \frac{g}{s} \right) \times \left( \frac{1}{g} \right) = \left( \frac{g}{s} \right) \times \left( \frac{1}{g} \right) + \left( \frac{1}{s} \right) + \left( \frac{1}{s} \right) \]

\[ m \times 46300 = (m \times 1896) + 70 + 1430 \]

\[ m \times (46300 - 1896) = 70 + 1430 \]

\[ \left( \frac{g}{s} \right) \times \left( \frac{1}{g} \right) = \left( \frac{1}{s} \right) \]

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

This calculation shows that 2 g/min pellets are required to heat this laboratory-scale pyrolyser 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 I

Calculation of the feed-rate of low density polyethylene (LDPE) required to maintain miniature steam engine operation

The steam engine purchased from Mini Steam (Wilesco) Company was run on ethylene, and the flow of gas was regulated to produce consistent steam pressure in the boiler (and consistent operation of the steam engine). The ethylene gas flow was measured to be 0.25 L/min, or 250 cm$^3$/min.

$$Q_{\text{ethylene}} = 0.25 l/min = 250 \text{ cm}^3/\text{min}$$

To find out the equivalent amount of solid powder required, first we need to figure out the volumetric expansion of solid LDPE to gaseous LDPE. The ratio of solid to gaseous volume is inversely proportional to the ratio of the densities of the LDPE and ethylene.

$$\frac{\rho_{\text{LDPE}}}{\rho_{\text{ethylene}}} \approx \frac{V_{\text{ethylene}}}{V_{\text{LDPE}}}$$

Given that the density of solid LDPE is 940 kg/m$^3$, and the density of ethylene is 1.178 kg/m$^3$, the ratio between them is calculated as follows:

$$\frac{\rho_{\text{LDPE}}}{\rho_{\text{ethylene}}} = \frac{940 \text{ kg/m}^3}{1.178 \text{ kg/m}^3} = 798$$

This gives a volumetric expansion coefficient of 798 for converting solid
LDPE to gaseous ethylene.

\[ V_{\text{LDPE}} = \frac{V_{\text{ethylene}}}{798} \text{ (cm}^3\text{)} \]

Assuming the flow rate of gaseous LDPE should be the same as the ethylene gas, the following relationship is used to compute the amount of solid plastics required.

\[ m_{\text{LDPE}} = \rho_{\text{LDPE}} \cdot V_{\text{LDPE}} \]

Substitute in the volumetric relationship from above:

\[ m_{\text{LDPE}} = \rho_{\text{LDPE}} \cdot \frac{V_{\text{ethylene}}}{798} \]

Input values for density, flow rate, and unit conversions:

\[ \dot{m}_{\text{LDPE}} = 940 \text{ kg/m}^3 \cdot \frac{250 \text{ cm}^3/\text{min}}{798} \cdot \left( \frac{1 \text{ m}^3}{1,000,000 \text{ cm}^3} \right) \]

\[ \dot{m}_{\text{LDPE}} = 0.000295 \text{ kg/min} = 0.295 \text{ gr/min} \]

The final answer yields a result of approximately 0.3 gr/min of LDPE needed to run the miniature steam engine at about 1800 RPM.
Appendix II

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

The self-sustaining efficiency, $\eta_s$ is defined as follows:

$$\eta_s = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{E_{\text{out}}}{E_{\text{in}}} = \frac{\dot{E}_{\text{out}}}{\bar{E}_{\text{in}}}$$

Equation (1)

where $E_{\text{out}}$ 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 pyrolyse 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 $\bar{E}$ refers to $E$ per unit mass. A simplified energy balance can therefore be obtained as:

$$E_{\text{Out}} = E_{\text{in}} \cdot E_{\text{Pyrolysis}} \cdot E_{\text{Loss}}$$

Equation (2)

$$\frac{\dot{E}_{\text{Out}}}{\text{kg of PE}} = \frac{E_{\text{in}}}{\text{kg of PE}} \cdot \frac{E_{\text{Pyrolysis}}}{\text{kg of PE}} \cdot \frac{E_{\text{Loss}}}{\text{kg of PE}}$$

Equation (3)

$$\frac{\dot{E}_{\text{Out}}}{\text{kg of PE}} = \frac{E_{\text{in}}}{\text{kg of PE}} \cdot \frac{E_{\text{Pyrolysis}}}{\text{kg of PE}} \cdot \frac{E_{\text{Loss}}}{\text{kg of PE}}$$

Equation (4)

$$\bar{E}_{\text{Out}} = \bar{E}_{\text{in}} \cdot \bar{E}_{\text{Pyrolysis}} \cdot \bar{E}_{\text{Loss}}$$

Equation (5)

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

\[
\underbrace{E_{\text{Pyrolysis}@800^\circ C}}_{\text{(Equation (6))}} = \underbrace{E_{\text{Pyrolysis}@455^\circ C}}_{\text{Equation (6)}} + C_p \times \Delta T
\]

\(C_p\) 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,

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

\(C_{p@900K} = 3.18 \frac{kJ}{kg \cdot ^\circ C}\), and Equation (6) yields

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

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,

\[
\overline{E_{\text{Loss}}} = \frac{t \times \dot{Q}_{\text{Insulation}}}{\text{kg of PE}} = \frac{t \times k \Delta T \times \epsilon}{\text{kg of PE}}
\]

Equation (7)

Where \( \dot{Q}_{\text{Ins}} \), is the heat loss through the insulation per second,
\[ \dot{Q}_{\text{Ins}} = \frac{kA\Delta T}{d} \quad \text{Equation (8)} \]

A was defined as the outer surface area of insulation and L as the insulation thickness. \( \Delta T \) is temperature difference between heater and ambient. The thickness of insulation is shown in Figure A1.

\[ d = 12.375 = 8.25'' = 0.2 \text{ m} \]

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

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

Therefore, Equation (7) yields:

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

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

\[ t = \frac{1000 \text{ g}}{0.3 \text{ g/min}} = 3333.3 \text{ minutes} = 200,000 \text{ seconds} \]

Based on Equation (1)

\[ \eta_s = \frac{46,300 - 1,352 - 0.06 \times t}{46,300} = \frac{46,300 - 1,352 - 0.06 \times 60 \times \frac{1000}{m}}{46,300} \]

\[ = \frac{32,948}{46,300} \approx 71.16\% \quad \text{Equation (9)} \]

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.

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

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

Recycling Center-Based Waste-to-Energy Conversion

Currently there are 31.04 million tons of plastics generated in U.S alone, of which 2.36 million tons are recycled (2). With the assumed energy content of these plastics, 25 MJ/kg, as the averaged value, a simplified calculation can be applied to estimate the potential electricity amount which can be produced by adopting the proposed self-sustaining process:

\[
P_{\text{Electricity}} = \eta_{\text{power plant}} \times P_{\text{Out}}
\]

\[
= \eta_{\text{power plant}} \times \eta_{S} \times P_{\text{In}} 
\]

Equation (10)

\[
= \eta_{\text{power plant}} \times \eta_{S} \times \frac{E_{\text{in}}}{\text{time}}
\]

\[
\approx 0.3 \times 0.71 \times 25 \frac{\text{MJ}}{\text{kg}} \times 2.36 \times 10^6 \text{ tons} \times \frac{1000 \text{ kg}}{\text{ton}} \times \frac{1 \text{ year}}{365 \text{ days}} \times \frac{24 \text{ hours}}{\text{day}}
\]

\[
= 1,434 \text{ GWh}
\]

In 2010, the average annual electricity consumption for a U.S. residential utility customer was 11,496 kWh; therefore, the electricity produced using recycled waste plastics can supply the residential utility customer with the number of

\[N = 1,434 \text{ GWh}/11,496 \text{ kWh} \approx 125,000\]

It should be noted that this estimation takes conservative measures on both the available waste plastics and the efficiency. Improvements on increasing the recycling rate as well as on the self-sustaining efficiency, as mentioned in
Appendix II, could further provide more energy from these waste plastics.
Appendix IV

Nitrogen Dilution

As it mentioned the system should be purged by the inert gas nitrogen to prevent ignition and combustion during pyrolysis. On the other hand, the amount of nitrogen should be controlled to reduce the consumption of this carrier gas, as well as to not affect the combustion of the pyrolyzate gases. For this issue the mixture of nitrogen with ethylene gas (the major exhaust gas [F-1.3]) in different rate has been tested to find out the amount of nitrogen could be mixed with the exhaust gas to produce stable blue flame, upon mixing with air. The experiment was started with a fuel lean fuel/air mixture. The equivalence ratio was set to be $\phi=0.72$.

$$C_2H_4 + 3(O_2 + 3.76N_2) \rightarrow 2CO_2 + 2H_2O + 11.28N_2$$

$$\phi = \frac{\frac{n_{\text{fuel}}}{n_{\text{air}}}}{\frac{n_{\text{fuel}}}{n_{\text{air}}}_{\text{stoichiometric}}} = \frac{\frac{n_{\text{fuel}}}{n_{\text{air}}}}{\frac{1}{3 + 3 \times 3.76}} = 0.72$$

$$\frac{n_{\text{fuel}}}{n_{\text{air}}}_{\text{actual}} = 0.05 \text{ or } \frac{n_{\text{air}}}{n_{\text{fuel}}}_{\text{actual}} = 20$$

$$C_2H_4 + \frac{3}{1.8}(O_2 + 3.76N_2) \rightarrow \alpha CO_2 + \beta CO + \gamma H_2O + \delta H_2 + 6.26N_2$$

$$\begin{cases} 
\alpha + \beta = 2 \\
\gamma + \delta = 2 \\
2\alpha + \beta + \gamma = \frac{6}{20} \\
\delta = \frac{\beta}{2} \text{ Assumption for } \phi > 1.2 
\end{cases}$$
\[ C_2H_4 + \frac{3}{1.8}(O_2 + 3.76N_2) \rightarrow 2CO_2 + 0CO + 2H_2O + 0H_2 + 6.26N_2 \]

\[ \dot{V}_{C_2H_4} = 0.12 \text{lit/min}, \rho_{C_2H_4} = 1.178 \text{g/lit} = \frac{\dot{m}}{V} \Rightarrow \dot{m} = 1.178 \left( \frac{\text{g}}{\text{lit}} \right) \times 0.12 \left( \frac{\text{lit}}{\text{min}} \right) = \]

\[ \Rightarrow \dot{n}_{C_2H_4} = \frac{0.14 \left( \frac{\text{g}}{\text{min}} \right)}{28 \left( \frac{\text{g}}{\text{mol}} \right)} = 0.005 \left( \frac{\text{mol}}{\text{s}} \right) \]

Now nitrogen added to the system at the different volumetric flow rates of 0.12, 0.24, and 0.36 lit/min.

\[ \rho_{N_2} = 1.2 \text{g/lit} = \frac{\dot{m}}{V} \Rightarrow \dot{m} = 1.2 \left( \frac{\text{g}}{\text{lit}} \right) \dot{V}_{N_2} \left( \frac{\text{lit}}{\text{min}} \right) \Rightarrow \dot{n}_{N_2} = \frac{1.2 \dot{V}_{N_2} \left( \frac{\text{g}}{\text{min}} \right)}{14 \left( \frac{\text{g}}{\text{mol}} \right)} = 0.086 \dot{V}_{N_2} \left( \frac{\text{mol}}{\text{s}} \right) \]

\[ \dot{V}_{N_2} = 0.12 \Rightarrow \dot{n}_{N_2} = 0.01 \left( \frac{\text{mol}}{\text{s}} \right) \]

\[ \dot{V}_{N_2} = 0.24 \Rightarrow \dot{n}_{N_2} = 0.02 \left( \frac{\text{mol}}{\text{s}} \right) \]

\[ \dot{V}_{N_2} = 0.36 \Rightarrow \dot{n}_{N_2} = 0.03 \left( \frac{\text{mol}}{\text{s}} \right) \]

So the chemical balance with this amount of ethylene gas is going to be,

\[ 0.005C_2H_4 + 0.02(O_2 + 3.76N_2) \xrightarrow{\dot{n}_{N_2}=0} 0.01CO_2 + 0.01H_2O + 0.075N_2 \]

\[ 0.005C_2H_4 + 0.02(O_2 + 3.76N_2) + 0.01N_2 \xrightarrow{\dot{n}_{N_2}=0.01} 0.01CO_2 + 0.01H_2O + 0.085N_2 \]

\[ 0.005C_2H_4 + 0.02(O_2 + 3.76N_2) + 0.02N_2 \xrightarrow{\dot{n}_{N_2}=0.02} 0.01CO_2 + 0.01H_2O + 0.095N_2 \]

\[ 0.005C_2H_4 + 0.02(O_2 + 3.76N_2) + 0.03N_2 \xrightarrow{\dot{n}_{N_2}=0.03} 0.01CO_2 + 0.01H_2O + 0.105N_2 \]

With these amounts of additive nitrogen, all the above diluted mixtures of ethylene gas and nitrogen resulted in stable flames.

The ensuing graph shows the ratio of ethylene gas over the total gas, i.e., the amount of ethylene gas plus air plus diluent nitrogen plotted versus the ratio of
diluent nitrogen over the amount of the diluents nitrogen gas plus plus the amount of ethylene gas.

<table>
<thead>
<tr>
<th></th>
<th>( \dot{n}_{C_2H_4} )</th>
<th>( \dot{n}_{\text{air}} )</th>
<th>( \dot{n}_{N_2} )</th>
<th>( \frac{\dot{n}<em>{C_2H_4}}{\dot{n}</em>{C_2H_4} + \dot{n}<em>{\text{air}} + \dot{n}</em>{N_2}} \times 100 )</th>
<th>( \frac{\dot{n}<em>{N_2}}{\dot{n}</em>{N_2} + \dot{n}_{C_2H_4}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.005</td>
<td>0.02</td>
<td>0.01</td>
<td>14%</td>
<td>0.67</td>
</tr>
<tr>
<td>2</td>
<td>0.005</td>
<td>0.02</td>
<td>0.02</td>
<td>11%</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>0.005</td>
<td>0.02</td>
<td>0.02</td>
<td>9%</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Figure A3. Flammability and Nitrogen Dilution of Ethylene Gas
Figure A4. Flammability of Ethylene at Different Ratio

Figure A5. Nitrogen Dilution of Ethylene
Figure A3 shows our dilution experiment. The ethylene gas has been diluted with nitrogen with different ratios, as shown. Compare with the Extended Le Chatelier’s formula and nitrogen dilution effect on the flammability limits. The results are a good match with each other. The Figure A3 has been matched on the Figure A4 and the graph has the similar flammability ratio.

Figure A5 shows a visual result of the experiment regarding to the flammability and nitrogen dilution.
References

Chapter One


3 EPA, Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010

4 http://plastics.americanchemistry.com/Life-Cycle. Lifecycle of a Plastic Product by American Chemistry Council


18 Panagiotou, T.; Levendis, Y.A.; Carlson J.; Vouros, P. Proceedings of The Combustion Institute, 1996, 26, 2142-2460
20 Wheatley, L.; Levendis, Y.A.; Vouros, P. Environmental Science and Technology, 1993, 27, 2885-2895
21 Font, R.; Aracil, I.; Fullana, A.; Conesa, J.A. Chemosphere, 2004, 57, 615-627
26 Zhuo, C. ”Synthesis of carbon nanotubes from waste polyethylene plastics” 2009, [http://hdl.handle.net/2047/d20000794](http://hdl.handle.net/2047/d20000794)
Chapter Two

29 http://www.rotationalmoulding.ca/materials/polyethylene.htm
30 http://www.ministeam.com/acatalog/Wilesco_Steam_.html

Chapter Three

31 Kondo;S., Takizawa;K., Takahashi;A., Tokuhashi;K. “Extended Le Chatelier’s formula and nitrogen dilution effect on the flammability limits”