

# PYROLYSIS OF PLASTIC WASTE INTO FUEL AND OTHER PRODUCTS

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**SUMMARY:** In this article, we propose, design and implement a sustainable systems approach that converts plastic solid waste (PSW) into useful chemical products. The nature of the feed material for our process (PSW) make our proposed technology serve a dual purpose of not only taking care of the waste management problem, but also producing cheaper, safer and more easily accessible products for the rural communities. We will also employ the attainable region method as an optimization technique in improving the efficiency of our process. The envisaged outcomes of our research outputs are an improvement in the general lifestyle of our people living in less advantaged communities as well as an opportunity for employment creation of the local youth if our process is scaled up into an industrial plant.

## 1. INTRODUCTION

Traditionally, the production of liquid fuels, organic chemicals and energy, has relied heavily on the gasification of coal, distillation of crude oil and hydro-power. As our natural resources are becoming depleted, and continue to do so due to the exponential growth of our population, the need to look elsewhere for sources of alternative raw materials and processes is imperative.

Domestic and industrial plastic solid waste (PSW) collection and disposal systems in Botswana are not as efficient as those in other developing African countries. Specifically, the mode of disposal of PSW in smaller cities and villages in Botswana is a major concern. Even in bigger cities, the current waste management systems mostly entail use of dumping sites and landfills, where the majority of the waste (Al-Salem et al. 2010) has been identified to be different classes of polymers namely: high density polyethylene (HDPE), low density poly ethylene (LDPE), poly vinyl

chloride (PVC), poly propylene (PP), poly styrene (PS) and poly ethylene terephthalate (PET) (Singh et al. 2017)

Although the rate of reaction associated with the biodegradation process of plastic waste is said to be slow that it is kinetically approximated not to be taking place (Guerrero et al. 2013), it is however thermodynamically feasible. Some chemical engineering reaction based researchers have argued that pigments used in plastics as well as plastics can be broken down by acidic leachates under certain harsh conditions of temperature and pressure to give products that are both deleterious and obnoxious to the environment and to the underground water sources which in some areas serve as drinking water for livestock, wildlife and even the rural folk.

Due to these highlighted PSW issues, the Botswana Government has responded to this societal challenge by implementing its environmental policies and inviting some NGOs and private companies on-board in assisting to combat this waste situation. But this approach has not yielded any positive results in villages like Palapye, Pilikwe, Serule and smaller towns like Serowe, Selibe Phikwe, Maun. In these parts of the country, PSW will continue to increase with negative implications on the local municipalities and environment. The major challenge in these locations is mainly the state of the roads, which make it practically impossible for refuse collection trucks to access the domestic and industrial waste. The finances usually allocated to the local municipalities by the central government in order to run their towns is also a constraint as it is never enough to address the water supply, sanitary, accommodation and other service delivery challenges, let alone cater for the waste collection and disposal services. Even at a government level, rarely is waste treatment a priority as there are more pressing national issues such as electricity supply, food security, agricultural inputs and mining challenges to take care of.

In this research, we focus on designing and implementing a sustainable process that uses the PSW as its raw material in producing useful products of a chemical nature. We will demonstrate the feasibility of our process by first producing a measureable quantity of pyrolysis oil that can be further upgraded into its separate fuel fractions. Our technology will not only solve the PSW disposal problems in our community but will also assist in addressing landfill challenges as well as produce products that are of economic value to the rural populace thereby improving their livelihood. We will also use the attainable region optimization technique to improve the efficiency of our process.

## **2. THEORETICAL BACKGROUND**

Botswana is a major market for most South African manufactured products. This is mainly due to the fact that the manufacturing industry in Botswana is hardly existing. This situation poses challenges on proposals of how to recycle PSW as there is no local plastic industry that will process the recycled material. In neighbouring countries

such as Zimbabwe and South Africa, there are plastic processing companies like Megapak and Nampak, respectively. These companies have led to the development of downstream recycle companies that supply them with recycled material to be used as feed. These downstream companies have also created a lot of jobs for local people who are willing to collect the PSW.

We propose that PSW should be collected from the villages and processed into finished products that are of economic value to the same villagers. There are four generally acceptable and well developed techniques used to process PSW, namely gasification, hydrogenation, biodegradation and pyrolysis (Marshall & Farahbakhsh, 2013). For this research, we chose to use a batch pyrolysis method because of its simplicity in design, operation and relative ease in adjusting the experimental parameters.

## **2.1 The pyrolysis process**

The pyrolysis process of synthesizing useful chemical products uses a technique that is the opposite of the Fischer-Tropsch (F-T) process. In the F-T process, carbonaceous material e.g. coal, is first combusted in order to give syngas ( $\text{CO} + \text{H}_2$ ). The syngas is then synthesized into targeted higher molecular chain hydrocarbons e.g. petrol, diesel and paraffin. The pyrolysis process starts with higher molecular chain hydrocarbons (polymers) and then break it down (cracking) using either heat, a catalyst or hydrogen gas (Al-Salem et al. 2017) into targeted smaller chain hydro-carbons e.g. liquid fuels. Since pyrolysis is basically a thermal degradation process, it is essential to understand the effect of mixing feed material that has different melting points, on the process. The other factors that affect the efficiency of a pyrolysis process are pressure, type of reactor, temperature, residence time and cooling mechanisms.

## **2.2 The Attainable Region Approach**

In this article, we apply the Attainable Region (AR) optimization technique to optimize our objective function by way of manipulating the input variables in order to give result to maximum process outputs. The AR method is a modern day geometric optimization technique that has been used successfully in the different disciplines of chemical engineering. This approach owes its origins to the field of chemical reaction engineering where Hildebrandt and Glasser (1990) tested it in choosing optimal reactor configurations. Over the years, different researchers have applied this optimization method on their laboratory scale data with the aim of either minimizing an experimental manipulated variable or maximizing an associated process variable. Since one of the objectives of operating any process is to make profit, the AR technique assists in this regard by way of specifying optimal experimental parameters that will result in either a maximum or minimum condition of the objective function.

The greatest advantage of the AR method is its versatility. The versatility of the approach lies in that it is generic across the field of chemical engineering and a researcher can apply this technique on any process parameter of choice. Smith and Malone (1997) also applied the technique in organic industrial chemistry where they optimized the molecular weights, monomer conversions and residence time in isothermal polymerization systems. In 1998, McGregor et al. went on to use the geometric ideas of the AR method in process synthesis in which they optimized a reactor-separator-recycle system. Godorr et al. (1999) extended the application of the technique in selecting optimal control and operating policies to situations where the rate vector depends on a control parameter. In the year 2000, Book and Challagulla used the technique in order to obtain optimal design and operating conditions for the adiabatic oxidation of sulfur dioxide to sulfur trioxide. Nicol et al. (2001) applied the technique in order to find an optimum process design for an exothermic reversible reaction system where provision was made for an external heating and cooling source. Over the years, the technique has been further modified and employed in various fields of process engineering.

### **3. EXPERIMENTAL PROCEDURE**

First we collected and grouped our plastics into their six different classes namely: HDPE, LPDE, PVC, PET, PP, PS. using their resin identification number (RIN). Other different classification techniques we could have used, if resources permitted include the froth flotation, laser induced breakdown spectroscopy and the X-ray fluorescence spectrometer. The AR technique proves that separating the feed material into its different classes has an added advantage of minimising the variability in the product spectrum. Co-pyrolysis of different classes give result to quite a wide range of products that makes the separation process quite challenging. The different plastic types are then taken through a process of size reduction to increase the surface area for heat to act on them, improve handling characteristics, to mix the solid particles more intimately. The mechanism used for size reduction was impact which is particle concussion by a single rigid force.. Size reduction also enhances packing within the reactor. Dicers could have been used if we had enough funding to acquire all the required equipment. The reduced material is introduced into the reactor for heating under a temperature range of 350°C – 400°C and at a pressure above atmospheric, initially the opening in the reactor leading to the delivery pipe is closed so that no vapour should escape until a certain period of time. The molecular vibrations are directly proportional to temperature therefore at higher temperatures the molecular vibrations are increased. The increase in molecular vibrations causes the bonds holding the molecules to break into smaller molecules (solid to liquid then vapour state). After a period of time succeeding the start of the reverse polymerisation process, the pipe is open to allow the flow of vapour through to the condenser where

it is condensed to liquid and collected. The chemical analysis of the condensate for organic product composition was then carried out using a gas chromatography-mass spectrometer (GC-MS). Product upgrade through various separation techniques can they follow in order to classify the pyrolysis oil into its constituent fuel fractions.

### 3.1 Batch reactor design

It is generally accepted that the pyrolysis process follows a first order irreversible reaction model, given by the equations below, in which equation 1 shows the first order irreversible equation, equation 2 is the differential form of equation 1 and equation 3 is the integral forms of the same rate equation.



$$-\frac{d[A]}{dt} = \frac{d[P]}{dt} = k[A] \quad (2)$$

$$\frac{[A]}{[A_0]} = e^{-kt} \quad (3)$$

Where:  $k$  is the rate constant

$A_0$  is the initial concentration

$A$  is the final concentration

In designing our batch pyrolysis reactor, we evaluated the volume of the reactor, as shown by equation 4 below:

$$t = N_{A0} \int_0^{X_{AF}} \frac{dX_A}{(-r_A)V_R} \quad (4)$$

From the residence time, initial number of moles of feed material, conversion of the reactants and the rate of the reaction (first order) of the pyrolysis process, we can easily find the volume of the batch reactor.

The temperature of the reactor required was calculated from the Arrhenius equation (5), where:

$$k = Ae^{-\frac{E_a}{RT}} \quad (5)$$

Where:

$k \rightarrow$  rate constant

$A \rightarrow$  Frequency factor

$E_a \rightarrow$  Activation energy(J/mol)

$T \rightarrow$  Temperature (K)

$R \rightarrow$  The gas constant (8.314 J/mol.K)

$e \rightarrow$  mathematical quantity  $e$

Figure 1, is a pictorial view of our designed batch pyrolysis reactor, showing the heating and condensation mechanisms.



Figure 1: Experimental set-up



#### 4. RESULTS AND DISCUSSION

Figure 2 shows the GC-MS analysis results of the pyrolysis oil that we obtained by the co-pyrolysis of HDPE and LDPE classes of PSW. We co-pyrolised the two classes of plastics in order to have enough material to use as feed, that will help in pressuring the reactor to the desired experimental pressure. Our results show that there are more than a hundred different liquid components in the pyrolysis oil. The high number of organic components obtained could have resulted from the fact that different pigmented plastics were used as feed material. The other reason for the high number of organic components could have been because the sample was heated to higher temperatures and high temperatures gave high conversions of more than 80 %. High pyrolysis temperatures and pressure also ensured that less gaseous components are formed as they are converted into liquid products. The high number of organic components in the pyrolysis oil complicated the analysis of our results as each peak had to be analysed for relative abundancy. A possible way of minimising the number of peaks would have been to pyrolysize either HDPE or LDPE samples separately as well as sorting feed material in terms of colour of their pigments. Ways of reducing the number of components should be implemented in order to make the analysis more easy and efficient. Figure 2 shows a sample of our results we obtained from the co-pyrolysis of HDPE and LPDE forms of PSW. The calculated conversion was around 70%, under the experimental conditions investigated. The pyrolysis oil produced was end-user tested in paraffin fuelled lamps and gave a very good luminous flame. We also observed from our other experimental runs that the class of plastic material used as feed material plays a major role in determining the type of fuel that can be obtained because when we used PP and PS forms of PSW we mainly got non-condensable gaseous products.

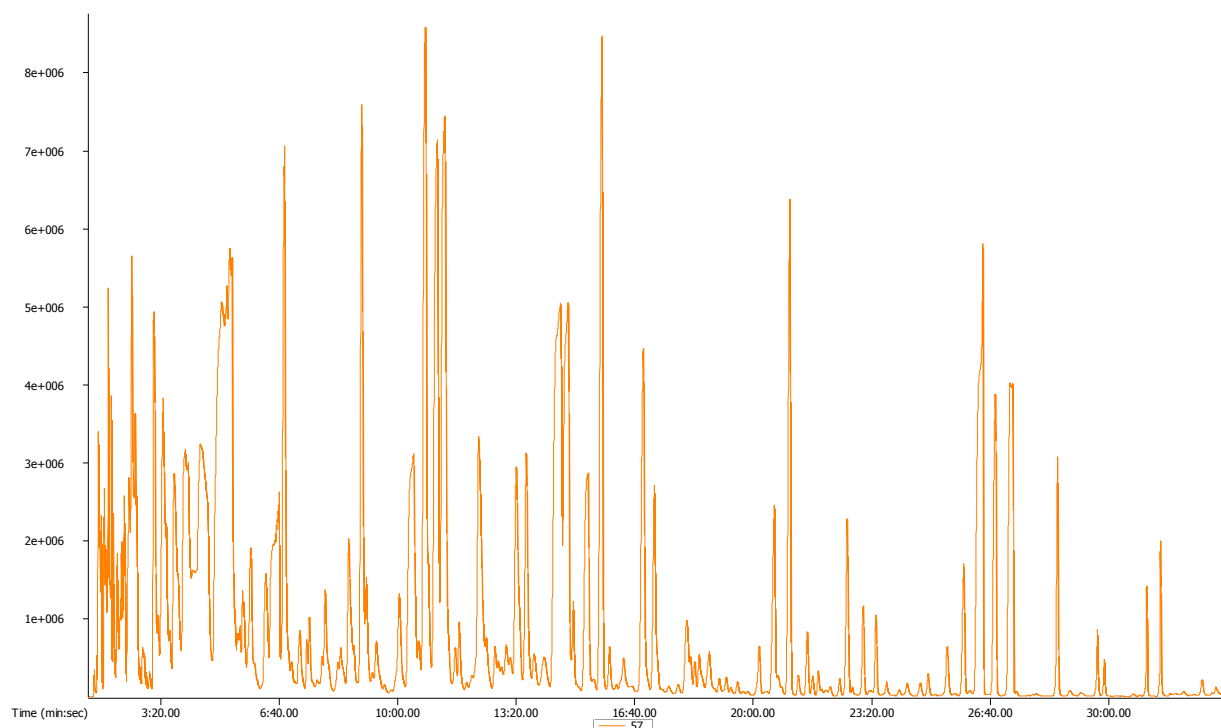


Figure 2: GC-MS results of oil pyrolysis

Where sample results are analysed as:

Peak #	Sample	Area %	Name	Area	Group	R.T. (min:sec)	Weight	Similarity
	UniqueMass	S/N						
95	PR1:4	5.9301	Ethylbenzene	467973040	>0.08%	5:40.00	106	949
	91	249531						
227	PR1:4	3.5677	2-Isopropyl-5-methyl-1-heptanol	281544689	>0.08%			
	16:54.90	172	822	57	89956			
22	PR1:4	3.4051	2-Pentene, 4-methyl-, (E)-	268712491	>0.08%	1:53.70		
	84	877	69	155389				
91	PR1:4	3.1178	Cyclohexane, 1,3,5-trimethyl-, (1à,3à,5á)-	246038268	>0.08%			
	5:34.20	126	903	111	162647			
277	PR1:4	2.6611	1-Octanol, 2-butyl-	209996246	>0.08%	26:48.80	186	
	862	57	79116					
			57599					
59	PR1:4	1.4169	Cyclohexane, methyl-	111813466	>0.08%	2:50.10	98	
	891	42	60924					
282	PR1:4	1.3659	n-Tridecan-1-ol	107789837	>0.08%	28:33.90	200	
	857	57	62724					

## 5. CONCLUSION AND RECOMMENDATION



From our experimental results, we can conclude that the proposal, laboratory scale design and implementation of a simple pyrolysis process unit used to convert PSW into pyrolysis oil was a success. Our objective was achieved as we managed to employ the AR technique in choosing optimal temperature, pressure and type of feed material in order to maximise our process throughput of the desired products. The added advantage of our proposed process lies in that there is a variety of organic products that can be produced, and it is up to the market to define what it prefers to be optimised. We also concluded from our findings that the different types of plastics give result to different types of products, and the heating and cooling effects also have a bearing on the product spectrum. Even though the experiment was successful there are possible areas of improvement that we recommend in order to improve the efficiency of the process. A catalyst should be used to improve the degradation process and lower the degradation temperature, similar types of plastics should be heated per batch in order to reduce the variability of components per sample, lastly the process should be operated under isothermal conditions by maintaining the process temperature within 350-400 by some process control means.

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