

Studies on Microwave Pyrolysis of Polypropylene

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Abstract: Microwave heating is gaining tremendous acceptance in today's world as a fast and intensive heating medium. Its use for pyrolysis is off late developing as a viable option for recycling of plastic wastes. This process has been studied widely for plastics such as polyethylene and polystyrene for the laboratory scale design of the pyrolysis equipment and the optimization of conversion to liquid fuels such as diesel. Polypropylene is widely used in our daily lives and constitutes about 25% of the total plastic waste generated. This work attempts to study the conversion of polypropylene to liquid hydrocarbon fuels in a microwave pyrolysis reactor and optimize the process variables for maximum conversion. A conversion of 75-80% was obtained at optimum process conditions. The liquid products are identical to petroleum refinery feed stocks and thus present a healthy potential of being processed further in existing petroleum refineries for final conversion of waste plastics into valuable fuels and petrochemicals.

INTRODUCTION

1.1 Background

Plastic is a high molecular weight material that was invented by Alexander Parkes in 1862 [1]. Plastics are also called polymers. The term polymer means a molecule made up by repetition of simple unit. Plastic is one of the most commonly used materials in daily life which can be classified in many ways such as based on its chemical structure, synthesis process, density, and other properties. In order to assist recycling of the waste plastic, Society of Plastic Industry (SPI) defined a resin identification code system that divides plastics into the following seven groups based on the chemical structure and applications [3]:

PET (Polyethylene Terephthalate)
HDPE (High Density Polyethylene)
PVC (Polyvinyl Chloride)
LDPE (Low Density Polyethylene)
PP (Polypropylene)
PS (Polystyrene), Other

The above seven types of plastics are marked on various plastic products as follows [3]:



Figure 1, Symbols used for various types of plastics.

Due to the convenience to manufacturing and use, the world plastic production has been increasing since it was firstly commercially manufactured, from 1.5 million tons in 1950 to 260 million tons in 2007 as shown in Figure 2 [4].

One of the major concerns for extensive use of the plastics is the disposal of the waste plastic. In addition, the plastics are produced from non-sustainable oil or coal, and thus it is a non-sustainable product. There were 30.7 million tons of waste plastic generated in the U.S. in 2007, which accounts for 12.1% of the total municipal solid wastes [5]. In U.K., 4.9 million tons of plastics were consumed in 2007. Europe consumes about 25% of the global plastic production, which is equivalent to 60 million tons per year [4]. The 2015 plastic waste generation figure in India was around 5.6 million tons, i.e. 15000 tons/day, out of which only 9000 tons is collected and recycled or dumped in the landfills. 6000 tons of plastic waste is daily littered in the open in India due to reasons ranging from collection constraints, lack of awareness to unavailability of proper disposal methods.

Thermoplastics contribute to the total plastic consumption by roughly 80%, and are used for typical plastics applications such as packaging but also in non-plastics applications such as textile fibres and coatings [11]. While plastics are found in all major MSW categories, containers and packaging plastics (bags, sacks, and wraps, other packaging, other containers, and soft drink, milk, and water containers) represent the highest tonnage [12, 13]. In durable goods, plastics are found in appliances, furniture, casings of lead-acid batteries, and other products. In the UK, recent studies show that PSW make up 7% of the final waste stream [14]. Packaging accounts for 37.2% of all plastics consumed in Europe and 35% worldwide [15].

Traditional treatments for post-consumed plastics were landfills or incineration [6, 7]. However, landfill of the post-consumed plastics has potential problems because of limited land resource and high durability (low biodegradability) of plastics. Incomplete incineration may generate poisonous substances and causes serious health problems. Other methods like gasification and bioconversion are mainly used for organic materials [8].

Microwave heating has clear inherent advantages over conventional heating. It provides for a (i) a reduction in waste volume, (ii) rapid heating, (iii) selective heating, (iv) enhanced chemical reactivity, (v) the ability to treat waste in-situ, (vi) rapid and flexible processes that can also be controlled remotely, (vii) ease of control, (viii) energy savings, (ix) overall cost effectiveness, (x) portability of equipment and processes, and (xi) cleaner energy source.

From existing processes for the harnessing of energy and raw materials from waste, thermochemical conversion routes are suitable candidates for the application of microwave technology. One of the thermochemical

processes which is rapidly gaining in importance in this field is pyrolysis.

1.2 Literature review:

Insight into pyrolysis:

Pyrolysis is a thermal cracking reaction of the large molecular weight polymer carbon chains under an oxygen free environment and produces small molecular weight molecules.

HDPE, LDPE, PP and PS are all hydrocarbons consisting entirely of carbon and hydrogen, which are similar to hydrocarbon fuels such as liquefied petroleum gas (LPG), petrol and diesel. Plastics are derived from petroleum and have calorific values in a similar range as those of LPG, petrol and diesel as given in figure 3. [8].

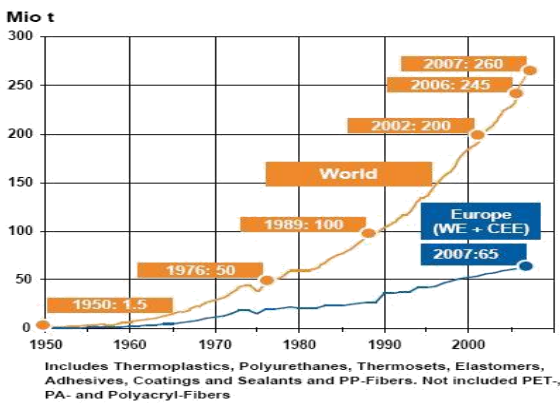


Fig 2, Plastic production in the world and in Europe from 1950 to 2007 [4].

The major factors influencing the plastic pyrolysis process and pyrolysis product molecular distribution include chemical composition of the feedstock, cracking temperature and heating rate, operation pressure, reactor type, residence time and application of catalyst.

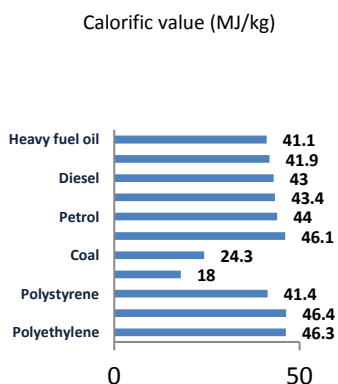


Fig 3, Energy densities of plastics and fuels.

Pyrolysis of MSW plastics

Pyrolysis is the chemical and thermal decomposition of molecules in the absence of oxygen. As most thermoplastics begin to degrade above 300 °C, plastic pyrolysis can be proceed at low (< 400°C), medium (400°C-600°), or at high temperatures (>600°C). Process pressure is generally atmospheric (8). Temperature is the most important operating variable, as it determines both the

rate of decomposition, and the stability of reaction products (lower temperatures favor formation of larger molecules, whereas high temperature favors formation of smaller molecules). Reaction time is also important as short residence times favor primary products like monomer whereas longer times favor more thermodynamically stable products with longer times. Reactor type is also important. This determines the quality of the heat transfer, as well as the gas and liquid residence times [16, 17].

Pyrolysis reaction mechanism

The chemical reactions occurring during decomposition of polymers can be divided into those involving atoms in main polymer chain and those involving side chains or side groups. The two groups of chemical reactions are shown in figure 3.1, as main chain reactions and side chain reactions. These two types of chemical reactions can again be divided into two groups. The decomposition of some polymers can be explained by one of these general mechanisms. For simple thermoplastics such as polyethylene, the most common reaction mechanism is the reaction involving the breaking of the bonds in the main polymer chain, termed chain scission. The eight generic types of reactions shown in figure 7 are involved in this simple decomposition process. These eight generic reactions are 1) random chain scission, 2) end chain scission 3) intramolecular H* transfer, 4) intermolecular H* transfer, 5) unzipping, 6) termination, 7) recombination and 8) disproportionation. Chain scission can occur in the chain end (termed end chain scission, E) or at any random location in the chain (termed random chain scission, R). Random chain scissions generally result in the generation of both monomers and oligomers and a variety of other chemical species. Hence, the volatile products of decomposition depend on the relative volatility of the resulting molecules.

It is generally accepted that there are two possible steps in any pyrolysis process (Conesa et al., 1998): (i) primary pyrolysis, which comprises the devolatilization of the material where different reaction zones can appear corresponding to the thermal decomposition of the main constituents; and (ii) secondary pyrolysis, which covers the secondary decomposition reactions in the solid matrix, as well as secondary reactions between the volatiles release(homogeneous reactions), or between the volatiles and the carbonaceous residue(heterogeneous reactions).

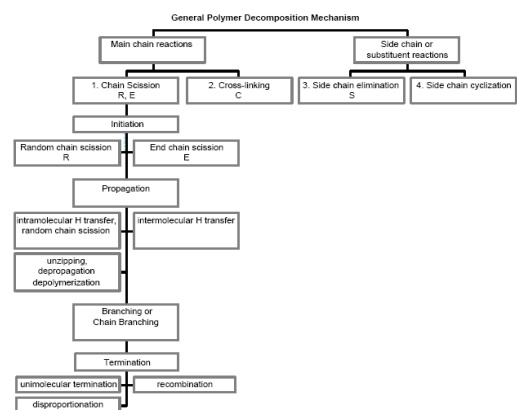


Fig. 4. Pyrolysis mechanism.

The first stage mainly involves dehydration, dehydrogenation, decarboxylation or decarbonilation reactions. The second comprises of processes such as cracking (thermal or catalytic), where heavy compounds further break into gases, or char is also converted into gases such as CO, CO₂, CH₄ and H₂ by reactions with gasifying agents, as well as partial oxidation, polymerization and condensation reactions.

Pyrolysis technologies and products

Apart from the raw material composition, the pyrolysis conditions mainly temperature, heating rate and residence time of vapors present in the reactor, influence the yield and characteristics of the pyrolysis products. Depending on these variables, the pyrolysis processes can be divided into three sub-classes as shown in the table 1 below. Generally, increasing the pyrolysis temperature reduces the char yield and increases the gas yield [18]. The liquid yield reaches a maximum value at intermediate temperatures and decreases at higher temperatures due to thermal cracking of heavy compounds.

TABLE 1, OPERATING PARAMETERS FOR PYROLYSIS PROCESSES [9].

Pyrolysis Technology	Residence time (sec)	Heating rate (K/sec)	Temperature (K)
Slow	450-550	0.1-1	550-950
Fast	0.5-10	10-200	850-1250
Flash	<0.5	>1000	1050-1300

Long residence times of volatiles in reactor and high temperatures decrease tar production but increase char formation as a result of the extension of secondary reactions [9]. Higher heating rates favour a quick release of volatiles, modifying the solid residue structure with an increased yield of the liquid and gaseous fractions. Pyrolysis process has the ability to provide three end products: gas, oil and char. The composition and applications of pyrolysis fraction are presented below in table 2.

TABLE 2, RANGE OF THE MAIN OPERATING PARAMETERS FOR PYROLYSIS PROCESSES [9].

Composition	Products		
	Gas	Oil	Char
Combustible gases such as H ₂ , CO, C ₂ H ₂ , CH ₄ , C ₂ H ₄ , C ₂ H ₆ , etc.	Complex mixture of several organic compounds accompanied by inorganic species depending on feed.	Elemental carbon originating from thermal decomposition of the organic components and unconverted organic compounds, e.g. additives.	
Uses	Direct firing of boilers, gas turbines/ engines, syngas applications.	Diesel engine fuels, production of chemicals and resins.	Solid fuels for boilers, feedstock for activated carbon/ carbon nano filaments/ high surface area catalysts.

Microwave Heating

As all electromagnetic waves, microwaves consist of electric and magnetic field components, both perpendicular to each other. Generally, there are three qualitative ways in which a material may be categorized with respect to its interaction with the electric field component of the microwave field: (i) insulators, where microwaves pass through without any losses (transparent), (ii) conductors, where microwaves are reflected and cannot penetrate, and (iii) absorbers. Materials that absorb microwave radiation are called dielectrics, thus, microwave heating is also referred to as dielectric heating.

When materials are exposed to a microwave field, there are essentially three different ways by which the material will be heated. These mechanisms are based on how the molecules of the material behave when subjected to the microwaves. The first mechanism is polarization- having either the electrons of individual atoms (electronic polarization) or the nuclei of the atoms themselves (atomic polarization) are displaced from their equilibrium position, which results to induced dipoles which respond to an applied field. This effect is more pronounced in molecules that have permanent dipoles from asymmetric charge distributions-like water. The second mechanism is interfacial polarization—which arises from a buildup of charge in contact areas of heterogeneous systems (heterogeneous being defined as multiple components that have different conductivities or dielectric constants). The third mechanism is via ionic conduction where some materials produce electric currents when subjected to EM fields. As the atoms of the molecules of a given material undergo one of these phenomena, the movements aligned with the EM fields cause a localized friction or heating.

The heating of materials can be further described by the following dielectric power absorption equation:

$$P = KfE^2 \epsilon \tan \delta \quad (\text{Thostensin 1999})$$

Where, P is the power dissipation in W/cm^3 , K is a constant equal to 55.61×10^{-14} , f is the applied frequency in Hz, E is the electric field strength in V/cm , ϵ is the dielectric constant, and $\tan \delta$ is the dielectric loss tangent. Both ϵ and $\tan \delta$ have a dependence on operating frequency and the sample temperature. In practice these values also vary with moisture content and physical state (solid or liquid). The electromagnetic field energy dissipated as heat per unit volume is proportional to the dielectric loss factor, the square of the field strength, and the frequency of the applied field. This expression assumes that the influences upon heating rate due to the heats of the reaction are negligible [19].

Based on the above dissipation expression, the dielectric loss factor is largely important as to whether a material can be heated and possibly pyrolyzed by microwave radiation. This quantity is directly

proportional to a more common material property, the dielectric constant.

Thermoplastics (with the exception of nylons) normally have very low dielectric constants and low loss factors and are known as ‘transparent’ to microwaves. Therefore they have not been thought of as candidates for microwave processing in the past. For example, polyethylene, polystyrene, and polypropylene--three common polymers that belong in MSW streams--have dielectric loss factors between 0.0007-0.0008 respectively at room temperature in response to 2.45 GHz radiation—the most common microwave source—with little improvement at lower frequencies or higher temperatures up to 100 °C (Source: *Engineer’s Handbook of Industrial Microwave Heating*). The magnitude of this transparency can be understood by comparing those values to a dielectric loss factor of 13.0 for distilled water at room temperature (25 °C). At 2.45 GHz, substances with dielectric loss factors on order of 10 require an electric field of 4.69 V/cm to increase 11°C/min, whereas substances with dielectric loss factors of 0.01 require 148 V/cm for the same temperature rate—which are unsafe electric fields to be generated by commercial devices.

The poor dielectric properties of plastics are aggravated by the fact that when plastics are heated and have reached their melting point or gel transition, absorption of microwaves increases substantially [19]. This can result in a poorly controlled pyrolytic reaction.

In order to take advantage of microwave heating with plastics, an additional material must be intimately mixed with a microwave-absorbent material. By doing so, the plastics are not directly heated via the mechanism previously discussed above, but rather by conduction from the quickly heated-highly microwave absorbent material to the plastics. This is referred to often as “microwave-induced” or “**microwave-assisted**” pyrolysis where the microwaves are considered for the most part an indirect source of heat. The material that is most known for its use as absorbent is graphitic carbon since it has dielectric properties of the same magnitude as water (dielectric loss factor: ~12-15) and is cheap and highly abundant [20].

MP techniques for treating plastic waste were initially developed by Tech-En Ltd in Hainault, UK [20]. The process involves mixing plastic-containing wastes, which are known to have very high transparencies to microwaves, with a highly microwave-absorbent material such as particulate carbon. The carbon reaches temperatures around 1000 °C within a few minutes in the microwave field, and energy is transferred to the shredded plastic by conduction, providing the efficient energy-transfer associated with microwave-heating processes.

Ludlow-Palafox et al [20] implemented a lab scale, modified microwave furnace system which is represented by the schematic in figure 9 below. Plastics, in shredded or pelletized form, are fed by a hopper (3) to a quartz vessel (2) within the microwave

cavity (1). Pulverized carbon is also added as the material which is susceptible to microwave heating. Nitrogen is fed into the reactor vessel to ensure the oxygen-depleted reaction environment (5). Upon pyrolysis, the products volatilize and exit the microwave system. The vapors are condensed (7) into the respective liquid (8, 9) and light gas fractions (10). 50 grams of HDPE was mixed with a kilogram of particulate carbon. The microwave furnace (maximum operating power: 5 kW) operated at 1250 W (2.45 GHz, for 500 °C) for 350 seconds upon addition of the plastic. The carbon was heated additionally for a few minutes prior as well.

Slow agitation (6 rpm) maintained the intimate mixture between the carbon and the HDPE pellets while nitrogen was continuously flowed (1.4 L/min) to remove oxygen from the quartz chamber. After 350 seconds there was no plastic remnant within the reactor. The overall recovery was a gaseous stream (19% by mass) and an oil/liquid fraction (81%). Thermocouples measuring the temperature of the degrading plastics reported a system temperature of 500 °C. Additional results were reported at 600 °C and 700 °C respectively. Temperature was reportedly maintained by switching on and off various magnetrons. The product stream from the condensing system was analyzed via gas chromatography-mass spectrometry (GC/MS). They had several key findings.

The first was that reactor temperature had the greatest effect on the rate of reaction/decomposition as shown in figure 10 below. This was quantified by the accumulation of volume in the main collection flask over reaction time. At 600°C, no additional oils or waxes accumulated in the collection vessel after 120 seconds, suggesting that the entire 50 gram sample was pyrolyzed within that duration. It should be noted that reactions reported at 700°C were extremely fast (flash pyrolysis) and were not able to report accumulated volumes over a comparable time scale.

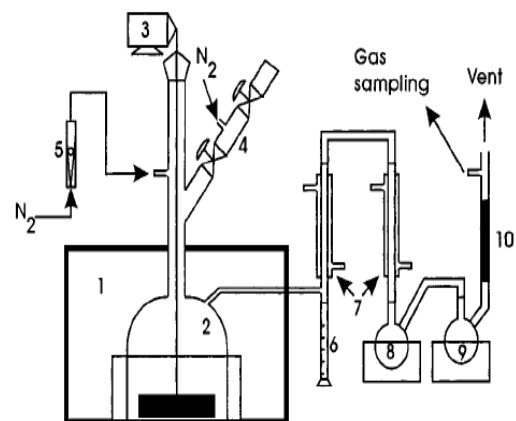


Figure 5, Schematic of MWP set-up [20]

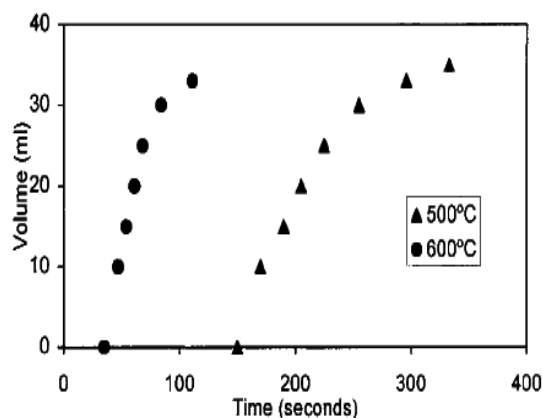


Figure 6, Cumulative Yield of Products for MWP of 50 grams of HDPE at 500 °C and 600 °C [20].

Microwave pyrolysis of PS was carried out using metals like iron as antenna to produce useful hydrocarbons [22]. From their results it was concluded that MP provides a more even distribution of heat and better control over the heating process than conventional heating techniques. Ludlow-Palafox & Chase performed a novel microwave-induced pyrolysis process to evaluate the degradation of high-density PE and aluminum/polymer laminates (toothpaste tube) in a semi batch bench-scale apparatus.

Timothy T Sharobem [21] compared some of the results from *Ludlow-Palafox et al* versus literature of polyethylene pyrolysis for alternate reactors. From this two conclusions were made. First, an increase in the temperature causes little difference in the liquid/gas yields of the microwave reactor whereas it had quite an impact for the fluidized and fixed beds respectively. Secondly, the magnitude (wt. %) of the oil and wax seems to be largest for the microwave pyrolysis reactor. This is a favorable result for the consideration of upgrading the pyrolysis oil/wax into a crude liquid fuel.

Although literature and process data from microwave pyrolysis applications report a high oil/wax product yield, there are concerns that its energy requirement, and subsequent carbon footprint, make this process inefficient and undesirable as an environmentally acceptable. A life cycle assessment (LCA) was performed [21] using pilot conditions from a commercial process of microwave pyrolysis. By using the exit gas stream as a feed for an internal generator, *Climax Global Energy's* process significantly decreases its carbon footprint by not drawing electricity from the grid. In a comparative analysis given a set of assumptions, this process was found to have an auspicious carbon footprint versus another tertiary recycling process, gasification and F-T synthesis, and versus the heat extracted from waste-to-energy.

OBJECTIVE OF WORK

The main objectives of this study are to understand and optimize the process of plastic pyrolysis for maximizing the naphtha and diesel range products, and to design a batch type laboratory scale pyrolysis apparatus. Pyrolysis

of polypropylene (PP) has been investigated in a lab-scale pyrolysis reactor. The key factors have been investigated and identified.

The cracking temperature in the pyrolysis is around 350 °C. High reaction temperature and heating rate significantly promote the production of light hydrocarbons. Long residence time also favors the yield of the light hydrocarbon products. The effects of other factors like type of reactor, catalyst, pressure and purge rate have been explored in the literature review through the past studies.

DESIGN OF EXPERIMENT:

A batch type microwave reactor was designed with specifications given in table 4.

TABLE 4, SPECIFICATIONS OF THE MICROWAVE PYROLYSIS EQUIPMENT.

SI No	Parameter	Specification
1	Microwave distribution system	Multiple magnetron with diffusers.
2	Microwave Power	1.5 KW, 2450 MHz
3	Pyrolysis reactor: Capacity Material of construction Sample holder	30 L microwave cavity made of SS 304. 1L capacity, made of quartz
4	Condensers and material construction	Water cooled Glass condensers with 1L capacity vessels for oil collection
5	Safety interlock	Safety interlocks are provided to prevent microwave leakage
6	Microwave leakage	Less than 1.5 mW/ Cm ²
7	Temperature measurement	Microwave compatible thermocouple. Digital display of temp.
8	Control system.	Sequential control of power On/ Off for magnetrons through PLC.
9	Cooling system for magnetrons	Air cooling with exhaust blower
10	Input power	15 Amp, 440 Volt, 3 phase, 50 HZ.

The microwave cavity was designed to hold a quartz flask of 1 liter capacity. A line diagram of the experimental set-up is shown in figure 4. The flask had three necks, one each for inert gas inlet, pyrolysis product outlet and the thermocouple element slot. Microwave was equipped with 8 different power levels ranging from 150 W to 1500 W and a thermostat based temperature controller. A flexible type direct insertion thermocouple was used for sensing the reaction temperature. Two cooling water condensers were used to get the liquid products. The gases generated were sampled using a bleed-bladder arrangement.

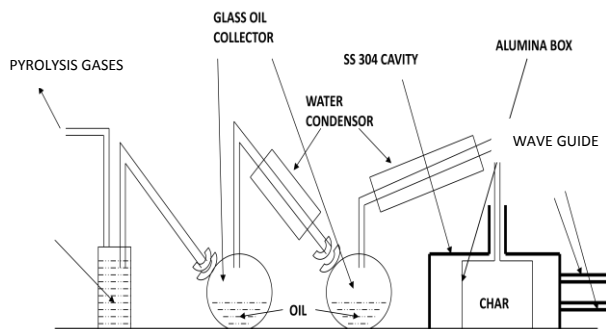


Fig. 7. Schematic of the pyrolysis system



Fig 8, Microwave pyrolysis reactor system.

Most important process conditions affecting the product yield and pyrolysis process conversion were identified through literature survey. The microwave power levels, reaction temperature, feed/susceptor ratio and the inert gas flow rate were varied as to get the optimum process conditions for maximizing the yield of desired product (liquid fuel in this case). The liquid products were collected in flasks placed below the water cooled condensers. Gaseous products were collected in the bladder with a bleed purge system shown in figure 9 above. The process conditions employed are tabulated below.



Fig 9, Gas products sample collection bladder.

TABLE 5, EXPERIMENT PROCESS CONDITIONS.

SI No.	Parameter	Value
1	Temperature	400
		430
		500
		525
		570
2	Microwave power level, W	750
		900
		1100
		1200
3	N ₂ purge rate, cc/min	50
		75
		100

RESULTS

Various results in tabular and graphical forms are as below:

I. Product yield v/s pyrolysis temperature: The liquid, gas and solid products yield on weight percent basis was derived at various temperatures from 400 °C to 570 °C. The variation of the yield is shown as in figure 10. The liquid yield has started declining after around 525 °C. Hence, this was considered as the optimum temperature for further analysis. The UOP K characterization factor is calculated for the liquid product at various reaction temperatures.

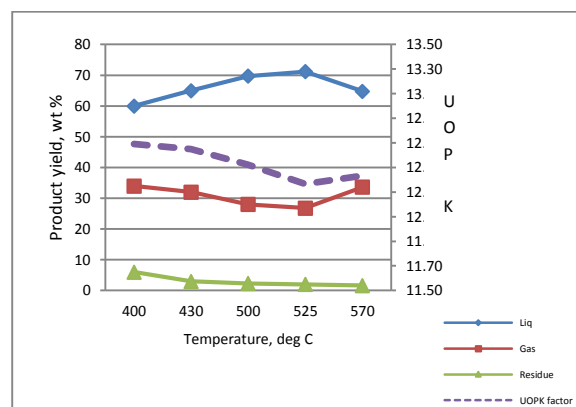


Figure 10, Product yield v/s temperature at constant microwave power.

II. Pyrolysis liquid property v/s temperature: The pyrolysis liquid obtained was analyzed for boiling point by Simdist (simulated distillation) and the boiling points of the mixtures were plotted as below in figure 11. The initial boiling point (IBP) of the liquid mixture was found to be 55-60 °C. The final boiling point (FBP) decreased from around 550 °C to 370 °C as the pyrolysis temperature was increased from 400 °C to 525 °C.

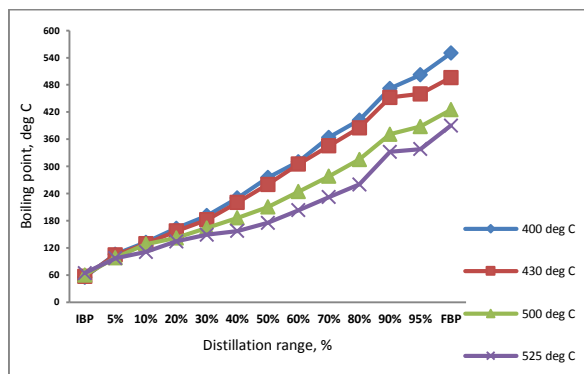


Figure 11, Product boiling point v/s pyrolysis temperature.

III. Variation of run time with microwave power: The run time is the time after which there was no considerable liquid product yield. This depended on reaction temperature and the microwave power. The plot is shown below in figure 12.

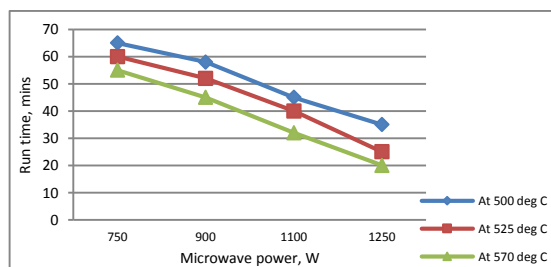


Figure 12, Experiment run time v/s MW power.

The various runs for this study were conducted at constant temperature of 525 0C and microwave power was varied from 700 W to 1250 W.

IV. Variation of product yield with nitrogen purge rate: The plot is shown in figure 13. The nitrogen gas purge rate was varied from 50 to 150 cc/min, at constant pyrolysis temperature. The microwave power was also kept constant. The effect of purge rate was more pronounced above 75 cc/min. So, the other runs were conducted at a purge rate of 75 cc/min.

V. Physical properties v/s temperature: The density and viscosity of the pyrolysis liquid obtained at different process temperatures were plotted and is shown below in figure 13. The reduction in both the viscosity and density is due to increase of the lighter fractions in the liquid hydrocarbon mixture.

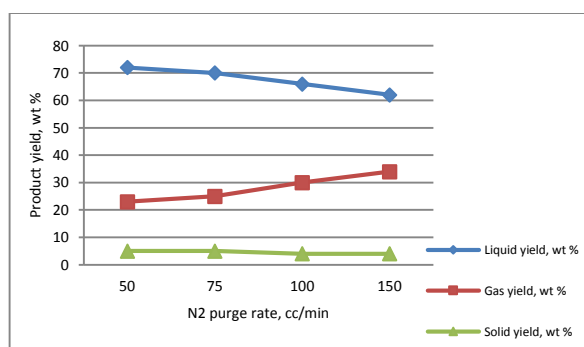


Fig 13 , Effect of N₂ purge rate.

VI. Composition of products: The composition of the pyrolysis liquid product was obtained by simulated distillation method for the run conducted at 525 0C and 1100 W microwave power. The results are shown in table 6 below.

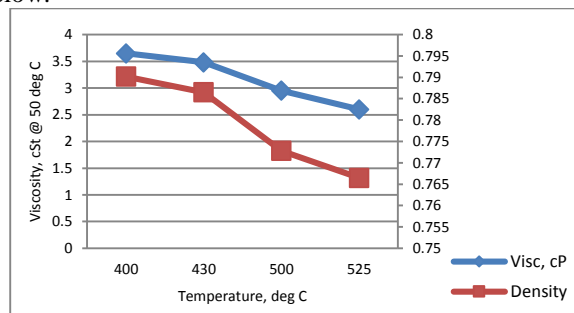


Figure 14, Physical properties v/s pyrolysis temperature.

TABLE 6, PYROLYSIS GAS COMPOSITION.

Sl No.	Component	Composition, wt %
1	Propylene	30
2	Propane	8
3	Ethene	18
4	Methane	38
5	Hydrogen	6

The gaseous products were collected in a suction bladder arrangement after sufficient purging of the bladder before actual sampling to avoid any air ingress. Gases were analyzed by gas chromatography and the composition obtained is shown in figure 15.

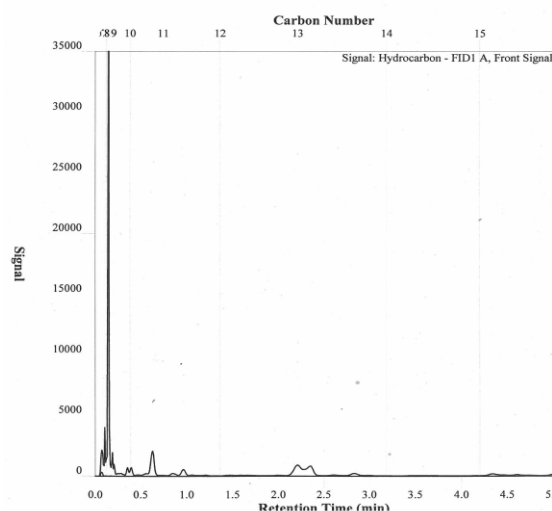


Fig. 15, Carbon number wise composition of naphtha range liquid product.

DISCUSSION

Some of the important inferences of the experimental results are as below:

I. Variation of pyrolysis liquid properties with reaction temperature and feed: It was observed that as the reaction temperature was increased, the final boiling point of the liquid product came down. Also, due to more cracking of

the higher boiling fraction, the naphtha range saw an increase with reaction temperature. At 525 deg C, the liquid yield was maximum meeting the objective of our experiment. As shown in figure 5.1, this liquid resembled a mixture of naphtha, kerosene and diesel range hydrocarbons at higher temperatures and a mixture of naphtha, kerosene and gas oil range products at lower pyrolysis temperatures.

II. Pyrolysis versus petroleum refinery streams: The pyrolysis liquid products, when distilled further, bear resemblance to the petroleum products such as naphtha and diesel. As such straight run pyrolysis liquid is a mixture of naphtha, kerosene and diesel cuts. The microwave pyrolysis, if scaled-up appropriately, has a fair potential of fulfilling some demand of petroleum products without increase in crude oil processing. The plastics pyrolysis products are low in sulfur. Hence they can be mixed in the feeds of refinery processing units such as diesel hydrotreater unit. Its feed boiling range is identical to the pyrolysis liquid distillation range.

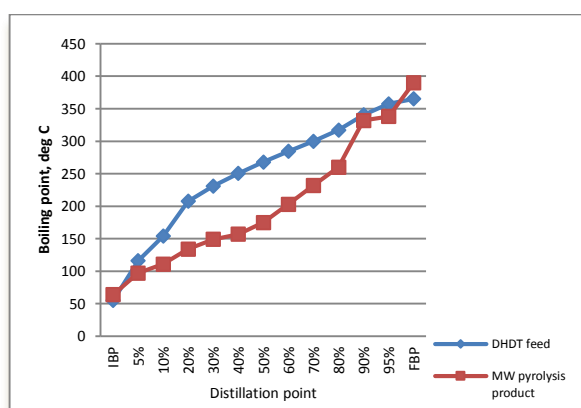


Figure 16, Boiling point comparison for DHDT feed and pyrolysis liquid product.

A comparison of the two is shown above in figure 16. Diesel hydrotreater (DHDT) gives products ranging from ultra low sulfur naphtha, kerosene and diesel catering to the demand of Euro-IV/V environment norms. In this way, the waste plastics can be converted into Euro-VI grade fuels. DHDT process will yield around 8% naphtha, 9% kerosene and 80% diesel. The wider boiling pyrolysis liquid (50-550 °C) obtained at lower reaction temperatures can be processed in the crude distillation unit to get various straight run products which are further enhanced in the secondary units. This option is easier to exercise as the pyrolysis product will have to be mixed with the crude oil and processed.

III. Microwave versus conventional pyrolysis: The pyrolysis reaction temperature and time through conventional heating methods is much higher than through microwave heating. This is because of the inherent property of microwave heating in which, the feed gets heated inside out. It makes the cracking to occur much faster. The reduced reaction time decreases the power/energy requirements. Loss of energy is also lesser in

case of microwave heating as the surroundings do not absorb any microwave radiation during the process.

The reaction time in case of microwave pyrolysis depends on the heat absorbent material (susceptor) being used, in addition to the microwave power. The most widely used susceptor is carborundum or carbon disulfide powder, but was not available readily for this experiment. So, the experiment was done with wood char prepared by pyrolysis of wood in this microwave reactor. The reaction times will drop a notch when carborundum will be used as susceptor as it is a better absorbent of microwave than wood char. It may also change the product yield pattern slightly.

IV. Waste collection process: The whole of this exercise will be fruitless, if plastic waste is not segregated properly at the very first instance. The foremost way of doing this is to promote segregation at domestic level. A properly separated plastic waste will reduce great deal of effort and time to sort out the required materials besides cutting down the waste handling and transportation costs.

V. Involving people in converting plastic to fuel: Installing small and medium MW pyrolysis units in localities with the help of municipality and self-help groups will help in easy collection of waste and its processing. The product generated can be collected by an agency and transferred to the nearest refinery or a bulk storage/transportation facility. The usage of pyrolysis products in refinery feed stocks will complete the cycle of consumption and will lead to sustainable development with minimum waste generation.

CONCLUSIONS AND FUTURE WORK

Microwave pyrolysis offers a fair potential for an instant and deep cracking of waste plastics. The yield of liquid products is in the range of 65-75% with balance gas and a negligible solid ash. This product, upon further distillation, will yield low sulfur naphtha and diesel. On the other hand, the gaseous product consists of around 40-50% propylene which can be collected and used as petrochemical feedstock earning huge profits. MW pyrolysis offers high flexibility for variation in gas/liquid yields. The optimum pyrolysis conditions are 525 °C temperature, 1100 W power, 75 cc/min of N₂ purge rate. The liquid products are paraffinic as the UOP K factor is around 12.5. This also proves their blend ability in the refinery streams.

The future of this technology will be bright if a medium/large scale continuous processing reactor can be designed and operated. This process has a potential to reduce the menace of plastic waste along with generating valuable transportation fuels. The use of catalyst can further improve the product slate. There has been some work in the catalytic pyrolysis of plastics, but the amalgamation of catalytic and microwave process is yet to be seen due to difficulties in design and control of the process. The effect of microwave radiation on the catalyst properties too remains an unknown area. All-in-all a proper

scale-up of this technology offers a very sustainable platform for handling the menace of the burgeoning plastic waste generation.

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