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List of Abbreviations

BAU	
Business as Usual.....	5
CAD	
Computer Adds Design.....	71
FCI	
Fixed Capital Cost.....	78, 79
FRP	
Fiberglass Reinforced Plastic.....	45
GAH	
Gross Available Heat	37
GDP	
Gross Domestic Product	4
HDP	
High Density Polymer.....	5
HDPE	
High-Density Polyethylene.....	5
LDP	
Low Density Polymer	5
LDPE	
Low-Density Polyethylene.....	5
MS	
Mild Steel.....	22
MSW	
Municipal Solid Waste.....	2
MTOE	
Million of Oil Equivalent.....	4
NCV	
Net Calorific Value	36
NPT	
National Pipe Tapered.....	47, 49, 50, 56
NUC	
High Nuclear Capacity.....	5
OC	
Overload Cost (.....	76
PA	
Polyamide	7
PEC	
Purchase Equipment Cost	74
PET	
Polyethylene Terephthalate.....	5
POC	
Product of Combustion	36
PP	
Polypropylene	5
PS	
Polystyrene.....	5
PVC	

Poly Vinyl Chloride	5, 7, 8
REN	
Aggressive Renewable Energy	5
SV	
Salvage Value	79
TCI	
Total Capital Investment.....	79
TDC	
Total Depreciation Cost.....	75, 79
Total Direct Cost.....	75
TERL	
The Energy and Resources Institute	4
TIC	
Total Indirect Cost	76
TPD	
Tons Per Day.....	2
WCI	
Working Capital Cost	79
WTE	
Waste to Energy.....	1

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Summary

Economic growth and change in consumption and production patterns are resulting in rapid increase in generation of waste plastics in the world. In Asia and the Pacific, as well as many other developing regions, plastic consumption has increased much more than the world average 300 million tons due to rapid urbanization and economic development. The world's annual consumption of plastic materials has increased from around 5 million tons in the 1950s to nearly 100 million tons; thus, 20 times more plastic is produced today than 50 years ago. This implies that on the one hand, more resources are being used to meet the increased demand of plastic, and on the other hand, more plastic waste is being generated.

Due to the increase in generation, waste plastics are becoming a major stream in solid waste. This increase has turned into a major challenge for local authorities, responsible for solid waste management and sanitation. Due to lack of integrated solid waste management, most of the plastic waste is neither collected properly nor disposed of in appropriate manner to avoid its negative impacts on environment and public health and waste plastics are causing littering and choking of sewerage systems.

In 2020, the world produced 367 million metric tons of plastic and generated seven billion tons of plastic waste. Only 10% have been reported as “recycled”; the rest of plastic wastes were discarded in landfills or combusted with energy recovery (“waste to energy” or WTE). Since 1950 when plastics come to use, about 4.6 billion tons of plastic waste have been discarded, mostly in landfills or WTE power plants.

However, landfilling as the primary waste management for plastic wastes, is not sustainable. Environmental pollution and limited land resources close to urban centres indicate that landfilling is no longer a wise method to manage the increased plastic waste, and a more efficient and environmental-friendly way should be implemented.

Since plastic are material derived from petrochemicals, the idea of converting plastic wastes back into oil by pyrolyzing has been pursued. Pyrolysis is a thermal decomposition process at high temperature in the absence of oxygen. Plastic material is composed of high-molecular carbon chains that are cracked into liquid and gas molecules during the pyrolysis process. By combining other non- convectional energy resources and green energy to run the process of pyrolysis, we can create a close loop cycle for fuel generation. In this project, industrial-scale processes for transforming mixed plastic wastes to fuel oil were examined.

Chapter 1. Introduction

1.1 Background

It is estimated that approximately 10 thousand tons per day (TPD) of plastics waste is generated i.e. 9% of 12 million TPD of MSW in the country. The disposal of these poses a threat because incineration of these results in air pollution, land filling causes land pollution and land availability is limited. All these factors kindled state governments to ban the usage of plastics. The slogan "REDUCE, REUSE and RECYCLE" is spreading everywhere now. Creating wealth from plastic waste seems an optimistic approach and is the need of the hour. Recently plastic wastes are used for fuel generation and in polymer coated bitumen roads. The recent inflation has resulted in a hike in petrol and diesel prices (which have gone up by 11 per cent and 8.5 per cent, respectively and will increase the inflation rate by about 0.3 per cent). Fuel from plastic waste can provide a short-term solution for this. Thus, fuel out of plastic waste can contribute to proper waste management and to the current economic scenario. One significant advantage of making fuels out of plastics is that they need not be segregated since polymer pyrolysis of mixed wastes including different plastics and another biomass is feasible.

More research concerning plastic pyrolysis has been carried out in the last decade than ever before. Japan has developed a method for decomposing polyolefins. The Fuji process uses catalysts to form a gasoline-rich oil from polyethylene, polypropylene and polystyrene. Polymers such as polyethylene, polypropylene and tires under different reaction conditions have been pyrolyzed. Also, in Germany, the energy and chemical company, Veba, is operating a plastic recycling process by which polymers hydrocracked into a synthetic oil. BASF has recently built a pilot plant to produce naphtha's, polyolefins and aromatics from mixed plastic wastes. In the UK, BP Chemicals is leading a consortium in developing a plastics recycling plant. Their process is based on Nuid bed technology and the resultant waxes have been shown to be suitable for feeding straight into a steam cracker for ethylene production.

Plastic materials have been crucial to the development of science, technology, and almost all aspects of modern progress since the mid-twentieth century. However, the increasingly unsustainable culture of plastic consumption and the accumulation of plastics in landfills, oceans, and broader ecosystems has also made negative, potentially irreversible environmental impacts. In recent decades, scientists and engineers have spent significant time and resources searching for more effective plastic waste management techniques based on

thermochemical routes like pyrolysis. Indeed, plastic to fuel conversion has the potential to severely limit plastic pollution and to contribute to the circular economy, but industrial scale plastic pyrolysis has not been achieved. (IndiaTimes | Plastic waste generation, 2023)

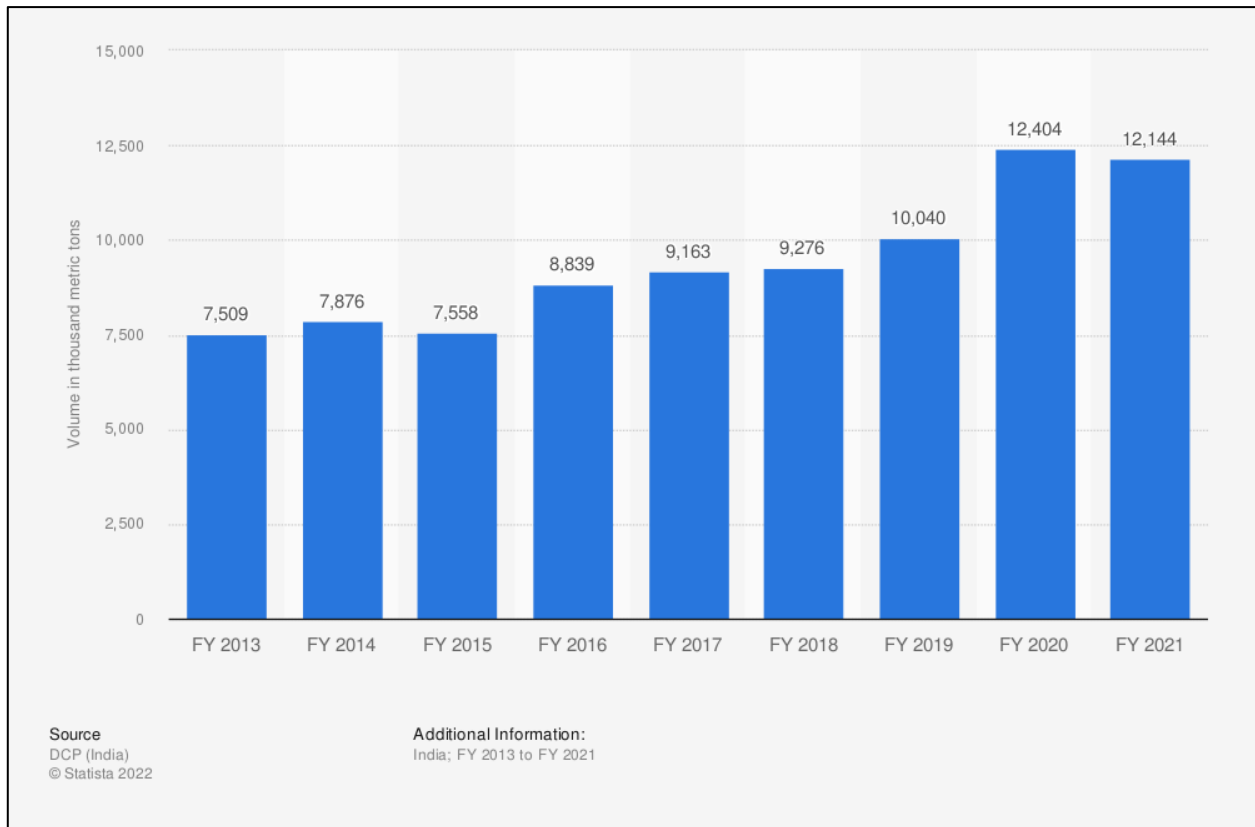


Figure 1: Production volume of plastic across India from 2013 to 2021, DCP India Report.

1.2 Energy Scenario of India

India has been gifted well enough with both exhaustible and renewable energy resources. Coal, Oil, and Natural Gas are the three primary commercial energy sources on which India has relied upon for decades till the end of 1980s, India's energy policy was mainly based on availability of native resources which made coal the largest source of energy. India lacks in oil assets and there has to depend on crude imports to meet a major share, around 70% of its needs in 2009.

However, India's primary energy mix has changed a lot over the decades but coal has remained the most significant & ample fossil fuel in India till now and is expected to be the dominant source for energy till 2030 with a contribution of around 51% of India's energy need contributes around 52% (283 MTOE) of commercial energy requirements whereas petroleum products accounts for 30-35%, nearly 9 per cent by natural gas and 2% by nuclear and 2% hydro energy.

The Indian economy relies heavily on commercial fuels but a sizable energy requirement, especially in the rural household sector, is met by non-commercial and traditional energy sources such as fuel wood, crop residue, liquid mass and animal waste, human and draught animal power. The usage of such sources of energy is estimated at around 155 MTOE/annum. However, higher quality and more efficient commercial energy sources have started to replace the traditional energy resources.

In the Planning Commission 2002, it was desired by the Government of India to achieve 10% GDP (Gross Domestic Product) growth rate during the Eleventh Five Year Plan and to maintain an average growth rate of about 8% for the next 15 years. It confirmed that country's requirements for energy and supporting infrastructure is going to increase rapidly and in order to facilitate the policy makers to make prompt decisions, estimation of the total energy requirements as well as look at the economic, environmental, and geopolitical implications of India's alternative energy pathways for the next few decades is very crucial. Demographic profile change in lifestyle, and consumer preferences determined the level of useful energy demands, whereas the availability, prices of resources and technologies influenced the levels and patterns of final energy requirements in the future.

In order to estimate the total energy requirements in future, The Energy and Resources Institute (TERI Office of the Principal Scientific Adviser, Govt) modelled a system to determine the total commercial energy requirements over the period of 2001-2031 under different

scenarios such as BAU (business as usual), REN (aggressive renewable energy), NUC (high nuclear capacity), EFF (high efficiency). HYB (hybrid), LG (low growth), HG (high growth) and HHYB (high hybrid) which almost dictated the routes toward the future and increase in energy consumption as the cost for the route. (India Energy Outlook, 2021)

1.3 Plastic

1.3.1 Introduction to Plastics

Plastics are synthetic organic materials produced by polymerization. They are typically of high molecular mass and may contain other substances besides polymers to improve performance and/or reduce costs. These polymers can be moulded or extruded into desired shapes. There are two main types of plastics: thermoplastics and thermosetting polymers.

Thermoplastics can repeatedly soften and melt if enough heat is applied and hardened on cooling, so that they can be made into new plastics products. Examples are polyethylene, polystyrene and polyvinyl chloride, among others. Thermosets or thermosetting can melt and take shape only once. They are not suitable for repeated heat treatments; therefore, after they have solidified, they stay solid. Examples are phenol formaldehyde and urea formaldehyde.

Waste plastics such as polyethylene terephthalate (PET), LDP, HDP, beverage bottles are large municipal waste that can cause a variety of environmental problems if not properly recycled. Current economic growth is unsustainable due to the depletion of fossil fuel sources such as oil, natural gas, and coal. As a result, many renewable energy sources have been utilized, but the potential of some other resources, such as plastic waste, has not yet been fully utilized as an economic activity. Development and modernization have significantly increased the production of all types of plastic products that generate waste directly or indirectly due to their wide range of uses, variety of types, and relatively low cost. Investigating four types of real plastics High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS)).

1.3.2 Types of Plastics

1.3.2.1 Thermoplastic

Thermoplastics can repeatedly soften and melts if enough heat is applied and hardens on cooling, so that they can be made in to new plastic products Ex: Polyethylene, Polystyrene and PVC, among others.

1.3.2.2 Thermosetting

Thermosetting can melt and take shape only once. They are not suitable for repeating heat treatment therefore after they have solidified, they stay solids. Ex: Phenol formaldehyde and Urea formaldehyde. Cellulose based plastics.

In 1855, an Englishman from Birmingham named Alexander Parkes developed a synthetic replacement for ivory which he marketed under the trade name Parkesine, and which won a bronze medal at the 1862 World's fair in London. Parkesine was made from cellulose (the major component of plant cell walls) treated with nitric acid and a solvent. The output of the process (commonly known as cellulose nitrate or pyroxylin) could be dissolved in alcohol and hardened into a transparent and elastic material that could be moulded when heated. By incorporating pigments into the product, it could be made to resemble ivory.

1.3.2.3 Bakelite

The first plastic based on a synthetic polymer was made from phenol and formaldehyde, with the first viable and cheap synthesis methods invented in 1909 by Leo Hendrik Backeland. Backeland was searching for an insulating shellac to coat wires in electric motors and generators. He found that mixtures of phenol (CH_3OH) and formaldehyde (HCHO) formed a sticky mass when mixed together and heated, and the mass became extremely hard if allowed to cool.

Bakelite was the first true plastic. It was a purely synthetic material, not based on any material or even molecule found in nature. It was also the first thermosetting plastic. Conventional thermoplastics can be moulded and then melted again, but thermoset plastics form bonds between polymers strands when cured, creating a tangled matrix that cannot be undone without destroying the plastic. Thermoset plastics are tough and temperature resistant.

Bakelite was cheap, strong, and durable. It was moulded into thousands of forms, such as radios, telephones, clocks, and billiard balls.

Phenolic plastics have been largely replaced by cheaper and less brittle plastics, but they are still used in applications requiring its insulating and heat-resistant properties. For example, some electronic circuit boards are made of sheets of paper or cloth impregnated with phenolic resin.

1.3.2.4 Polystyrene and PVC

Polystyrene is a rigid, brittle, inexpensive plastic that has been used to make plastic model kits and similar knick-knacks. It would also be the basis for one of the most popular "foamed" plastics, under the name styrene foam or Styrofoam. In the late 1950s, high impact styrene was introduced, which was not brittle. It finds much current use as the substance of toy figurines and novelties.

PVC has side chains incorporating chlorine atoms, which form strong bonds. PVC in its normal form is stiff, strong, heat and weather resistant, and is now used for making plumbing, gutters, house siding, enclosures for computers and another electronics gear. PVC can also be softened with chemical processing, and in this form, it is now used for shrink-wrap, food packaging, and rain gear.

1.3.2.5 Nylon

The real star of the plastics industry in the 1930s was polyamide (PA), far better known by its trade name nylon. Nylon was the first purely synthetic fibre, introduced by DuPont Corporation at the 1939 World's Fair in New York City structure and physical properties. He took some of the first steps in the molecular design of the materials.

The first application was for bristles for toothbrushes. However, Du Pont's real target was silk, particularly silk stockings. Subsequently polyamides 6, 10, 11, and 12 have been developed based on monomers which are ring compounds, ex: Caprolactam.

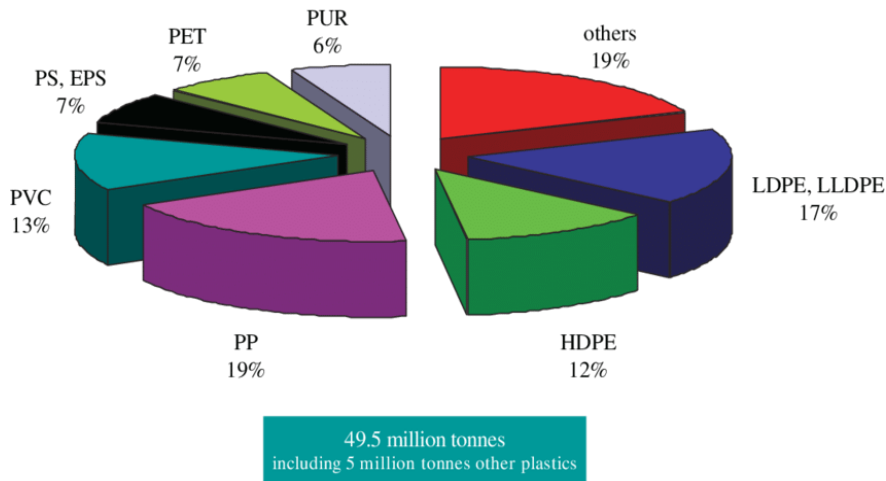


Figure 2: Share of different plastics manufactured in India annually.

Nylon 66 is a material manufactured by condensation polymerization. Nylons remain important plastics, and not just for use in fabrics. In its bulk form it is very wear resistant, particularly if oil-impregnated, and so is used to build gears, plain bearings, and because of good heat-resistance, increasingly for under-the-hood applications in cars, and other mechanism. (Plastic, 2023)

Table 1: Characteristics of different plastics.

Polymer Name	Polyethylene Terephthalate	High-Density Polyethylene	Polyvinylchloride	Low-Density Polyethylene	Polypropylene	Polystyrene
Resin Identification Code	1	2	3	4	5	6
Abbreviation	PET or PETE	HDPE	PVC	LDPE	PP	PS
Recyclability	Commonly Recycled	Commonly Recycled	Sometimes Recycled	Sometimes Recycled	Occasionally Recycled	Commonly Recycled (but difficult to do)
Percentage Recycled Annually	36%	30-35%	<1%	6%	3%	34%
How Long to Decompose Under Perfect Conditions	5-10 Years	100 Years	Never	500-1000 Years	20-30 Years	50 Years
Temperature	70 °C	120 °C	70 °	80 °C	135°C	90 °C
Brittleness Temperature	-40 °C	-100 °C	-30 °C	-100 °C	0 °C	-20 °C
Toxicity level	High	Low	High	Low	Low	High
Most Commonly Used Toxin(s)	Antimony Oxide, Bromine, Diazomethane, Lead Oxide, Nickel Ethylene Oxide, and Benzene	Chromium Oxide, Benzoyl Peroxide, Hexane, and Cyclohexane	Benzene, Carbon Tetrachloride, 1,2-Dichloroethane, Ethylene Oxide, Methanol, Tetrahydrofuran, and Tribasic Lead Sulphate.	Benzene, Chromium Oxide, Cumene Hydroperoxide, and Tert-butyl Hydroperoxide	Methanol, 2,6-di-tert-Butyl-4-Methyl Phenol, and Nickel Dibutyl Dithiocarbamate	Styrene, Ethylbenzene, Benzene, Ethylene, Carbon Tetrachloride, Polyvinyl Alcohol, Hydroperoxide, Benzoquinone

Source: <https://www.britannica.com/science/plastic>

1.4 Potential of Plastic Waste

Used low density polyethylene from household and industries are recognized to be a major environmental problem. There are several methods for disposal of municipal and industrial LDPE waste, i.e. landfill, incineration, true material recycling, and chemical recovery. Landfill treatment and incineration destruction are quite expensive and may raise problems with unacceptable emissions. True material recycling, i.e. to convert the waste material into products that can be reused, can significantly reduce the net cost of disposal. However, it is generally accepted that true material recovery is not a long-term solution to treat waste LDPE.

Chemical recycling was investigated, through which waste plastics were converted into fuel oil and valuable chemicals.

Thermal and catalytic degradation of waste plastics are two kinds of chemical recycling processes. The main drawbacks of thermal degradation are wide product distribution and requirement of high temperatures, typically more than 500 °C and even up to 900 °C. Since thermal degradation demands relatively high temperatures and its products require further processing for their quality to be upgraded, catalytic degradation of polymer waste offers considerable advantages. Catalytic pyrolysis gives a means to solve these problems.

Suitable catalysts can control both the product yield and product distribution from polymer degradation as well as to reduce significantly the reaction temperature. LDPE was both decomposed thermally and catalytic in a continuous reactor via as an oxidative media in the temperature range of 400-500 °C.

So, for the studies reported in the literatures about waste LDPE pyrolysis have been carried out in the presence of various expensive catalysts and derived oils of high boiling point range at comparatively high temperature. (Antelava, 2021)

1.5 Target Plastic Waste

Waste plastics are one of the most promising resources for fuel production because of its high heat of combustion and due to the increasing availability in local communities. Additionally, the effective conversion requires appropriate technologies to be selected according to local economic, environmental, social and technical characteristics. In general, the conversion of waste plastic into fuel requires feedstocks which are non-hazardous and combustible. Each type of waste plastic conversion method has its own suitable feedstock.

The composition of the plastics used as feedstock may vary in properties and characteristics, while some plastic articles might contain undesirable substances (e.g. additives such as flame-retardants containing bromine and antimony compounds or plastics containing nitrogen, halogens, Sulphur or any other hazardous substances) which pose potential risks to humans and to the environment. The types of plastics and their composition will condition the conversion process and will determine the pre-treatment requirements, the combustion temperature for the conversion and therefore the energy consumption required, the fuel quality output, the flue gas composition (e.g. formation of hazardous flue gasses such as NO_x and HCl), the fly ash and bottom ash composition, and the potential of chemical corrosion of the equipment.

For this study we will use LDPE extensively as target plastic waste because LDPE is widely used for general purpose plastics and found abundantly in Municipal Solid Waste. General properties of LDPE are present in table 2.

Table 2: Physical properties of low-density polyethylene.

Maximum Temperature	80 °C
Brittleness Temperature	-100 °C
Toxicity Level	Low
Toxins Involved	Benzene, Chromium Oxide, Cumene Hydroperoxide, and Tert-butyl Hydroperoxide
Commonly Used For	Plastic wrap, plastic carry bags, bubble wrap, food storage containers, irrigation pipes, wire and cable covering, beverage cups, plastic coating.
Properties	Tough, flexible, waxy surface, scratchable, good transparency, low melting point, stable electrical properties, good moisture barrier.
Health Risks	LDPE is less toxic than other plastics and relatively safe to use, although studies have shown that LDPE could leach estrogen-mimicking chemicals which can disrupt human hormones and can alter the structure of human cells.
Can Be Recycled Into	LDPE is difficult to recycle but not impossible. When recycled, LDPE can be used as: Plastic Lumber Trash Cans Floor Tiles

Source: <https://omnexus.specialchem.com/selection-guide/polyethylene-plastic>

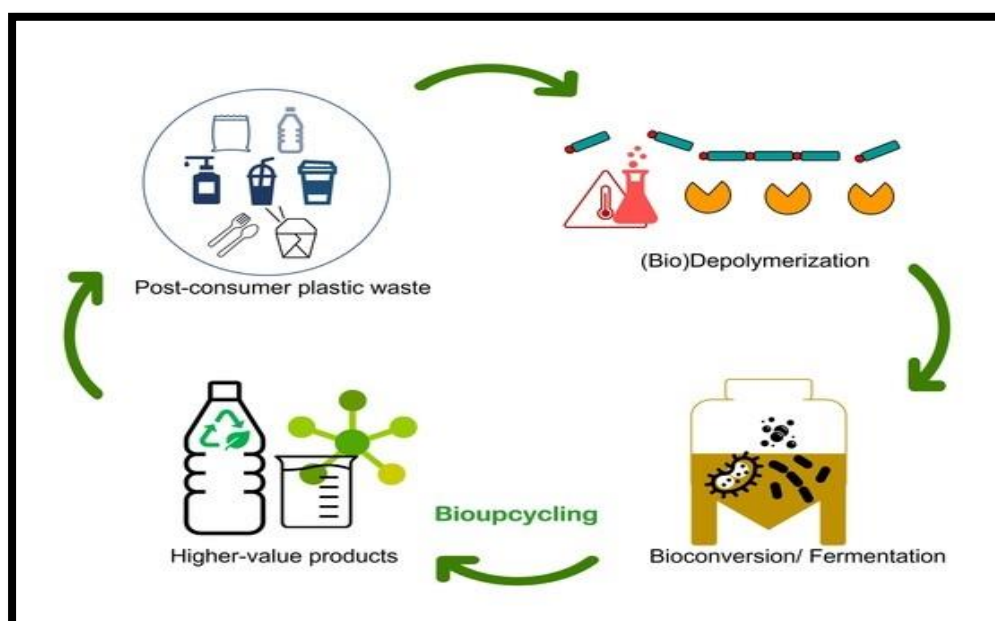


Figure 3: Close loop cycle depicting conversion of plastic waste into valuable resources. Source: MDPI

1.6 Disposal Methods for Plastics

1.6.1 Landfilling or Controlled Tipping Method

In this method of refuse disposal, refuse is carried and dumped into the low-lying area (earmarked as the land fill site) under an engineered operation, designed and operated in an environmentally sound manner, as not to cause any public nuisance or hazards to public health or safety.

In this method, the refuse is dumped and compacted in layers of about 0.5 m thickness, and after the day's work-when the depth of filling becomes about 1.5 m, it is covered by good earth of about 15 cm thickness. This cover of good earth is called the daily cover. Since the refuse is well compacted with bulldozers, trucks, rollers, etc. and is well covered daily with good-earth, it does not cause any public nuisance, like scattering of windblown litter, and evolution of unpleasant odours and foul smells, as may be caused by an ordinary dumping of refuse on land.

The filling of refuse is done in sanitary land filling by dividing the entire land-fill area into smaller portions, called cells. These cells are initially filled with daily compacted refuse of about 1.5 m depth, in turn. After filling all the cells with first lift, the second lift is laid in about 15 m height and covered with good earth cover of about 0.15 depth, called the intermediate cover. After all the cells have been filled up with second lift, the third and more lifts can be piled up in about 1.5 m depth each, all laid over by the intermediate earth covers, turn by turn. The process will continue till the top most lift is piled up, over which the final cover of good earth of about 0.6 m depth shall be laid, and well compacted, to prevent the rodents from burrowing into the surface. A cap-system may also be installed over the top of the final cover.

With the passage of time, the filled-up refuse will get stabilized due to the decomposition of organic matter and subsequent conversion into compounds. The land filling operation is essentially a biological method of waste treatment, since the waste is stabilized by aerobic as well as anaerobic bacterial processes.

Advantages:

- This method is most simple and economical. No costly plant or equipment is required in this method, as is required in other methods of incineration or pulverization.

- Separation of different kinds of refuse, as required in incineration method, is also not required in this method.
- There are no residues or by-products left out/evolved in this method, and hence no further disposal is required; this being a complete method.
- Low lying water-logged areas and odd quarry pits can be easily reclaimed and put to better use. The mosquito-breeding places are also, thus, eliminated.

Disadvantages:

- Low lying depressions or dumping sites may not always be available; or even if they are available today, they may ultimately become scarce or unavailable in future, since the production of solid waste is a continuous process.
- There is a continuous evolution of foul gases near the fill site, especially during the times the refuse is being dumped there. These gases may often be explosive in nature and are produced by the decomposing or evaporating organic matter. These gases, known as land fill gases, become a serious environmental problem at sanitary land fill sites. These gases need be estimated, and properly disposed of.

1.6.2 Shredding and Pulverization Landfilling

The size and volume reduction of municipal solid waste (MSW) is accomplished by the physical processes of shredding and pulverization. Shredding refers to the actions of cutting and tearing; whereas, pulverization refers to the actions of crushing and grinding. Shredding and pulverizing may help in reducing the overall volume of the original MSW, by as much as 40%. The shredding and pulverizing not only helps in reducing the volume of MSW, but also helps in changing the physical character of the waste, which becomes practically odourless and unattractive to the insects.

The pulverized refuse, though contains fertilizing elements like potash, phosphorus, and nitrogenous materials, yet cannot be suitably used as manure. It has, therefore, to be further disposed of either by filling in trenches or is digested in open windrows or closed digestors.

The pulverization of MSW is usually achieved in a hammer mill, where the raw solid waste is cramped with a force, enough to crush or tear individual components of the waste. Impact is provided by several hammers that rotate at high speeds (up to 1500 revolutions/minute) around a central horizontal or vertical shaft. The mill helps to produce a uniform or homogeneous mass of solid waste. Such a hammer mill proves to be a very versatile

device for size reduction of solid wastes, because it accepts almost any type of solid waste material (except of course, very bulky or dense ones, such as tree stumps, or engine blocks, etc.). A hammer mill, thus, makes it possible to reduce the size of the various components of solid waste material, to uniform fragments of size 25 to 50 mm or so.

In order to further reduce the waste volume, and facilitate handling of the pulverized MSW, it is usually compacted to form rectangular blocks or bails. MSW bails are typically of about 1.5 m² in size and weigh roughly 1 kN. The pulverized MSW is converted into bails by compacting the pulverized MSW under high pressures (of about 700 kPa) in either vertical or horizontal presses. This process is called bailing of MSW. The bails are frequently wrapped with steel wire to help retain their rectangular shape during handling. They may also be coated and stabilized with Portland cement or hot asphalt, or tied with metal bands, depending upon the intended use, or the method of disposal. If moisture content and compaction pressures are high enough, the bails may retain their shape without being wire-wrapped or encased. Semi-automatic horizontal presses can bail up to kN of pulverized waste per hour. Volume reduction due to pulverizing and bailing together, may occur by as much as 90% of the original waste volume.

The bailing process, thus, has significant advantages in decreasing the waste volume, and in providing an easy way for handling waste as blocks rather than as litter, thereby reducing the litter nuisance of scattering, etc.

1.6.3 Incineration

Burning of refuse at high temperatures in furnaces, called incinerators, is quite a sanitary method of refuse disposal, and is widely adopted in developed countries like USA, where the collected refuse is of high calorific value, and is, hence quite suitable to burning.

Normally, however, only the combustible matter, such as garbage, rubber and dead animals are burnt, and the incombustible matter like broken glass, chinaware, metals, etc. are either left unburnt or are separated out recycling and reuse, before burning the solid wastes. Prior separation of such materials will reduce the load on the furnaces and shall more than compensate the cost of this separation.

The left-out ashes and clinkers from the incinerators along with the recycled incombustible materials may, however, measure as much as 10 to 25% of the original waste, which in any case, shall have to be disposed of either by sanitary land filling, or in some other

productive manner. Say for example, the clinkers can be used as aggregates for making low grade concrete or as road metal, and the ashes can be used for making bricks.

The heat produced during burning of the refuse is used in the form of steam power for running turbines to generate electricity. The quantity of steam generated as a by-product in this method, shall, however, be uncertain, as it will depend on the moisture and calorific value of the refuse. Hence, the power so generated will fluctuate and will need stand-by diesel units to obtain continuous and assured power.

Incinerators, besides being useful for burning city refuse, are also quite useful for burning the hazardous solid and liquid wastes of the hospitals and the industries. Rotary kiln type of incinerators and liquid waste incinerators are widely used for disposal of hazardous biomedical and industrial wastes. Incinerators are also used for disposing of the wet waste sludge of waste-water treatment plants, where sufficient land for converting it into manure or burying it underground for land filling, is not available.

Merits:

- This is the most sanitary method of refuse complete destruction of pathogenic bacteria and insects.
- There is no odor trouble or dust nuisance.
- Some cost can be recovered by selling the steam power and clinkers.
- The disposal site can be conveniently located within the city near its outskirts, and transportation problems sorted out easily.
- It requires very less space for refuse disposal.

Demerits:

- It is a very costly method and requires technical expertise.
- Solid wastes to be burnt should have a high calorific value.
- Smoke, odor, and ash nuisance may result due to the improper and incompetent operation of the plant.

1.6.4 Pyrolysis

Upon heating in closed containers in oxygen free atmosphere, most of the organic substances of solid waste can be split through a combination of thermal cracking and condensation reactions into gaseous, liquid and solid fractions. This process is known as pyrolysis or thermal pyrolysis.

In contrast to the combustion process which is highly exothermic (releasing heat on burning in the presence of oxygen), the pyrolysis is highly endothermic (consuming heat). That is why, this process is also known as **destructive distillation**.

When the organic solid waste is pyrolyzed, we obtain the following three types of products at different stages or temperatures:

- The gas stream, which primarily contains hydrogen, methane, CO, CO₂, and other gases, depending upon the organic character of the solid waste being pyrolyzed.
- A liquid fraction, consisting of a tar and/or an oil stream, which is a liquid at room temperature and is found to contain chemicals such as acetic acid, acetone, and methanol; and
- A solid fraction, consisting of charcoal like product of almost pure carbon plus any inert material that may have entered the process.

The respective quantity of three end products (i.e. gas, oil and charcoal) is found to depend upon the temperature of pyrolysis. Under conditions of maximum gasification, the energy content of the resulting gas is found about 26000 kJ/m³; and that of the resulting oil to be about 23000 kJ/kg. Pyrolysis may be used for reducing the quantities of sludge produced water or a wastewater treatment plant, before their ultimate disposal by methods like landfill and land application.

1.6.5 Barging it Out into the Sea

This method had been used in the past to dispose of refuse by throwing it away into the sea, after carrying it at reasonable distance from the coast (say 16 to 20 kilometres inside the sea) on barges. The sea depth at such disposal point should not be less than 30 m or so, and the direction of the currents should be such as not to bring it back towards the shore. This method may, however, have a limited use, and that too only in a few coastal towns.

This method, however, proves to be quite cheap and simple, but possess the following disadvantages:

- The bulky and lighter parts of the refuse do not settle down, remains floating, and tend to return to the shores, especially during high tides.
- This method requires ships or barges for taking the refuse into the interior of the sea, the movement of which may be difficult during monsoon and stormy weathers. During such periods, the refuse will either have to be collected or disposed of by some other method.
- Even despite the best care and efforts, some refuse, in this method returns to the shores, spoiling their beauty.
- The dumping of refuse in sea may cause pollution of sea, leading to large scale fish kills, if the refuse happens to contain any toxic material.

Due to such disadvantages and due to general ban imposed on wastes into the sea under the International Treaty of Law of the Sea, this method has now become obsolete. (Santosh Kumar Garg, Sewage Disposal Engineering, 37th Edition)



Figure 4: Image depicting plastic pollution in sea. Source: UNDP

Chapter 2. Production Process

2.1 Pyrolysis

Pyrolysis is a thermochemical decomposition of organic materials at elevated temperatures without the participation of oxygen with macromolecules breaking into smaller fragments consisting of valuable mixtures of hydrocarbons. It involves the simultaneous change of chemical composition and physical phase and is irreversible. It is also known as thermolysis and has emerged as a powerful chemical and thermal degradation process which has the potential to achieve petrochemical feedstock recycling and convert waste to fuel as an energy recovery technique. Pyrolysis of plastic yields pyrolytic liquid product or oil, gaseous products and char.

Pyrolytic oil consists of a mixture of petroleum fractions such as gasoline and diesel. Pyrolysis differs from other high-temperature processes like combustion and reforming in that it usually does not involve reactions with oxygen, water, or any other reagents. In practice, it is not possible to achieve a completely oxygen-free atmosphere. In any pyrolysis system, there always some amount of oxygen is present and because of this oxidation at very small scale will always occurs. While some of the pyrolytic reactions are exothermic, some are endothermic. Pyrolysis is partly an endothermic process.

Pyrolysis is generally defined as the controlled heating of a material in the absence of oxygen. In plastics pyrolysis, the macromolecular structures of polymers are broken down into smaller molecules or oligomers and sometimes monomer units. Further degradation of these subsequent molecules depends on several different conditions including (and not limited to) temperature, residence time, presence of catalysts and other process conditions. The Pyrolysis reaction can be carried out with or without the presence of catalyst. Pyrolysis process thus results in the formation of a mixture of organic compounds including oligomers and smaller molecules. When the intended application of pyrolysis is to generate petrochemical feedstock or fuel oil, it becomes critical to know a priori an estimate of the composition of the oil before its further processing. This is not a straightforward problem, since there are literally hundreds of products that may be formed through hundreds of reactions. For instance, if fuels/feedstock such as kerosene, petrol (gasoline), diesel, and light and heavy gas oils are the intended final products upon fractionation of pyrolytic oil, it is sensible to predict the composition of fuel oil in terms of these product cuts.

As a result, it was found that it is possible to make liquid products from waste plastics that are comparable to petroleum fuels and valuable chemical raw materials. The purpose of this project is to explore the possibilities of the thermal decomposition of plastic waste generated by our day to day activities. Converting plastic waste into fuel is a good example of waste to energy also it is a better alternative to other disposal methods like landfill, incineration and other as the calorific value of plastic is somewhere equal to hydrocarbon fuel if carry out at ideal conditions.

2.2 Pyrolysis Products

Syngas (from synthetic gas or synthesis gas) is a gas mixture that comprises carbon monoxide, carbon dioxide and hydrogen. The syngas is produced due to the gasification of a carbon containing fuel to a gaseous product that has some heating value. Syngas has 50% the energy density of natural gas. Syngas can be burnt and is used as a fuel source. It is also used as an intermediate in the industrial synthesis of hydrogen and ammonia. During this process, methane (from natural gas) combines with water to generate carbon monoxide and hydrogen. As a residue of energy gasification, syngas is produced, and this is used as a fuel to create electricity.

Charcoal is the dark grey residue consisting of impure carbon obtained by removing water and other volatile constituents. Charcoal is usually produced by slow pyrolysis, the heating of wood or other substances in the absence of oxygen. The resulting soft, brittle, lightweight, black, porous material resembles coal.

Main Products (Final products):

Pyrolysis oil is a dark brown liquid produced from a Pyrolysis process. It is composed of a complex mixture of oxygenated hydrocarbons with an appreciable proportion of water. It may contain some solid char. The easiest way to utilize the fuel is to use it in the combustion process. Pyrolysis oil would have a higher value if it could be used as engine fuel for cars and trucks. Alternatively, the oil can be upgraded to either a special engine fuel or converted into a syngas through a gasification process and thereafter to fuel.

Char- The devolatilization of biomass during pyrolytic reactions yields a solid residue (char). Increasing the heat treatment temperature reduces char yield and increases the aromatization of char as measured by the aromatic carbon content of the acids. The by-products obtained are electricity and thermal energy.

2.3 Liquid Fuel Production Process

Liquid fuel here is defined as plastic-derived liquid hydrocarbons at a normal temperature and pressure. Only several types of thermoplastics undergo thermal decomposition to yield liquid hydrocarbons used as liquid fuel. LDPE and other mixed plastics are preferred for the feedstock of the production of liquid hydrocarbons. The addition of thermosetting plastics, wood, and paper to feedstock leads to the formation of carbonic substances. It lowers the rate and yields of liquid ducts. Depending on the components of the waste plastic being used as feedstock for fuel production, the resulting liquid fuel may contain other contaminants such as amines, alcohols, waxy hydrocarbons and some inorganic substances. Contamination of nitrogen, Sulphur and halogens gives flue gas pollution. Unexpected contamination and high-water contents may be the product yields and shorten the lifetime of a reactor for pyrolysis.

Liquid fuel users require petroleum substitutes such as gasoline, diesel fuel and heavy oil. In these fuels, various additives are often mixed with the liquid hydrocarbons to improve the burner or the engine performance. The fuel properties such as viscosity and ash content should conform to the specifications of the fuel user's burners or engines. No additives would be needed for fuel used in a boiler.

2.4 Procedure

The production method for the conversion of plastics to liquid fuel is based on the pyrolysis of the plastics and the condensation of the resulting hydrocarbons. Pyrolysis refers to the thermal decomposition of the matter under an inert gas like nitrogen. For the production process of liquid fuel, the plastics that are suitable for the conversion are introduced into a reactor where they will decompose at 450 to 550°C. Depending on the pyrolysis conditions and the type of plastic used, carbonic matter gradually develops as a deposit on the inner surface of the reactor. After pyrolysis, this deposit should be removed from the reactor in order to maintain the heat conduction efficiency of the reactor. The resulting oil (mixture of liquid hydrocarbons) is continuously distilled once the waste plastics inside the reactor are decomposed enough to evaporate upon reaching the reaction temperature. The evaporated oil is further cracked with a catalyst. The boiling point of the produced oil is controlled by the operation conditions of the reactor, the cracker and the condenser.

After the resulting hydrocarbons are distilled from the reactor, some hydrocarbons with high boiling points such as diesel, kerosene and gasoline are condensed in a water-cooled

condenser. The liquid hydrocarbons are then collected in a storage tank through a receiver tank. Gaseous hydrocarbons such as methane, ethane, propylene and butanes cannot be condensed and are therefore incinerated in a flare stack. This flare stack is required when the volume of the exhaust gas emitted from the reactor is expected to be large.

There may be variations in the feeding methods used depending on the characteristics of the waste plastic. Soft plastics such as films and bags are often treated with a shredder and a Melter (hot melt extruder) in order to feed them into the reactor because otherwise they would occupy a large volume of the reactor. Due to the formation of carbonic matter in the reactor, which acts as a heat insulator, in some tank reactors the stirrer is used to remove the carbonic matter rather than for stirring. After the liquid product of the pyrolysis is distilled, the carbonic matter is taken out either with a vacuum cleaner or in some cases reactors are equipped with a screw conveyor at the bottom of the tank reactor to remove the carbonic matter.

2.4.1 Products and By-products

Liquid fuel is used in burners or engines as a substitute for liquid petroleum. Below Table represents the properties of waste plastic-derived fuel and petroleum fuels. Samples A and B are a whole distillate and middle distillate of waste plastic pyrolytic oil respectively. After considering the burner or engine operating stability, it is possible to mix plastics-derived oil with petroleum fuel. Some plastics yield residual substances such as carbonic matter and other inorganic matter during pyrolysis. Carbonic matter can be used as a feedstock for solid fuel. Aluminium foil or other inorganic substances may be contained depending on the level of waste composition so suitable management is required. Pyrolysis of mixed plastics with nitrogen-containing plastics produces the corresponding liquid fuel with nitrogen compounds, which in turn produces nitrogen oxide in the flue gas at combustion. Similarly, liquid fuel derived from waste plastics containing chlorine will cause corrosion to the reactor and burner and it will form hydrogen chloride and dioxins. Flue gas treatment should therefore be considered to avoid the potential risks that those chemicals pose to workers and residents.

2.5 Description of Setup

Figure 7 shows a sketch of the test set-up for the pyrolysis reactor. It consists of the following components-pyrolysis reactor (primary reactor), muffle furnace condenser (heat exchanger), condenser stand, insulation and tubing fittings.

2.5.1 Pyrolysis Reactor

This is a fluidized-bed batch type reactor made of 3/4" SS304 (food grade: can withstand temperatures up to 700°C) tubing. The pyrolyser can hold about 600 gm of polymer material. Virgin polymer in the form of pellets (2 to 5 mm in size) is introduced from the top and is supported approximately at the centre of the pyrolyser by glass fibre packing. The pyrolyser is placed inside a cubical muffle furnace in which temperature can be set up to 700°C and set temperatures can easily be read. The pressure in the reactor is 0.02 to 1.0 bar. The reactor is connected to a nitrogen cylinder by means of gas tubes and SS pipes (1/2" thick) from beneath the reactor vessel.

2.5.2 Muffle Furnace

It is a simple furnace having a central heating core of 6"x6"x9" dimension and closed with a machined ceramic brick and glass fibre. The inner walls of the furnace are packed with glass for better insulation. A two holed (one of 90mm and one of 20mm) is drilled into the ceramic brick allowing the reactor and nitrogen vent to pass through it. The muffle can produce heat up to 700°C and is completely digitized.



Figure 5: Muffle Furnace

2.5.3 Condenser

This is a shell and tube type condenser made of (1/2") MS pipe tubing having height 300mm and 120 mm diameter. The condenser can hold up to three litres of water per minute. The condenser is supported by a tripod stand made of (10mm) MS (grade). The condenser is fed with water flowing at 3 l/m rate. The output of the reactor is fed into the condenser by means of (1/4") MS piping and cooled in the condenser. The condensed gasses (in the form of liquid) are collected in the container kept beneath the stand. Condenser Stand - Mild steel pipe and plates used Liquid collecting containers SS304 containers having 4 1/2" diameter and 6" height.

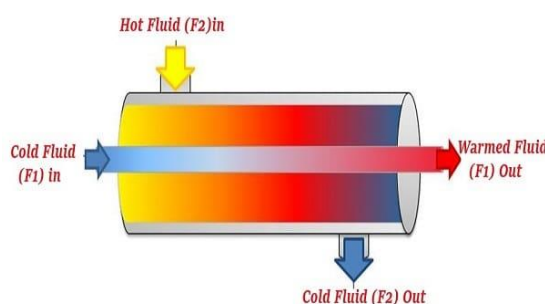


Figure 6: Double Tube Condenser

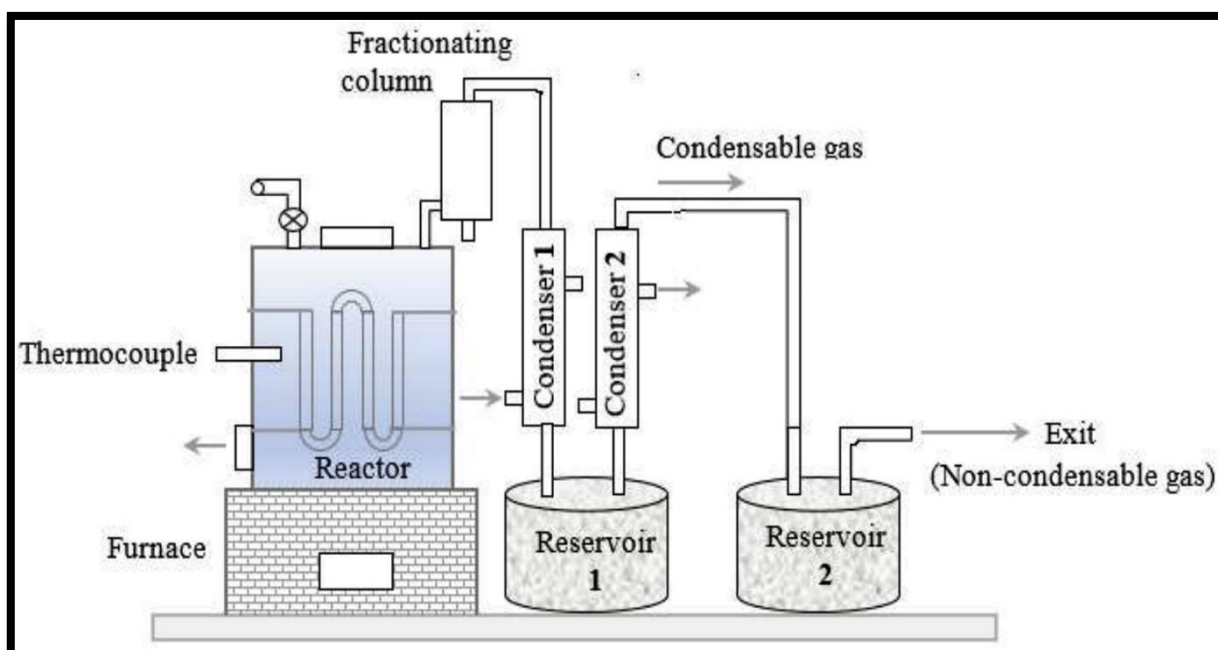


Figure 7: Schematic diagram of a pyrolysis plant.

2.6 Operating Procedure

The reactor was cleaned and dried. The muffle furnace was tightened, and the door was removed. The weighted polymer sample was fed into the reactor and kept inside the furnace. The opening was closed by the machined brick. The lid of the reactor was closed after applying an anti-sizing agent in the threaded part to avoid jamming of threaded part due to expansion while heating. The gap between the reactor and furnace mouth was filled with clay to prevent the heat radiating outside. The outlet from the nitrogen gas cylinder was connected to the pipe for gas inlet in the reactor. Next the condenser was kept on the stand vertically and the outlet of the reactor was connected to the condenser inlet. In order to circulate chilled water through the condenser, a tub is filled with water and a freezing mixture is taken in the tub. It was circulated through the condenser using an immersion pump placed in the tub. The condensate was collected in a stainless-steel container which had two openings: one inlet for the incoming gasses and condensate and an outlet for the non-condensable gasses. The gasses from the outlet were directed outside the building using a flexible hose. Leakage of fumes through the inlet and outlet holes was prevented by packing with aluminium foil.

After ensuring that the pipe fittings are made tight, the furnace was switched on and the temperature was set to 500°C. Nitrogen gas was purged in after the furnace temperature reached 300°C. Once the furnace temperature reached 400°C, the degradation began, and fumes started coming out. The immersion pump was switched on and chilled water was circulated into the

condenser using the pump. An initial temperature of 550°C was desired. However, the furnace temperature set-point was not directly set to 550°C to avoid overshoot. It was initially set to 500°C. Once the furnace temperature reached 500°C, the set-point was increased to 550°C and held for 20 minutes. We anticipate that the temperature inside the reactor might have reached about 400°C by this time. However no direct measurement of the temperature inside the reactor was possible. Finally, the furnace set-point was changed to 450°C and maintained throughout the experiment. The fumes formed were condensed into the steel container designed to collect the condensate and the non-condensable were let out of the building. Once all the material had degraded, the number of fumes coming out reduced. The chilled water supply to the condenser was stopped and the container was removed. The reactor could cool, and char was taken out weighed. The collected samples were characterized. (Dr John Scheirs, 2006)

Chapter 3. Literature Review

Table 3: Tabulated information related to various research paper studied under literature review.

Year of Publication	Author	Material Used	Method of Treatment	Equipment Used for the Method	Product, By-products with Amount	Process Parameter Condition
2019	(A Irawan, 2019)	Polyethylene, polypropylene.	Thermal pyrolysis	Fixed-bed pyrolysis reactor setup.	70-80% of bio oil, remaining is gas and biochar	Reaction Temperature: 300-500 C, Reaction Time: 30-60 minutes.
2019	(Bisrul Hapis Tambunan, 2019)	PET type plastic material, LPG as fuel.	Thermal pyrolysis followed by distillation.	Semi batch reactor with partial condenser.	49 gr Oil at 400 C (highest), with NCG and solid waste in some proportion.	Reaction Temperature: 300, 350, 400 C. Reaction Time: 35 minutes.
2021	(Maria Vargas Vilca, 2021)	PP virgin, Plastic waste. Natural Zeolite catalyst and synthetic zeolite catalyst.	Thermal & Catalytic Pyrolysis	Vacuum pyrolysis Reactor setup.	Carbonaceous solid, liquids, waxes and gases. Gaseous 75% for catalytic and 50% for thermal.	Catalyst polymer ratio(%p/p) = 10, Reaction Temperature: 450 C, Reaction Time: 20 minutes.
2021	(Rihad Miandad, 2021)	PET, beverage bottles, rubber tires.	Pyrolysis decomposition.	Fixed floor tubular heat reactors.	NA	NA
2020	(S Muzarpar, 2020)	PE, PP, PET, Polystyrene.	Thermal pyrolysis followed by distillation	Ablative reactor, condenser, heat exchangers	Oil, gas, wax and char.	Reaction Temperature: 500 C, increasing temp 6-14 C/min, Reaction Time: 14 minutes.
2016	(Madeeha Batool, 2016)	Commercial low-density polyethylene beads, ZSM-5 catalyst, CTA-POM,	Thermal catalytic cracking, thermal catalytic pyrolysis	Batch reactor, PID controller.	NA	Reaction Temperature: Between 220-280 C, Reaction Time: 1.5 hour.
2014	Gaurav, Madhukar M, Arunkumar K.N., Lingegowda	HDPE, PP, LDPE.	Thermal cracking process	Condenser, circulating bed reactor.	Light gas-methane, ethane, propane and butane. Also contain CO or CO2 emission. Production prcentage-6%	NA
2019	(Sunaryo, 2019)	PET, LDPE.	NA	NA	PPO- plastic pyrolysis oil.	NA
2022	(Jochen Uebe, 2022)	HDPE, PP.	Pyrolysis decomposition.	Fluidized bed reactor, reflux condenser.	Pyrolysis oil, solid residue.	Reaction Temperature: 410 C in case of PP, 440 C in case of HDPE, Reaction Time: 30-60 minutes.

3.1 Factors Affecting Pyrolysis

3.1.1 Chemical Composition of Feedstock

The pyrolysis products are directly related to the chemical composition and chemical structure of the plastics to be pyrolyzed. In addition, the chemical composition of the feedstock also affects the pyrolysis processes.

3.1.2 Cracking Temperature and Heating Rate

Temperature is one of the most important operating variables since temperature effect dominates the cracking reaction of the polymer materials. The other operating thermal dynamic parameter is heating rate. The term "heating rate" in this field means the increase of temperature per unit time. The influence of the heating rate on the plastic pyrolysis process and product distribution varies in different studies due to the differences in the pyrolysis reactor, operation conditions (temperature and pressure), and temperature measurement location. All our studies have been carried out under isothermal conditions. Therefore, while temperature is a significant variable, heating rate is irrelevant to this study. (A Irawan, 2019)

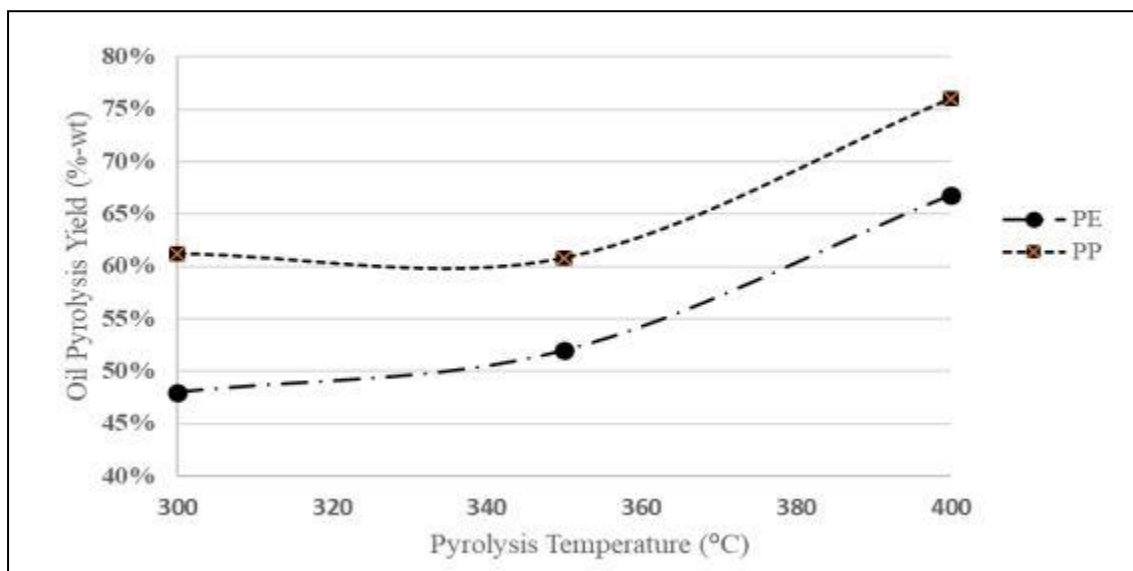


Figure 8: Influence of temperature (C) to the oil pyrolysis plastic yield (%-wt.) for polyethylene and polypropylene pyrolysis.

3.1.3 Type of Reactor

The reactor type for the plastic pyrolysis significantly influences the heat transfer rate, mixing of plastics with pyrolysis products, residence time and the reflux level of the primary products. Reactors can be classified into batch, semi-batch and continuous or classified based on types of reactor bed. In the batch reactor, the materials are fed into the reactor in batches for pyrolysis either at the start of the process or after all the fed materials are processed. In the continuous reactor, the feed materials are input from one part and the products are led out from the other part of the reactor. A semi-batch reactor removes the pyrolysis products continuously once they are generated but the feed materials are added initially before the pyrolysis process starts. The fluidized bed reactor has been used in most commercial plants in which gaseous products or inert gas flow through an expanded bed of feedstock and other bed materials, forming bubbles or eddies. The advantages of a fluidized bed reactor are the homogeneity of both temperature and composition. Heat and mass transfer rates are much higher than the fixed bed thus the low thermal conductivity in bed reactors is no longer a problem. A fluidized bed Reactor (FBR) is a type of reactor device that can be used to carry out a variety of multiphase chemical reactions. In this type of reactor, a fluid (gas or liquid) is passed through a granular solid material (usually a catalyst possibly shaped as tiny spheres) at high enough velocities to suspend the solid and cause it to behave as though it were a fluid. This process, known as fluidization, imparts many important advantages to the FBR. As a result, the fluidized bed reactor is now used in many industrial applications. (A Irawan, 2019)

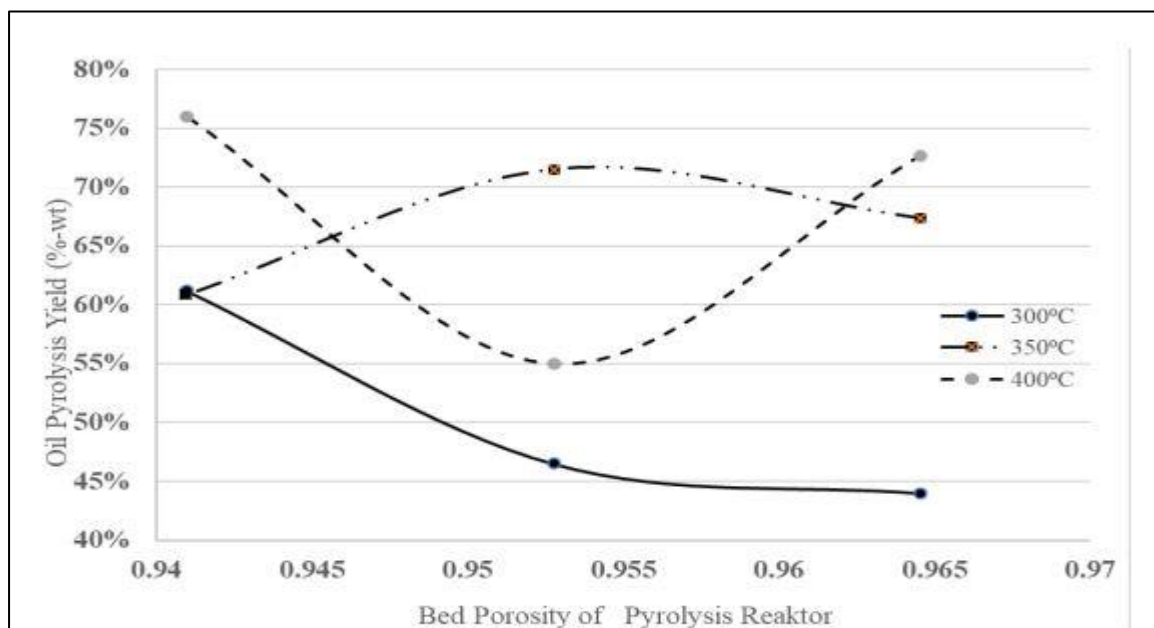


Figure 9: Influence of bed porosity and pyrolysis temperature (C) to the oil pyrolysis plastic yield polyethylene and polypropylene pyrolysis.

3.1.4 Residence Time

The definition of residence time differs in various studies. In fast pyrolysis or continuous pyrolysis process, it refers to the contact time of the plastic on the hot surface throughout the reactor. However, in slow pyrolysis and batch process, the residence time means the duration from the time when feedstock plastic starts to be heated to the time when the products are removed.

3.1.5 Use of Catalyst

In order to optimize plastic pyrolysis reactions and modify the distribution of pyrolysis products, catalysts are widely used in research and industrial pyrolysis processes. Experiments have shown that the use of various catalysts improves the yield of hydrocarbon products and provides better selectivity in the product distributions. *(Maria Vargas Vilca, 2021)*

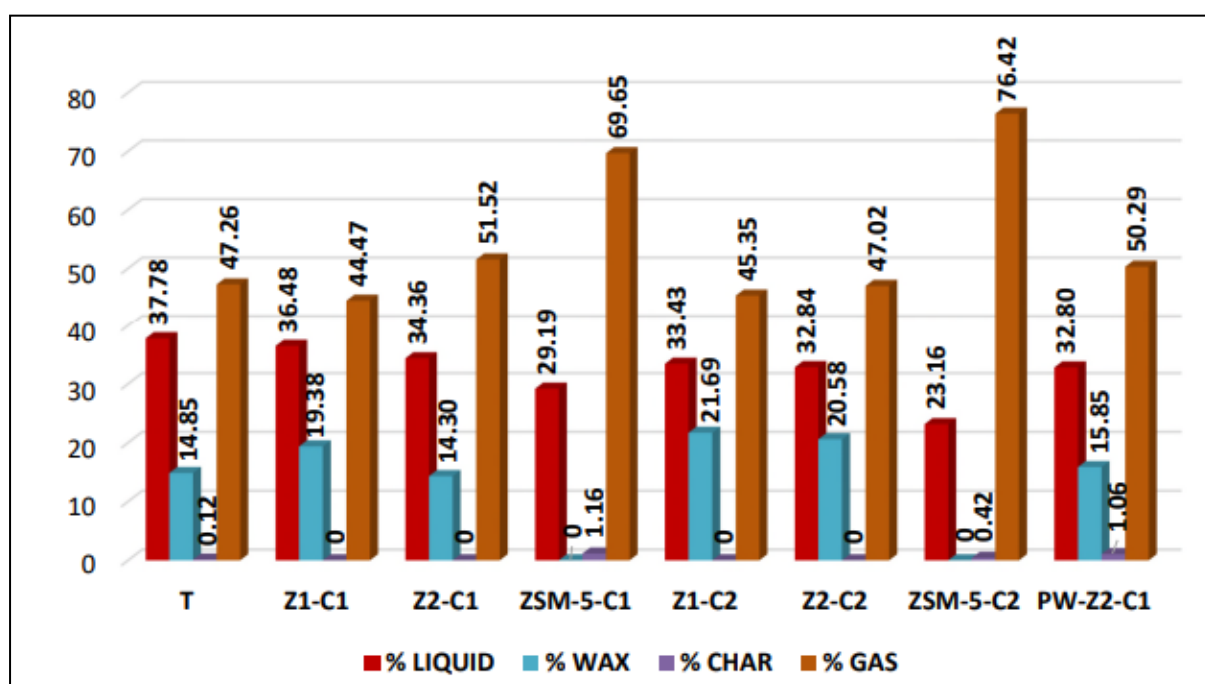


Figure 10: Pyrolytic residues (%) obtained in the catalytic and thermal pyrolysis process using PP and PE plastic waste.

3.1.6 Pressure

Operating pressure has a significant effect on both the pyrolysis process and the products. The boiling points of the pyrolysis products are increased under higher pressure, therefore, under pressurized environment heavy hydrocarbons are further pyrolyzed instead of vaporized at given operation temperature. In effect, under pressurized pyrolysis, more energy is required for further hydrocarbon cracking. It was also found that high pressure increases the yield of non-condensable gasses and decreases the yield of liquid products. Pressures in most cases were kept in a relatively low range. For pure polystyrene feed, pressures were varied from 0.31 Mpa to 1.6 Mpa.

Chapter 4. Mass Balance and Energy Balance

4.1 Mass Balance

Measurement of mass balance in a continuous process is not straightforward. The technique used here approximates a continuous process by using a discrete charge of feed and so having a discrete char yield but taking a running sample of gas phase products. Assuming conservation of matter and no accumulation in the system (which can be checked) the total mass of products initially in the gas phase (including non-condensable syngas and condensable vapours) as given by the feed mass less the char mass. Taking a representative sample of the gas phase product mixture and separating it quantitatively into non-condensable syngas and condensable liquids allows the proportions of these products to be defined and hence the total mass yields of the syngas and pyrolysis liquid products to be calculated. Moisture present in the feed will not be distinguishable from pyrolytic water in the product mixture and must be considered in the calculation.

The derivation of simple expressions for the total syngas mass and the total pyrolysis liquid mass is given below, based on quantities determined by the experimental methods described above.

The reactor (height: 990 mm, diameter: 480 mm) constructed in this experiment was made of stainless steel having a feeder header (height: 80 mm, diameter: 120 mm) at the top and an exit (diameter: 200 mm) for char removal at bottom of the reactor. At first a concrete slab supported by concrete wall was placed inside underground holes as base of the pilot plant. Then reactor was placed on the hole of the concrete slab. There are four ash ports in the slab for removing ash. For providing uniform and faster heating, two halves hexagonal stainless-steel pipe (diameter: 19 mm, total length: 2740 mm) installed inside the reactor in u-shape (bending radius: 76 mm). The heat is supplied to the reactor by a fuel burner. It has two openings for providing solid fuel into the furnace. There was another exit port at the top of the reactor which was connected to the two-vertical condenser (length: 1520 mm, diameter: 170 mm) as well as an oil reservoir (length: 470 mm, diameter: 360 mm). Two condensers were designed for capturing higher quantity of pyrolytic oil from condensable gas. The cooling was done by passing the cold water through the condenser. When the temperature of the reactor reaches at requires level, product volatile expands and raises its pressure, which leads the volatile comes out fast from the reactor through the condenser. A fraction column (height: 1830

mm, diameter: 160 mm) was installed between reactor and condenser for the separation of heavy components from the light fraction of condensable gas under the action of gravity. The heavy fraction usually blocks the connecting pipe (channels) and accumulates inside the reservoir. There was a flange at the bottom for clean-up heavy oil fraction from the fraction column. (Himmelblau, Material Balance, 1974)

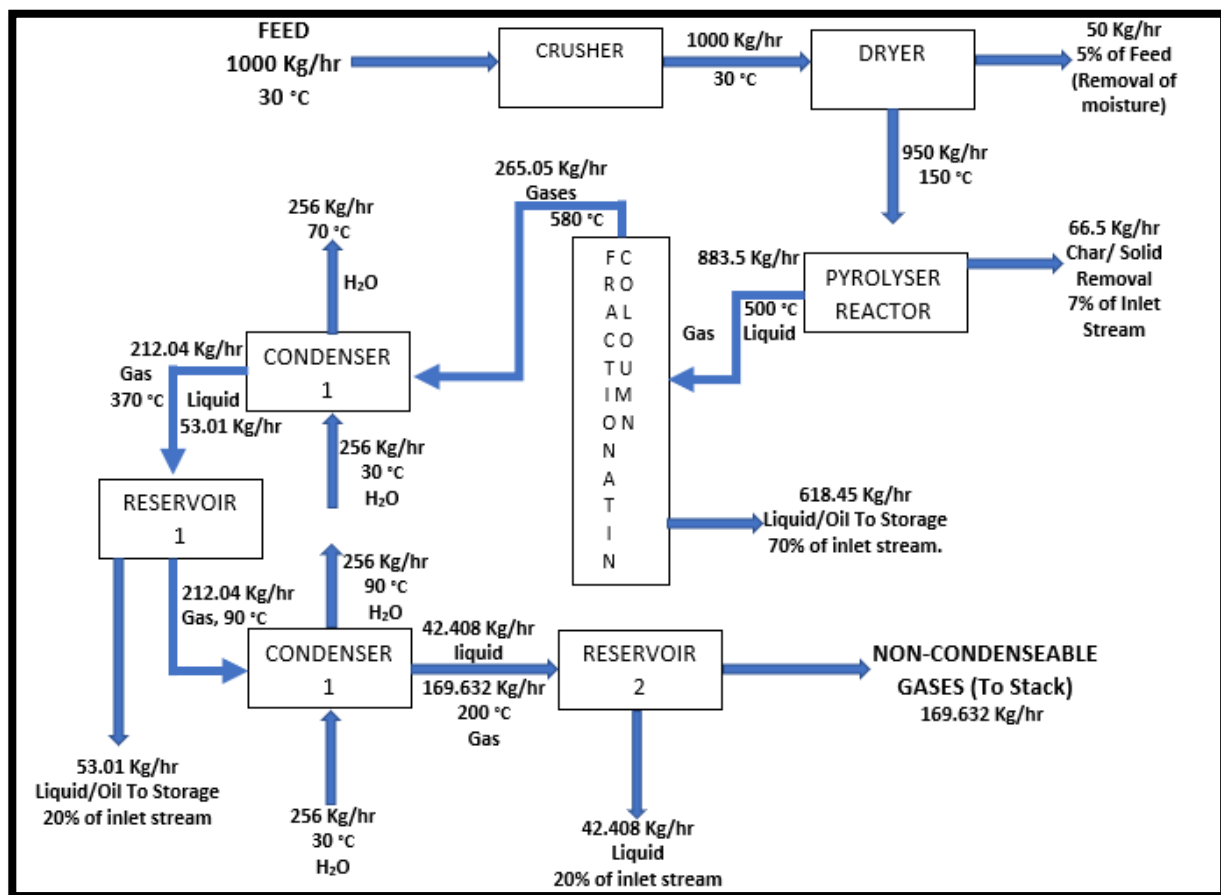


Figure 11: Process flow diagram of the pyrolysis plant for mass balance.

Here we are considering that the plant is in steady state to avoid complexity of calculations.

Basis: 1000 Kg/hr entering the feeder header.

4.1.1 Overall Mass Balance on the System

The overall mass balance for the system is given by the dynamics,

Rate of Mass In – Rate of Mass Out + Rate of Generation – Rate of Consumption = Rate of Accumulation

For steady state,

Accumulation = 0

Generation = 0 (Since no generation is occurring)

Consumption = 0 (Since no consumption is occurring)

Therefore,

Rate of Mass In = Rate of Mass out

1000 Kg/hr = 50+66.5+618.45+53.01+42.408+169.632 Kg/hr

4.1.2 Material Balance on the Individual Equipment

4.1.2.1 For Dryer

Input = Output

$1000 = 950 + X$

$X = 1000 - 950 = 50 \text{ Kg/hr}$

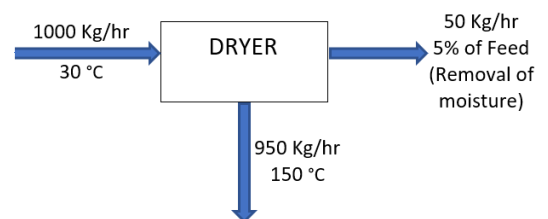


Figure 12: Mass Balance on dryer.

Here, X = Rate of Moisture Removal of Dryer

i.e. Dryer removes 5% of feed as moisture content.

4.1.2.2 For Pyrolyser Reactor

Input = Output

$$950 = 883.5 + C$$

$$C = 950 - 883.5 = 66.5 \text{ Kg/hr}$$

Here, C = Amount of solid/char formed

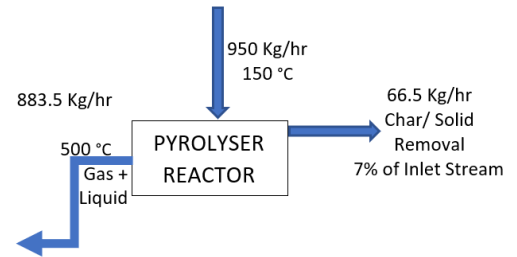


Figure 13: Mass balance on pyrolyser reactor.

i.e. 7% of the feed entering the reactor will be converted into solid char, while the remaining 98% will convert into a mixture of gas and oil.

4.1.2.3 For Fractionating Column

Input = Output

$$883.5 = 265.05 + 618.45$$

Liquid obtained = 618.45 Kg/hr i.e. 70% of feed.

Gas obtained = 265.05 Kg/hr i.e. 30% of feed.

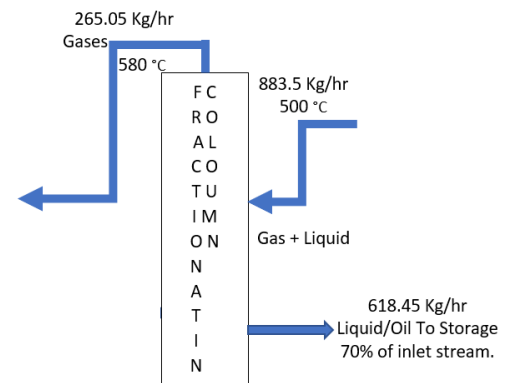


Figure 14 Mass balance for fractionating column.

4.1.2.4 For Condenser 1

Input = Output

$$265.05 = 212.04 + 53.01$$

Liquid obtained = 53.01 Kg/hr i.e. 20% of feed.

Gas obtained = 212.04 Kg/hr i.e. 80% of feed.

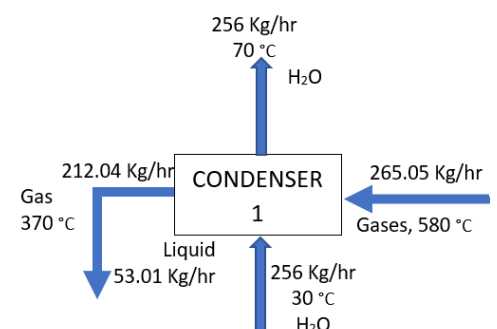


Figure 15 Mass balance for condenser 1.

Also, since the cooling liquid is entering and leaving the condenser with a higher temperature without being vaporized, therefore, there is no need of mass balance over the coolant.

4.1.2.5 For Condenser 2

Input = Output

$$212.04 = 169.63 + 42.408$$

Liquid obtained = 42.408 Kg/hr i.e. 20% of feed.

Gas obtained = 169.63 Kg/hr i.e. 80% of feed.

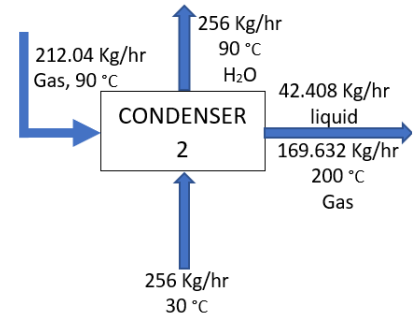


Figure 16: Mass balance for condenser 2.

Just like Condenser 1, the cooling liquid is entering and leaving the condenser with a higher temperature without being vaporize, therefore, there no need of mass balance over the coolant.

Table 4: Composition of different products obtained by pyrolysis.

Solid/ Char (%age Obtained)	7% (66.5 Kg/hr)
Gas/ Vapor (%age Obtained)	16.9% (169.632 /kg/hr)
Oil/ Liquid (%age Obtained)	76.03% (713.868 Kg/hr)

4.2 Energy Balance

The energy balances are only considered in terms of the material flows and their energy content, no attempt has been made to model the process heat input or heat losses from the system. However, the pyrolysis reaction will be exothermic for at least part of the heating phase and any heat loss from this conversion of chemical- to thermal-energy cannot be accounted because this effect is expected to be small in proportion to total heat loss as, for any particle, it is only experienced for a short period. (Himmelblau, Energy Balance, 1982)

Energy balance over the various equipment are given by the dynamics,

$$\text{Rate of Energy In} - \text{Rate of Energy Out} + \text{Rate of Generation} - \text{Rate of Consumption} = \text{Rate of Energy Accumulated}$$

For steady state, we have,

$$\text{Rate of Accumulation} = 0$$

4.2.1 Energy Balance for Dryer

$m_p = 1000$, mass flowrate of plastic waste in, Kg dry solid/hr.

$w_1 = 0.05$, moisture content of plastic at inlet of dryer, Kg water/Kg dry solid.

$w_2 = 0$, moisture content of plastic at outlet of dryer, Kg water/Kg dry solid.

$T_{p1} = 30$, Temperature of feed at dryer inlet, °C.

$T_{p2} = 150$, Temperature of feed at dryer outlet, °C.

$m_a = 100$, mass flowrate of cooling water in, Kg dry air/hr.

$W_1 = 0.02044$ Absolute humidity of air at outlet of dryer, Kg water/Kg dry air.

$W_2 = 0.08023$ Absolute humidity of air at inlet of dryer, Kg water/Kg dry air.

$T_{a1} = 40$, Temperature of air at outlet, °C.

$T_{a2} = 65$, Temperature of air at inlet, °C.

Q = Heat loss from the dryer.

$H_{a1} = 41.75$, Thermal energy of air at outlet, KJ/Kg dry air.

$H_{a2} = 75.93$, Thermal energy of air at inlet, KJ/Kg dry air.

$H_{p1} = 6323.1$, Thermal energy of plastic at inlet, KJ/ Kg dry solid.

$H_{p2} = 250.5$, Thermal energy of plastic at inlet, KJ/ Kg dry solid.

Energy balance for the dryer is given as,

$$m_a H_{a2} + m_p H_{p1} = m_a H_{a1} + m_p H_{p2} + Q$$

therefore,

$$Q = 60,76,018 \text{ KJ/hr} = 1452.20 \text{ Kcal/hr}$$

4.2.2 Energy Balance for Pyrolysis Furnace

$m_1 = 950$, mass flowrate of feed in, Kg/hr.

$m_2 = 66.5 + 883.5$, mass flowrate of feed out, Kg/hr.

$C_P = 1.67$, Specific Heat of Plastic fibres, KJ/ (KG K).

$T_2 = 150$, Higher Temperature, °C.

$T_2 = 500$, Lower Temperature, °C.

Here we have fuel fired furnace maintained at the temperature of 600 °C.

We are using Coal as the fuel which has 70% Carbon content.

Assume, Net Calorific Value or NCV of fuel = 27900 KJ/Kg

And, for combustion to take place air is flowing at the temperature of 25 °C.

Product of Combustion or POC with Volume % are as follows:

N₂ 76%, O₂ 7%, H₂O 5%, CO₂ 12 %.

All these components are in gaseous state.

Now assume,

Gross Available Heat or GAH requirement of Furnace = 1.5×10^3 kW

Temperature of POC = 500 °C

Basis: 150 °C, at this temperature the heat content values are known to us.

By Carbon balance, we have

Amount of POC = 0.486 Kg mol/ Kg Carbon

Heat to POC:

Heat contents of in gases phase for components N₂, O₂, H₂O, CO₂ is given as 66350 KJ/Kgmol, 43710 KJ/Kgmol, 54880 KJ/Kgmol, 41620 KJ/Kgmol respectively.

Therefore, heat to POC for components N₂, O₂, H₂O, CO₂ is given as 0.05832 kg mol, 0.0243 kg mol, 0.034 kg mol, 0.3694 kg mol respectively.

Now Heat carried by each component of flue gas, N₂, O₂, H₂O, CO₂ is given as 3869 KJ, 1334 KJ, 1489 KJ, 15374 KJ respectively.

Total heat to POC = 22063 KJ

Now,

GAH per kg of fuel = Calorific Value – Heat to POV = 5837 KJ

$$\text{Heat carried by POC} = (22063/27900) \times 100 = 79\%$$

This implies, 79% of calorific of fuel is carried away by flue gases and remaining 21% of calorific value is used for heating only.

Therefore,

$$\text{Fuel Consumption} = [(1.5 \times 10^3) \times 3600] / 5837 = 925 \text{ Kg/ hr}$$

4.2.3 Energy Balance for Reactor

Height of reactor, $H = 990 \text{ mm} = 0.99 \text{ m}$.

Diameter of reactor, $D = 480 \text{ mm} = 0.48 \text{ m}$.

Average Density of Reaction Mixture = 19.3284 Kg/m^3 .

Energy Requirement = $50\text{-}60 \text{ kW}$.

Maximum Temperature = $500 \text{ }^\circ\text{C}$.

Reaction Temperature = $350\text{-}500 \text{ }^\circ\text{C}$.

Length of Reactor, $L = (3.3) \times D = 1.584 \text{ m}$.

Reaction Time = $60 \text{ min} = 1 \text{ hr}$.

Heat of Reaction, $H_r = 132.71 \text{ KJ/Kg}$.

Volume of Reaction Mixture = $3.14 \times D \times 2(L/H) = 4.82 \text{ m}^3$

Therefore,

Weight of Reaction Mixture in Reactor = Density \times Volume = $19.3284 \times 4.82 = 93.22 \text{ Kg}$

*Energy Required for Reaction = Wt. of Reaction \times Heat of Reaction = 93.22×132.71
 $= 12,371.4 \text{ KJ/hr}$*

4.2.4 Heat Balance for Condenser 1

For cold fluid (Water):

Average Temperature of cooling water, $T_{av} = (70 + 30)/2 = 50 \text{ }^\circ\text{C}$

Specific Heat of Water, $C_{pw} = 4.187 \text{ KJ/(Kg K)}$

Mass flowrate of Cool Water, $m_w = 256 \text{ Kg/hr}$

Therefore,

$$Q_{cold} = m_w C_{pw} T_{av} = 256 \times 4.187 \times 50 = 53,593.6 \text{ KJ/hr}$$

For Hot Fluid (Feed):

Average Temperature of Feed, $T_{av} = (480 + 370)/2 = 425 \text{ }^\circ\text{C}$

Specific Heat of Feed, $C_{pp} = 1.6 \text{ KJ}/(\text{Kg K})$

Mass flowrate of Cool Water, $m_p = 265.05 \text{ Kg/hr}$

Therefore,

$$Q_{hot} = m_p C_{pp} T_{av} = 265.05 \times 1.6 \times 425 = 188,119.23 \text{ KJ/hr}$$

Logarithmic Mean Temperature Difference:

	Hot Fluid	Cold Fluid	Difference
Higher Temperature	480 °C	70 °C	410 °C
Lower Temperature	370 °C	30 °C	350 °C

$$\begin{aligned} LMTD &= (410 - 350) / \ln (410/350) = 60 / 0.15 \\ &= 400 \text{ }^{\circ}\text{C} \end{aligned}$$

4.2.5 Heat Balance for Condenser 2

For cold fluid (Water):

Average Temperature of cooling water, $T_{av} = (90 + 30)/2 = 60 \text{ }^{\circ}\text{C}$

Specific Heat of Water, $C_{pw} = 4.187 \text{ KJ}/(\text{Kg K})$

Mass flowrate of Cool Water, $m_w = 256 \text{ Kg/hr}$

Therefore,

$$Q_{cold} = m_w C_{pw} T_{av} = 256 \times 4.187 \times 60 = 64,312.32 \text{ KJ/hr}$$

For Hot Fluid (Feed):

Average Temperature of Feed, $T_{av} = (200 + 370)/2 = 285 \text{ }^{\circ}\text{C}$

Specific Heat of Feed, $C_{pp} = 1.6 \text{ KJ}/(\text{Kg K})$

Mass flowrate of Cool Water, $m_p = 212.04 \text{ Kg/hr}$

Therefore,

$$Q_{hot} = m_p C_{pp} T_{av} = 212.04 \times 1.6 \times 285 = 100,920.43 \text{ KJ/hr}$$

Logarithmic Mean Temperature Difference:

	Hot Fluid	Cold Fluid	Difference
Higher Temperature	370 °C	90 °C	280 °C
Lower Temperature	200 °C	30 °C	170 °C

$$\begin{aligned} LMTD &= (280 - 170) / \ln (280/170) = 11 / 0.49 \\ &= 229.489 \text{ }^{\circ}\text{C} \end{aligned}$$

Chapter 5. Equipment Design: Mechanical Aspects

5.1 Crusher

Designing a plastic shredder with proper calculations requires a detailed understanding of the specific requirements and materials being processed. Here is an example of a mechanical design with some basic calculations for a plastic shredder with a capacity of 1000 kg per hour.

5.1.1 Frame and Base

The frame and base of the shredder should be made of high-strength materials, such as steel, to support the weight of the shredder and withstand the stresses of operation. The frame should be designed with a suitable factor of safety to ensure it can withstand the loads and stresses imposed during shredding. For example, if the shredder weighs 5000 kg and the factor of safety is 2, the minimum allowable yield strength for the material used should be:

$$\text{Minimum Yield Strength} = (5000 \text{ kg} \times 2) / (\text{Area of the cross-section} \times \text{Allowable stress})$$

5.1.2 Cutting Blades

The cutting blades of the shredder should be designed to optimize the shredding process for the specific plastic materials being shredded. The blade thickness and spacing should be selected based on the thickness and hardness of the plastic materials. The number of blades and their size will depend on the capacity and power of the motor. A general rule of thumb for the blade speed is around 100-150 rpm.

5.1.3 Motor and Drive System

The motor and drive system should be selected based on the capacity and power requirements of the shredder. The required torque can be calculated using the following formula:

$$\text{Torque (Nm)} = 9.55 \times \text{Power (kW)} / \text{Speed (rpm)}$$

Assuming a shredder capacity of 1000 kg/hour, with a motor efficiency of 80%, the motor power required will be:

$$\text{Power (kW)} = (1000 \text{ kg/hour}) \times (1 \text{ hour} / 3600 \text{ seconds}) \times (1 / 0.8) = 347 \text{ kW}$$

Assuming a motor speed of 1500 rpm, the required torque will be:

$$\text{Torque (Nm)} = (9.55 \times 347 \text{ kW}) / 1500 \text{ rpm} = 2215 \text{ Nm}$$

5.1.4 Hopper and Feeding System

The hopper of the shredder should be designed to hold a enough volume of plastic waste, with a feeding mechanism to ensure a steady and consistent feed of materials into the shredder. The hopper should be designed with a slope to allow for gravity feeding of the materials into the shredder. The feeding mechanism can be a conveyor belt, screw feeder, or other device that can handle the specific plastic materials being shredded.

5.1.5 Discharge System

The shredded plastic material should be discharged from the shredder through a discharge chute or conveyor belt and should be collected in a container or bin for further processing or recycling.

5.1.6 Safety Features

The shredder should be equipped with appropriate safety features, such as emergency stop buttons, interlocks, and guards, to prevent accidents and injuries.

5.1.7 Maintenance and Cleaning

The shredder should be designed to be easy to maintain and clean, with easy access to the shredder blades, rotor, and motor. The shredder should also be equipped with sensors and monitoring systems to detect and alert operators to any issues or malfunctions.

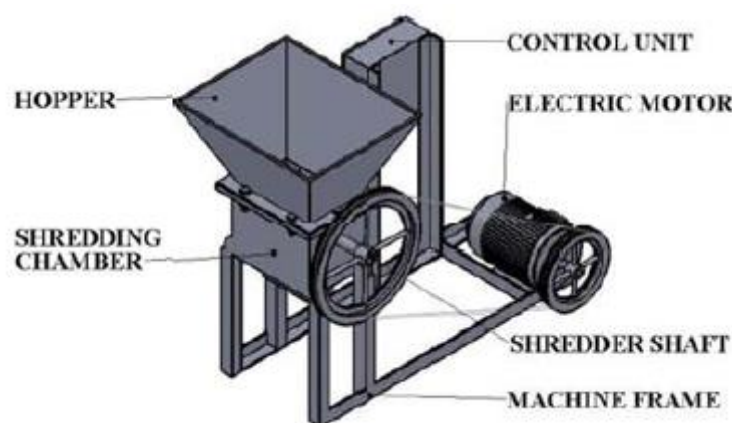


Figure 17: Isometric view of plastic shredder.

5.2 Rotary Dryer

The design of a rotary dryer for the feed of 1000 kg per hour requires several calculations based on various parameters such as the feed rate, inlet and outlet temperatures, heat transfer coefficient, and dryer dimensions. Here is an example calculation for the design of a rotary dryer for drying plastic waste:

Assuming a feed rate of 1000 kg per hour of plastic waste with an initial moisture content of 10% (by weight), and a desired final moisture content of 2% (by weight).

5.2.1 Calculation of the Amount of Water to be Removed

Initial moisture content = 10%

Final moisture content = 2%

$$\text{Total moisture to be removed} = (10\% - 2\%) \times 1000 \text{ kg/hour} = 80 \text{ kg/hour}$$

5.2.2 Calculation of the Required Heat Input

Heat of vaporization of water = 2260 kJ/kg

Total heat required to vaporize 80 kg/hour of water =

$$= 80 \text{ kg/hour} \times 2260 \text{ kJ/kg} = 180,800 \text{ kJ/hour}$$

Assuming an overall heat transfer coefficient of 150 W/m²K

Calculation of the required heat transfer area =

$$\begin{aligned} &= (180,800 \text{ kJ/hour}) / (150 \text{ W/m}^2\text{K} \times 60 \text{ minutes/hour} \times 60 \text{ seconds/minute} \times 1000 \text{ m}^2) \\ &= 0.84 \text{ m}^2 \end{aligned}$$

5.2.3 Calculation of the Dryer Dimensions

Assuming a drum diameter of 2.4 m and a length-to-diameter ratio of 4:1

Calculation of the drum length = (4/1) x 2.4 m = 9.6 m

Calculation of the drum surface area = $\pi \times 2.4 \text{ m} \times 9.6 \text{ m} = 72.38 \text{ m}^2$

Calculation of the required drum speed = (1000 kg/hour) / ($\rho \times \pi \times (2.4 \text{ m}/2)^2 \times 72.38 \text{ m}^2$) = 0.20 revolutions per minute (rpm)

Based on these calculations, a rotary dryer with a drum diameter of 2.4 m, a length of 9.6 m, a drum speed of 0.20 rpm, and a heat transfer area of 0.84 m² would be required to dry 1000 kg/hour of plastic waste from an initial moisture content of 10% to a final moisture content of 2%. However, it is important to note that these calculations are based on assumptions and simplifications, and a detailed analysis of the specific application is necessary to ensure the design meets the requirements.

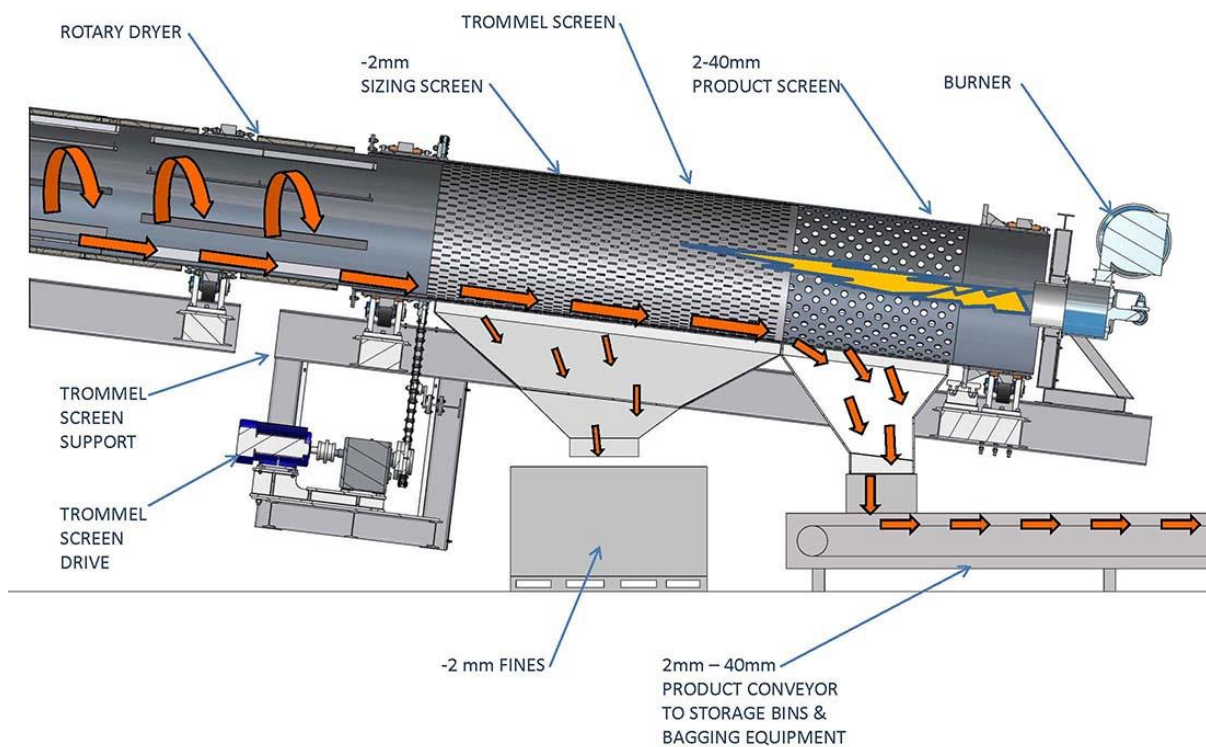


Figure 18: Components of rotary dryer.

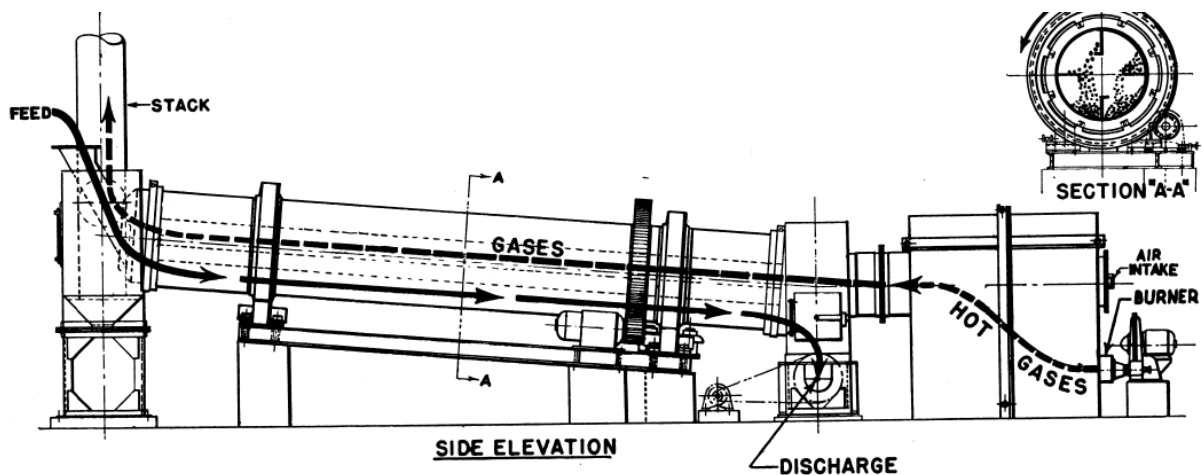


Figure 19: Sectional view of direct heat type rotary dryer.

5.3 Reservoir

A reservoir, or storage tank, is a simple vessel used to store fluids for later use. The equipment design for a reservoir will depend on the specific requirements of the application, such as the capacity of the tank, the type of fluid being stored, and the operating conditions.

5.3.1 General Outline of the Design Considerations for a Reservoir

5.3.1.1 Determination of Capacity of the Reservoir

The capacity of the reservoir will depend on the feed rate from the condenser, as well as the required holding time. Assuming a feed rate of 1000 kg/hr and a required holding time of 8 hours, the required tank volume can be calculated as:

$$V = Q \times t$$

Where,

V = volume of the tank (in m³)

Q = feed rate from the condenser (in kg/hr) = 1000 kg/hr

t = required holding time (in hours) = 8 hours

$$V = (1000 \times 8) / 1000 = 8 \text{ m}^3$$

5.3.1.2 Determination of Material of Construction

The material of construction will depend on the type of fluid being stored, as well as any chemical compatibility requirements. For example, if the fluid is corrosive, a material such as stainless steel or fiberglass reinforced plastic (FRP) may be required.

5.3.1.3 Design of Tank

The design of the tank will depend on the specific requirements of the application, such as the desired shape of the tank, the number of inlets and outlets, and any required accessories such as level sensors or agitators. Here are some general guidelines for designing a cylindrical tank:

5.3.1.3.1 Diameter

The diameter of the tank should be selected to provide the required volume while minimizing the height of the tank. For example, a tank with a diameter of 2.5 meters and a height of 3.2 meters would provide a volume of 8 m³.

5.3.1.3.2 Wall Thickness

The wall thickness of the tank should be selected to provide the required structural strength while minimizing material usage. The thickness of the tank walls will depend on the material of construction and any pressure or vacuum requirements.

5.3.1.3.3 Inlets and Outlets

The tank should have at least one inlet and one outlet, located at opposite ends of the tank. The size and location of the inlets and outlets will depend on the feed rate from the condenser and any flow requirements.

5.3.1.3.4 Accessories

Any required accessories, such as level sensors or agitators, should be designed and installed in accordance with industry standards and best practices.

5.3.1.3.5 Design of Supports

The tank should be supported by a suitable foundation or support structure to ensure stability and prevent overturning or collapse. The design of the supports will depend on the size and weight of the tank, as well as the specific requirements of the application.

5.3.2 Mechanical Design for a Cylindrical Reservoir

Here is a more detailed mathematical and mechanical design for a cylindrical reservoir with a capacity of 8 m³, based on the design considerations outlined in my previous response:

5.3.2.1 Determination of Material of Construction

Assuming the fluid being stored is non-corrosive, a mild steel material will be used for the construction of the tank.

5.3.2.2 Design of Tank

- **Diameter:** The diameter of the tank will be 2.5 meters, which will result in a cross-sectional area of 4.9 m².
- **Height:** The height of the tank will be 3.2 meters, which will provide a total volume of 8 m³.
- **Wall thickness:** The wall thickness of the tank will be calculated using the formula:

$$t = (PD) / (2SE + 0.6P)$$

Where,

t = wall thickness (in mm)

P = design pressure (in kPa) = atmospheric pressure (101.3 kPa)

D = tank diameter (in mm) = 2500 mm

S = maximum allowable stress for the material (in MPa) = 200 MPa

E = joint efficiency factor (dimensionless) = 0.85

Substituting these values into the formula, we get:

$$t = (101.3 \times 2500) / [(2 \times 200 \times 0.85) + (0.6 \times 101.3)] = 5.1 \text{ mm}$$

Therefore, a wall thickness of 5.1 mm will be used for the tank.

- **Inlets and outlets:** The tank will have two 2-inch NPT inlets located at the top of the tank, and one 2-inch NPT outlet located at the bottom of the tank. The inlets and outlets will be equipped with suitable valves and fittings.
- **Accessories:** The tank will be equipped with a level sensor, temperature sensor, and pressure gauge.

5.3.2.3 Design of Supports

- **Foundation:** The tank will be supported by a concrete foundation with a thickness of 300 mm.
- **Support structure:** The tank will be supported by a cylindrical support structure consisting of four columns and a ring beam. The columns will be made of structural steel and will be anchored to the foundation. The ring beam will be made of reinforced concrete and will be connected to the columns using bolts.
- **Bracing:** The support structure will be braced using diagonal steel members to prevent lateral movement.

5.3.2.4 Testing and Inspection

Before the tank is put into service, it will be tested and inspected to ensure that it meets all applicable industry standards and regulations. This will include hydrostatic testing to verify the strength and integrity of the tank and all associated fittings and valves, as well as a visual inspection for any defects or damage.

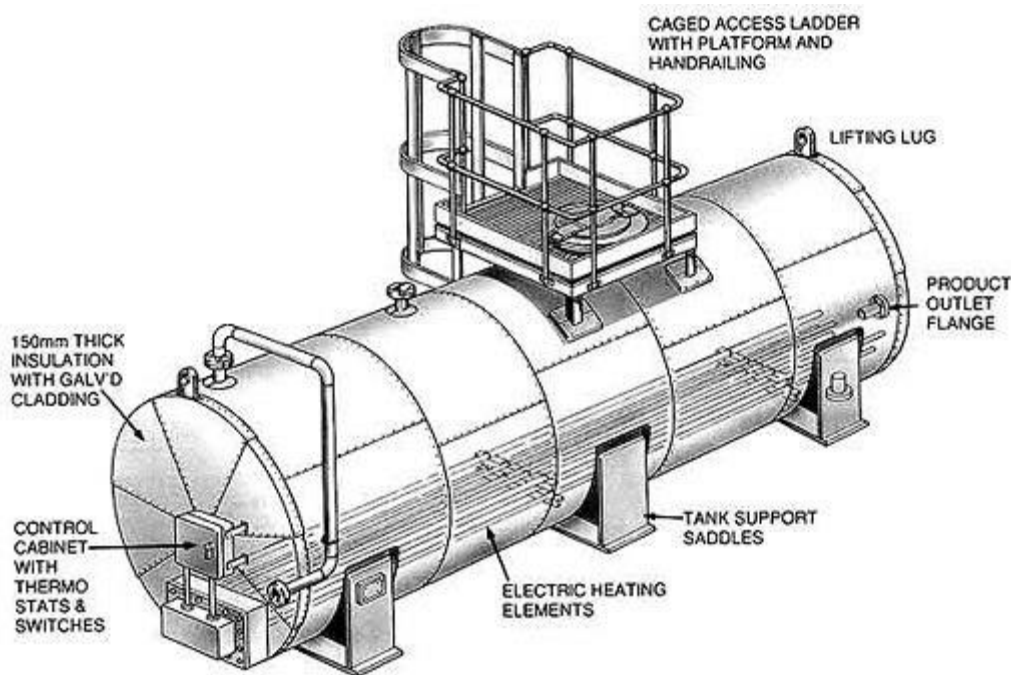


Figure 20: Components of a cylindrical storage tank.

5.4 Fractionating Column

The design of a fractionating column for the separation of pyrolysis products from plastic waste will depend on the specific composition of the feed and the desired product fractions.

Here is a basic design outline for a fractionating column:

- **Column vessel:** The column vessel can be made of stainless steel or other suitable material to withstand the corrosive environment of the process. The size of the column vessel will depend on the desired capacity and the number of trays or packing material used for the separation.
- **Tray or packing material:** The column can be filled with a packing material or equipped with trays to provide a large surface area for the separation of the components. The selection of the packing material or trays will depend on the specific composition of the feed and the desired product fractions.
- **Feed system:** The feed from the pyrolysis reactor can be introduced into the column through a feed tray or a reflux drum.
- **Reflux system:** The reflux system is used to provide the necessary vapor-liquid equilibrium in the column. The reflux is typically produced by condensing a portion of the vapor leaving the top of the column and returning it to the top of the column.

- **Heat source:** The heat source for the fractionating column can be provided by an external heat source or by a reboiler located at the bottom of the column. The reboiler can be heated using steam or another suitable heating fluid.
- **Product collection system:** The products from the column can be collected in a series of condensers and receivers. The condensers can be equipped with heat exchangers to recover the heat from the condensing vapors.
- **Emission control system:** The emission control system for the fractionating column will depend on the specific emissions produced by the process. The emissions can be controlled using a series of filters and scrubbers.

It is important to note that the design of a fractionating column for the separation of pyrolysis products from plastic waste is complex and depends on many variables specific to the application. A detailed analysis is necessary to ensure that the design meets the requirements for the specific feedstock and desired product yield.

Here is a detailed mathematical and mechanical design for a fractionation column with a diameter of 0.5 meters and a height of 10 meters:

5.4.1 Determination of Material of Construction

Assuming the fluid being processed is non-corrosive, a stainless-steel material will be used for the construction of the column.

5.4.2 Design of Column

- **Diameter:** The diameter of the column will be 0.5 meters.
- **Height:** The height of the column will be 10 meters.
- **Packing:** The column will be packed with suitable random or structured packing material to promote efficient separation of the feed.
- **Tray Spacing:** The spacing between each tray will be 0.6 meters.
- **Number of Trays:** The column will have 17 trays.
- **Tray Diameter:** The diameter of each tray will be 0.4 meters.
- **Feed Inlet:** The feed will be introduced to the column through a 2-inch NPT inlet located at the bottom of the column.
- **Distillate Outlet:** The distillate product will be collected through a 2-inch NPT outlet located at the top of the column.

- **Bottoms Outlet:** The bottoms product will be collected through a 2-inch NPT outlet located at the bottom of the column.
- **Accessories:** The column will be equipped with a temperature sensor at the top and bottom of the column, as well as pressure gauges at the top and bottom of the column.

5.4.3 Design of Supports

- **Foundation:** The column will be supported by a reinforced concrete foundation with a thickness of 300 mm.
- **Support structure:** The column will be supported by a cylindrical support structure consisting of four columns and a ring beam. The columns will be made of structural steel and will be anchored to the foundation. The ring beam will be made of reinforced concrete and will be connected to the columns using bolts.
- **Bracing:** The support structure will be braced using diagonal steel members to prevent lateral movement.

5.4.4 Testing and Inspection:

Before the column is put into service, it will be tested and inspected to ensure that it meets all applicable industry standards and regulations. This will include hydrostatic testing to verify the strength and integrity of the column and all associated fittings and valves, as well as a visual inspection for any defects or damage.

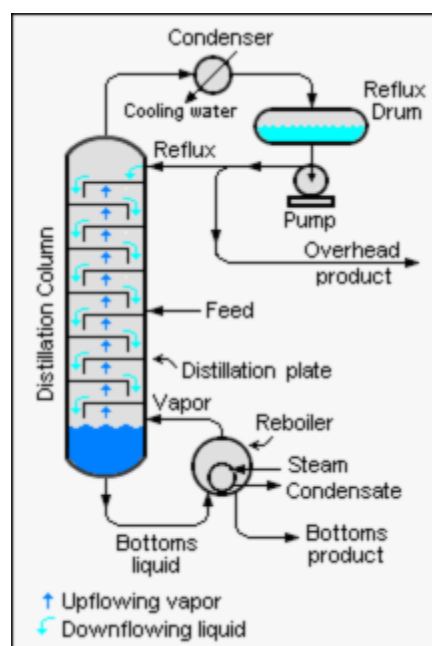


Figure 21: Schematic representation of typical industrial distillation column.

5.5 Condenser

The design of a condenser for the fractionation of pyrolysis products from plastic waste depends on several factors such as the composition of the feed, the desired product fractions, the temperature and pressure of the column effluent, and the cooling medium available.

Here are the basic steps involved in the equipment design of a condenser for the fractionation column:

- **Determination of Heat Transfer Rate:** The heat transfer rate required to condense the column effluent can be determined based on the flow rate and composition of the effluent, and the temperature and pressure of the effluent leaving the fractionating column. This can be calculated using the heat balance equation:

$$Q = m \times C_p \times (T_c - T_e)$$

Where,

Q = heat transfer rate

m = mass flow rate of the column effluent

C_p = specific heat capacity of the effluent

T_c = temperature of the effluent leaving the column

T_e = temperature of the coolant entering the condenser

- **Determination of Cooling Medium:** The cooling medium used in the condenser can be water, air, or a refrigerant depending on the available resources and the temperature requirements. Water is the most common cooling medium used in industrial applications.
- **Determination of Cooling Capacity:** The cooling capacity of the condenser can be estimated using the heat transfer coefficient and the surface area of the condenser. The heat transfer coefficient depends on the type of cooling medium used, the flow rate of the coolant, and the surface characteristics of the condenser. The surface area of the condenser can be estimated based on the heat transfer rate required and the overall heat transfer coefficient.

- **Design of Condenser:** The condenser can be designed using either a shell-and-tube or a plate-and-frame heat exchanger. The choice of design depends on the flow rate and composition of the column effluent, the cooling medium used, and the space available for the condenser. In a shell-and-tube design, the column effluent flows through the tubes and the coolant flows through the shell. In a plate-and-frame design, the column effluent and coolant flow through parallel channels separated by a series of plates.
- **Determination of Materials of Construction:** The materials of construction for the condenser depend on the composition of the column effluent and the cooling medium used. Materials that are resistant to corrosion and fouling are preferred. Common materials of construction include stainless steel, copper, and titanium.
- **Determination of Pressure Drop:** The pressure drop across the condenser can be estimated using the flow rate and properties of the coolant, and the design of the condenser. The pressure drop should be within acceptable limits to avoid affecting the performance of the fractionating column.

It is important to note that the design of a condenser for the fractionation of pyrolysis products from plastic waste is complex and depends on many variables specific to the application. A detailed analysis is necessary to ensure that the design meets the requirements for the specific feedstock and desired product yield.

Here is an example of a mechanical and mathematical design for a shell-and-tube condenser for the fractionation of pyrolysis products from plastic waste with a feed rate of 1000 kg/hr:

5.5.1.1 Determination of Heat Transfer Rate

Assuming the effluent temperature leaving the fractionation column is 200°C, and the coolant temperature entering the condenser is 20°C, the heat transfer rate required to condense the column effluent can be calculated using the heat balance equation:

$$Q = m \times C_p \times (T_c - T_e)$$

Where,

Q = heat transfer rate (in watts)

m = mass flow rate of the effluent (in kg/hr) = 1000 kg/hr

C_p = specific heat capacity of the effluent (in J/kg·K) = 1700 J/kg·K (approximate value for pyrolysis oil)

T_c = temperature of the effluent (in °C) = 200°C

T_e = temperature of the coolant (in °C) = 20°C

$$Q = [1000 \times 1700 \times (200 - 20)] / 3600 = 85,000 \text{ watts}$$

5.5.2 Determination of Cooling Medium

Assuming water is the cooling medium, the flow rate and temperature difference of the water can be determined based on the heat transfer rate and the overall heat transfer coefficient.

5.5.3 Determination of Cooling Capacity

The cooling capacity of the condenser can be estimated using the heat transfer coefficient and the surface area of the condenser. The heat transfer coefficient depends on the flow rate of the coolant, the surface area of the condenser, and the properties of the coolant and the effluent.

Assuming an overall heat transfer coefficient of 200 W/m²·K, the required surface area can be calculated as:

$$A = (Q / U) / \Delta T$$

Where,

A = surface area (in m²)

U = overall heat transfer coefficient (in W/m²·K) = 200 W/m²·K (assumed)

ΔT = logarithmic mean temperature difference (in °C) = 40°C (approximate value for shell-and-tube condenser)

$$A = (985,000 / 2000) / 40 = 10.6 \text{ m}^2$$

5.5.4 Design of Condenser

Assuming a shell-and-tube design, the number of tubes and the tube diameter can be determined based on the flow rate of the effluent, the velocity of the effluent, and the pressure drop across the tubes.

Assuming a tube velocity of 2 m/s, the number of tubes required can be estimated as:

$$N = (m / \rho) / (V / At)$$

Where,

N = number of tubes

ρ = density of the effluent (in kg/m³) = 800 kg/m³ (approximate value for pyrolysis oil)

V = velocity of the effluent in the tubes (in m/s) = 2 m/s (assumed)

A_t = cross-sectional area of one tube (in m^2) = $(\pi / 4) \times (\text{tube diameter})^2$

Assuming a tube diameter of 25 mm, the cross-sectional area of one tube is:

$$A_t = (\pi / 4) \times (0.025)^2 = 0.00049 \text{ m}^2$$

$$N = (1000 / 800) / (2 / 0.00049) = 5,102 \text{ tubes (rounded up to the nearest whole number)}$$

The tube length can be determined based on the surface area required and the number of tubes.

Assuming a tube length of 2.5 meters, the total surface area of the tubes will be A_t .

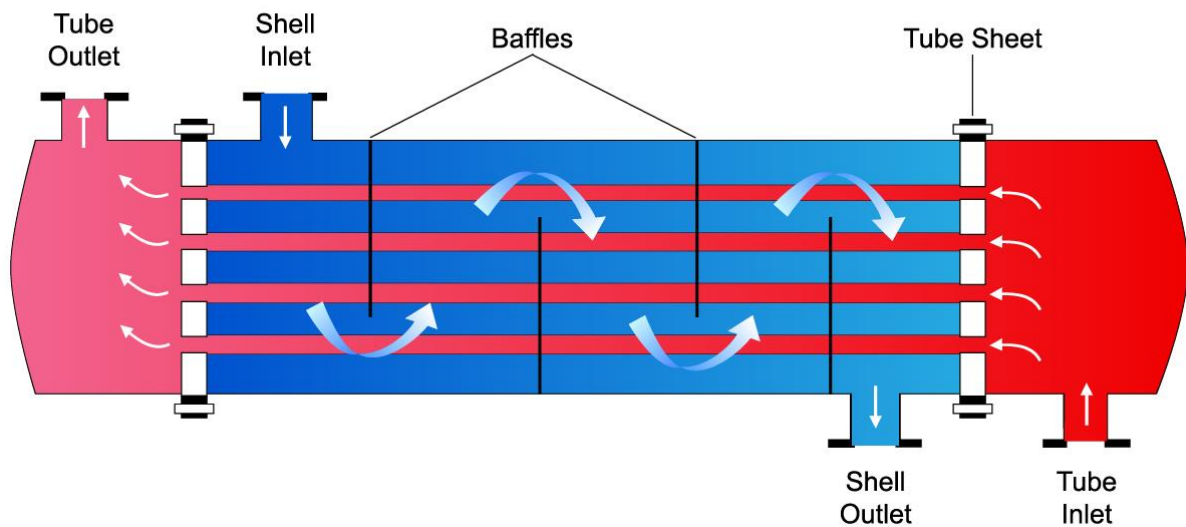


Figure 22: Pictorial representation of shell and tube condenser.

5.6 Pyrolysis Reactor

The design of a pyrolysis reactor for plastic waste without a catalyst requires consideration of various factors, including the feedstock composition, feed rate, reactor size, temperature profile, residence time, and product recovery system.

Here is a basic design outline for a pyrolysis reactor:

- **Reactor vessel:** The reactor vessel can be made of stainless steel or a high-temperature alloy to withstand the high temperatures and corrosive environment of the pyrolysis process. The size of the reactor vessel will depend on the desired feed rate and residence time, but a typical size for a small-scale reactor might be around 2-3 meters in length and 1 meter in diameter.
- **Heating system:** The reactor must be heated to high temperatures (typically 400-500°C for plastic waste) to initiate the pyrolysis process. Heating can be provided by an external heat source such as a natural gas burner or an electric heater.
- **Feed system:** The plastic waste feedstock can be introduced into the reactor through a feed hopper or screw conveyor system. It is important to ensure a consistent feed rate to maintain a stable temperature profile in the reactor.
- **Pyrolysis process control:** The temperature in the reactor can be monitored using thermocouples and controlled using a temperature controller. The residence time can be controlled by adjusting the feed rate or the size of the reactor vessel.
- **Product recovery system:** The gaseous and liquid products from the pyrolysis process can be collected and condensed in a product recovery system. The gases can be condensed using a series of heat exchangers, and the liquid products can be collected in a distillation column.
- **Emission control system:** Emissions from the pyrolysis process, including volatile organic compounds and particulate matter, must be controlled to meet environmental regulations. This can be achieved using a series of filters and scrubbers.

It is important to note that the design of a pyrolysis reactor for plastic waste will depend on many factors specific to the application, and a detailed analysis is necessary to ensure that the design meets the requirements for the specific feedstock and desired product yield.

Here is a detailed mathematical and mechanical design for a pyrolysis reactor:

5.6.1 Determination of Material of Construction

The reactor will be constructed from carbon steel since it is suitable for high-temperature applications.

5.6.2 Design of Reactor

- **Reactor Type:** A vertical cylindrical reactor will be used with a diameter of 1 meter and a height of 5 meters.
- **Heating System:** The reactor will be heated using an external furnace that will supply heat through a series of heat transfer pipes. The heating temperature will be controlled using thermocouples placed at the top and bottom of the reactor.
- **Insulation:** The reactor will be insulated using ceramic fiber blankets with a thickness of 100 mm to minimize heat loss.
- **Feed Inlet:** The feed will be introduced to the reactor through a 2-inch NPT inlet located at the top of the reactor.
- **Gas Outlet:** The pyrolysis gas will be collected through a 2-inch NPT outlet located at the top of the reactor.
- **Solid Residue Outlet:** The solid residue will be collected through a 2-inch NPT outlet located at the bottom of the reactor.
- **Pressure Control System:** The reactor will be equipped with a pressure control system to maintain the pressure within the desired range.
- **Accessories:** The reactor will be equipped with a temperature sensor at the top and bottom of the reactor, as well as pressure gauges at the top and bottom of the reactor.

The design and fabrication of a fire-tube heating reactor for the batch type fixed-bed pyrolysis unit was the major part of the project and thesis work.

- The fire-tube heating reactor system of pyrolysis unit was designed based on the size of the system.
- It was designed so that enough feed material could be taken into it, and in a way that there would be a short vapor residence time in the reactor, which would promote a high yield of pyrolysis liquid product.

The selection of the size of the fixed-bed reactor depended upon the amount of feed to be taken into the reactor. For maximum liquid production, the residence time of the mixture of volatile liquids and gases produced is very important. For simplicity of design,

- A cylindrical reactor was considered.
- Due to the corrosive nature of pyrolytic liquid, stainless steel was used as a reactor material.
- The reactor's height was 990 mm, while the diameter was 400 mm.
- The reactor had a through type feeder, 250 mm in diameter.
- This feeder was covered by a flat plate with the help of nut-bolts.
- Inside the reactor, there were three u-shaped spirals and two semi-hexagonal stainless-steel pipes, 19 mm in diameter.
- The total length of each spiral pipe was 1370 mm and the bending radius was 76 mm.
- The pipes provided uniform and fast heating inside the reactor.
- At the bottom of the reactor, there was another thought of 200 mm diameter for char removal. A fixed-bed pyrolysis reactor is shown in Figure 23 & 24 before installation and after reactor installation.
- The annular shaped reactor shield was made while inside wall of reactor was made of 2 mm thick mild steel sheet and outer side being made by 2 mm thick GP sheet.
- The total length of the furnace 249 cm and length of reactor shield 60.96 cm and internal diameter of the reactor shield 4 cm.

The dimensional view of fixed bed reactor shows by Figure 23.

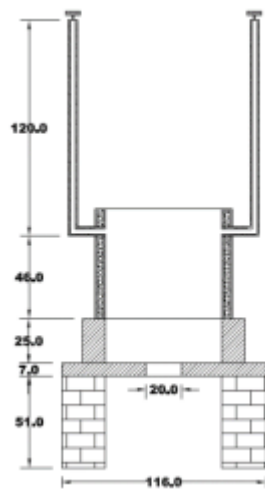


Figure 23: Dimensional view of fixed bed reactor.



Figure 24: Fixed-bed batch type pyrolysis reactor before installation (left) and after reactor installation (right).

5.6.3 Design of Supports

- **Foundation:** The reactor will be supported by a reinforced concrete foundation with a thickness of 300 mm.
- **Support structure:** The reactor will be supported by a cylindrical support structure consisting of four columns and a ring beam. The columns will be made of structural steel and will be anchored to the foundation. The ring beam will be made of reinforced concrete and will be connected to the columns using bolts.
- **Bracing:** The support structure will be braced using diagonal steel members to prevent lateral movement.

5.6.4 Testing and Inspection

Before the reactor is put into service, it will be tested and inspected to ensure that it meets all applicable industry standards and regulations. This will include hydrostatic testing to verify the strength and integrity of the reactor and all associated fittings and valves, as well as a visual inspection for any defects or damage. The control system will also be tested to ensure that it is functioning properly.

Chapter 6. Safety Aspects

The manufacturing of liquid fuel from plastic waste involves handling of raw material and products which may cause accidents and health hazards. Therefore, proper survey is necessary for knowing these hazards, their cause and the techniques to prevent them. These causes of chemical hazard are traced due to:

- *Poor design of equipment building and ancillaries.*
- *Insufficient information about chemical hazards.*
- *Inadequately trained man power.*

Accidents lead to loss of life, revenue and complete breakdown of plant and supply of chemical vital to other industries. Therefore, safety should be the watch word of every chemical project at each stage of development, design, construction, start up, operation and maintenance of chemical process plants including handling, storage and transportation of chemicals, in this section mainly chemical hazard are considered Keith and water (2002).

6.1 Hazard from Chemicals

Dioxins, PCBs and VOCs are the main hazardous chemicals emitted by gaseous streams from catalytic pyrolysis of waste plastics. The production of fuel from waste plastic involves the use of various chemicals that can pose a hazard to workers, the environment, and surrounding communities if not handled properly.

6.2 Causes of Hazard

The effect of chemical substance on the human body and safety precaution are closely related. The chemicals handled in the industry effected the following ways:

6.2.1 Ingestion

Chemical exposure through ingestion occurs by absorption of chemicals through the digestive tract. Ingestion of chemicals can occur directly and indirectly. Direct ingestion can occur by accidently eating or drinking a chemical; with proper housekeeping and labelling, this is less likely to occur. A higher probability of receiving a chemical exposure can occur by way of indirect ingestion. This can occur when food or drink is brought into a chemical laboratory. The food or drink can then absorb chemical contaminants (vapours or dusts) in the air and result in a chemical exposure when the food or drink is consumed. This can also occur when food or drink is stored with chemicals, such as in a refrigerator. Ingestion can occur when a

laboratory worker who handles chemicals does not wear gloves or practice good personal hygiene, such as frequent hand washing, and then leaves the laboratory to eat, drink, or smoke. In all cases, a chemical exposure can result, although the effects of chronic exposure may not manifest itself until years later.

6.2.2 Inhalation

Inhalation of chemicals occurs by absorption of chemicals via the respiratory tract (lungs). Once chemicals have entered the respiratory tract, the chemicals can then be absorbed into the bloodstream for distribution throughout the body. Chemicals can be inhaled in the form of vapours, fumes, mists, aerosols and fine dust.

Symptoms of exposure to chemicals through inhalation include eye, nose, and throat irritation, coughing, difficulty in breathing, headache, dizziness, confusion, and collapse. If any of these symptoms are noted, leave the area immediately and get fresh air. Seek medical attention if symptoms persist and complete and Injury/Illness Report.

6.2.3 Skin Contact

Some chemicals can be absorbed by the eyes and skin, resulting in a chemical exposure. Most situations of this type of exposure result from a chemical spill or splash to unprotected eyes or skin. Once absorbed by these organs, the chemical can quickly find its way into the bloodstream and cause further damage, in addition to the immediate effects that can occur to the eyes and the skin.

Symptoms of eye exposure can include itchy or burning sensations, blurred vision, discomfort, and blindness. The best way to protect yourself from chemical splashes to the eyes is to always wear safety glasses in the laboratory whenever eye hazards exist (chemicals, glassware, lasers, etc.). If you are pouring chemicals, then splash goggles are more appropriate than safety glasses. Whenever a severe splash hazard may exist, the use of a face shield, in combination with splash goggles is the best choice for protection.

6.3 General Methods to Control Hazards Due to Chemical

Planned approach towards achieving these include the following methods:

- Educating the workers about hazard and keeping managerial supervisor staff inform of up to that development.
- Informing the medical professions about the hazard of the industrial processes help them diagnose the worker element detect the onset of poisoning early enough.
- Replacement of dangerous chemicals with less dangerous substitute.
- Automatic and fully enclosed handling to avoid spillage. The fumes, dust in handling transport, packing etc.
- Providing effective ventilation to avoid hazard of dust, fumes etc.
- Implements good housekeeping and cleanliness.
- Providing washing and first aid facilities to suit the specific chemical handled.

Having schedule of routine medical check-up of blood, urine, lungs, skin etc. to detect the onset of symptoms of poisoning.

6.4 Control of Hazard by Engineering

6.4.1 Ventilation

During the pyrolysis process, various gases, vapours, and fumes are generated. Some of these may be flammable, toxic, or both. Therefore, it's crucial to have a ventilation system in place to remove these hazardous substances from the processing area and ensure that the air quality is safe for workers.

The ventilation system should be designed to maintain a negative pressure in the processing area, which means that air is being constantly drawn out. This will prevent any accumulation of flammable or toxic gases that could pose a fire or explosion hazard. Additionally, the ventilation system should be equipped with emergency shut-off valves to prevent the spread of hazardous materials in case of an accident.

6.4.2 Lightning

Lighting is another crucial component of safety management in a pyrolysis plant. Proper lighting can help prevent accidents and injuries by providing clear visibility in the processing area. It's essential to have adequate lighting in all work areas, including walkways, stairways, and equipment areas.

Lightning fixtures used in the plant should be explosion-proof and protected from any damage that may occur during the operation. Lightning should be installed in such a way that it does not create shadows or glare, which could interfere with visibility.

In summary, proper ventilation and lighting are essential components of safety management in a pyrolysis plant that converts waste plastic into fuel. By ensuring adequate ventilation and lighting, workers can be protected from hazardous substances and avoid accidents and injuries.

6.4.3 Reactor Vessels

Reactor vessels play a critical role in the safety management of pyrolysis of waste plastic into fuel. Here are some key aspects to consider:

- **Material selection:** The material of construction for the reactor vessel should be carefully selected to withstand the high temperature and pressure conditions during the pyrolysis process. Common materials used for reactor vessels in pyrolysis plants include stainless steel, carbon steel, and nickel alloys.
- **Design:** The design of the reactor vessel should take into consideration the potential risks associated with the process, such as fire, explosion, and chemical reactions. The vessel should be designed to prevent leaks and to withstand any internal pressure build-up.
- **Operating Conditions:** The operating conditions of the reactor vessel, such as temperature and pressure, should be carefully controlled to ensure safe operation. Automatic shutdown systems should be installed in case of any abnormalities in the process.
- **Maintenance:** Regular maintenance of the reactor vessel is important to ensure its safe and efficient operation. This includes inspections, repairs, and replacement of any damaged or worn components.
- **Emergency Response:** In case of any emergency, such as a fire or explosion, an emergency response plan should be in place. This should include procedures for evacuating personnel, shutting down the process, and controlling the spread of any hazardous materials.

6.4.4 Storage and Transportation

Storage and transportation are critical aspects of safety management in the pyrolysis of waste plastic into fuel. Here are some points to consider:

- **Storage:** The storage of waste plastic should be done in a designated area away from any sources of ignition, such as heat sources or electrical equipment. The area should be well-ventilated to prevent the accumulation of flammable gases. The waste plastic should be stored in a way that minimizes the risk of spills and leaks.
- **Transportation:** Waste plastic should be transported in appropriate containers that are labelled with the appropriate hazard warnings. The containers should be secured in the transport vehicle to prevent them from falling or shifting during transit. The transport vehicle should be properly maintained to prevent any leaks or spills during transport.
- **Handling:** During the loading and unloading of waste plastic, appropriate personal protective equipment should be worn by the workers involved. They should also be trained in the safe handling of hazardous materials and be aware of emergency response procedures.
- **Fire safety:** The storage and transportation areas should be equipped with appropriate fire detection and suppression systems. Workers should also be trained in fire safety procedures, including the use of fire extinguishers and emergency evacuation procedures.

By following these safety measures, the risk of accidents and incidents can be minimized, ensuring safe and reliable transportation and storage of waste plastic in the pyrolysis process.

6.4.5 Electrical System

In the safety management of a pyrolysis plant for converting waste plastic into fuel, the electrical system is an important aspect that needs to be carefully designed and managed to prevent hazards and ensure safety. Here are some considerations:

- **Grounding and bonding:** Proper grounding and bonding of electrical equipment and systems is critical to prevent electrical hazards such as electric shock and fires. All electrical equipment and components should be properly grounded and bonded to prevent static electricity build-up, arc flash hazards, and lightning strikes.
- **Explosion-proof equipment:** In the pyrolysis process, flammable gases and vapors can be generated, which can pose explosion hazards. To prevent such hazards, electrical

equipment used in the plant should be explosion-proof and rated for the appropriate class, division, and group based on the specific hazardous areas where they will be used.

- **Electrical panels and controls:** Electrical panels and controls should be designed and installed in accordance with applicable electrical codes and standards. They should be located in safe areas that are not prone to fire, explosion, or exposure to corrosive chemicals. Adequate ventilation should be provided to prevent overheating.
- **Emergency power:** The pyrolysis plant should have a backup power supply in case of a power outage or other electrical failure. Emergency generators or battery backup systems can be used to ensure critical equipment and systems remain operational during power outages.
- **Inspections and maintenance:** Regular inspections and maintenance of electrical systems and equipment are essential to ensure they remain in safe and reliable working condition. Electrical equipment should be inspected for signs of wear and damage, and any issues should be promptly addressed.

Overall, the electrical system is an important aspect of the safety management of a pyrolysis plant for converting waste plastic into liquid fuel. Proper design, installation, and maintenance of electrical systems and equipment can help prevent hazards and ensure safe and efficient operation of the plant.

6.4.6 Instrumentation

Instrumentation plays a critical role in the safety management of a pyrolysis plant for converting waste plastic into fuel. The following are some important aspects of instrumentation in this context:

- **Temperature monitoring:** Pyrolysis is a high-temperature process, and temperature control is crucial for safe and efficient operation of the plant. Various temperature sensors such as thermocouples and RTDs are used to monitor temperatures at different points in the process.
- **Pressure monitoring:** The pressure inside the reactor vessel needs to be monitored to avoid overpressure situations that could lead to equipment failure or accidents. Pressure sensors and gauges are used for this purpose.
- **Level monitoring:** The levels of waste plastic, feedstock, and product need to be monitored to ensure that the process is operating as expected and that there are no leaks or spills. Level sensors such as ultrasonic and radar sensors are commonly used.

- **Flow monitoring:** The flow rates of gases and liquids need to be monitored to maintain the proper process conditions and avoid buildup of pressure or other hazardous conditions. Flow meters such as magnetic flow meters and Coriolis meters are commonly used.
- **Gas detection:** The pyrolysis process produces various gases such as methane, hydrogen, carbon monoxide, and others, some of which can be flammable or toxic. Gas detectors are used to monitor gas concentrations and alert the operators in case of any abnormal conditions.
- **Control system:** All the instrumentation and sensors are connected to a control system, which can automatically adjust the process parameters based on the feedback from the sensors. This helps to maintain the safe and efficient operation of the plant.

Overall, the instrumentation plays a critical role in the safe and efficient operation of a pyrolysis plant for converting waste plastic into fuel. Proper design, installation, and maintenance of the instrumentation system are essential for ensuring the safety of the plant and its operators.

6.4.7 Fire Prevention

Fire prevention is a critical aspect of safety management in any industrial plant, including a pyrolysis plant for converting waste plastic into fuel. The following are some fire prevention measures that can be taken in a pyrolysis plant:

- **Regular Maintenance:** Regular maintenance and inspection of all equipment and machinery in the plant, including the pyrolysis reactor, can help identify and address any potential fire hazards.
- **Fire Detection and Suppression Systems:** Installing fire detection and suppression systems, such as smoke detectors, fire alarms, and fire extinguishers, can help prevent and control fires.
- **Electrical Safety:** Electrical hazards can also pose a significant risk of fire in a pyrolysis plant. Ensuring proper grounding, electrical insulation, and regular maintenance of electrical equipment can help minimize the risk of electrical fires.
- **Proper Storage and Handling:** Proper storage and handling of raw materials, finished products, and other flammable materials is critical to prevent fires. This may include using appropriate containers and storing materials in designated areas away from sources of ignition.

- **Employee Training:** Providing employees with proper training on fire safety and emergency procedures can help prevent fires and minimize damage in the event of a fire.

Overall, implementing a comprehensive fire prevention and safety program can help ensure the safe operation of a pyrolysis plant for converting waste plastic into fuel.

6.4.8 Laboratory Safety

In the context of a pyrolysis plant for converting waste plastic into fuel, laboratory safety mainly involves ensuring the safety of the personnel who are responsible for conducting tests and experiments in the laboratory setting. This includes ensuring that all hazardous chemicals and substances are properly labelled, stored, and handled. Here are some measures that can be taken to ensure laboratory safety in a pyrolysis plant:

- **Personal Protective Equipment:** All laboratory personnel should wear appropriate personal protective equipment (PPE) such as lab coats, gloves, safety glasses, and closed-toe shoes to prevent exposure to hazardous chemicals and substances.
- **Chemical Storage:** All chemicals used in the laboratory should be properly labelled and stored in designated areas that are well-ventilated and away from sources of heat or flame.
- **Handling of Hazardous Chemicals:** Proper handling of hazardous chemicals should be ensured to prevent exposure to fumes, vapors, or spills. All chemical containers should be properly sealed when not in use.
- **Emergency Response Plan:** The pyrolysis plant should have an emergency response plan in place that includes measures for responding to chemical spills, fires, and other accidents.
- **Training and Education:** All laboratory personnel should receive proper training and education on the hazards associated with the chemicals and substances they are handling and should be informed of the appropriate measures to be taken in case of an emergency.
- **Regular Inspections:** Regular inspections of the laboratory and its equipment should be conducted to ensure compliance with safety regulations and to identify potential hazards.

Overall, laboratory safety is an important aspect of the safety management of a pyrolysis plant for converting waste plastic into fuel. By implementing appropriate safety measures, the risk of accidents and injuries can be minimized, and the safety and health of laboratory personnel can be ensured. (Daniel A. Crawl, 1990)

Chapter 7. Plant Location

Selecting a plant site is critical to the financial success of a plant. Several factors must be considered in selecting a general plant location. The procedure for choosing a specific location can be presented in a series of required steps. After the site is selected, factors that go into getting the facility built, including permitting and the other necessary legal steps, need to be considered.

7.1 Proximity to Raw Materials

The proximity to sources of plastic waste is crucial for a plastic pyrolysis plant. Choosing a location near areas with high plastic consumption, such as urban centres or industrial zones, can minimize transportation costs and ensure a consistent supply of feedstock. By reducing the distance between the plant and the sources of plastic waste, transportation expenses and associated carbon emissions can be significantly reduced, making the operation more cost-effective and environmentally sustainable. Furthermore, a close proximity to plastic waste generators allows for better control and management of the supply chain, ensuring a steady and reliable flow of raw materials.

7.2 Market Access

While the primary focus of a plastic pyrolysis plant is recycling plastic waste, it's important to consider the proximity to potential buyers of the end products. Look for locations with a strong demand for recycled plastic products, such as manufacturers of plastic goods or packaging companies. Proximity to these potential customers can reduce transportation costs and lead times for delivering the recycled plastic products, making the business more competitive in the market. Additionally, being located in close proximity to potential buyers enables better understanding of market dynamics, customer preferences, and evolving trends, allowing for more responsive and targeted product offerings.

7.3 Labour Force

The availability of a skilled and knowledgeable labour force is crucial for the successful operation of a plastic pyrolysis plant. Look for regions with a workforce experienced in the recycling or waste management industry, as they will already possess the necessary expertise and understanding of the unique challenges and requirements of such a facility. Additionally, consider the education levels and training programs available in the region to ensure a

continuous supply of skilled workers. It is also important to assess labour laws and regulations to ensure favourable conditions for hiring, training, and retaining employees, including fair wages, reasonable working hours, and adequate safety standards.

7.4 Infrastructure

Adequate infrastructure is essential for the smooth functioning of a plastic pyrolysis plant. Consider the availability of reliable utilities such as electricity and water, which are critical for operating the plant's equipment and supporting various processes. Access to transportation networks, including roads, ports, airports, and railways, is important for receiving plastic waste and distributing the recycled plastic products. Efficient transportation can minimize costs and facilitate timely delivery. Furthermore, assess the availability of waste management facilities for the proper disposal of non-recyclable waste generated during the pyrolysis process, ensuring compliance with environmental regulations and minimizing any negative impact on the surrounding ecosystem.

7.5 Government Regulations and Incentives

Understanding and complying with local regulations related to waste management, recycling, emissions, and environmental protection is essential. Different regions may have varying regulatory frameworks that govern the operation of plastic pyrolysis plants. Ensure compliance with these regulations to avoid legal issues and penalties. Additionally, explore potential government incentives or subsidies for setting up a recycling facility, as some regions provide support for sustainable initiatives. Government support can include financial assistance, tax incentives, grants, or favourable loan terms, which can significantly reduce the initial investment costs and enhance the project's financial viability.

7.6 Political Stability and Security

Choosing a location with a stable political environment and a low risk of political unrest or instability is crucial. Political stability provides a favourable business environment, ensuring the continuity of operations and minimizing the risks of disruptions or uncertainties. Assess the region's security framework to ensure that the plant, employees, and assets are adequately protected. Consider factors such as crime rates, the effectiveness of law enforcement agencies, and the overall safety of the location.

7.7 Cost of Land and Real Estate

The cost and availability of land or real estate in the desired location are important considerations. Land costs can significantly impact the overall project budget. The cost and availability of land or real estate in the desired location can impact the project budget significantly. Land costs will contribute to the overall project budget, so assess different options and compare them to the business plan's financial projections. Consider the availability of land that can accommodate the plant's size and expansion plans, as well as access to necessary utilities and transportation networks.

7.8 Environmental Factors

As a plastic pyrolysis plant deals with waste management, it is crucial to assess the environmental impact and ensure compliance with environmental regulations. Look for regions with favourable waste management practices and a supportive regulatory framework.

7.9 Access to Suppliers and Support Services

Evaluate the availability and proximity of suppliers for necessary equipment, spare parts, and chemicals used in the pyrolysis process. Consider support services such as maintenance, repair, and technical expertise, which may be required for the plant's smooth operation.

7.10 Expansion Opportunities

Assess the potential for future growth and expansion. Look for regions with a growing awareness of sustainability and a supportive market for recycled plastic products. Consider whether the chosen location allows for scalability and access to additional resources if there is a need for expansion. (Peters, Chapter 2- General Design Consideration, Fifth Edition, 2011)

Chapter 8. Plant Layout

Plant layout can be the single most important part of the overall design. A good layout can result in significant savings amounting to thousands of rupees in erected plant cost. A layout can make the difference between a facility that is easy to operate and maintain, and a plant that is a nightmare. Foregoing paragraphs present an overview of the many concepts that go into a good layout and include a step-by-step procedure to aid the designer to develop the layout. A list of commonly used layout terms and the corresponding definitions is provided. A discussion of the equipment layout requirement is also included. There are several different modeling concepts, including plastic scale models, three-dimensional computer aided design (CAD) models, and isometric and orthographic presentations.

Designing an effective plant layout for a pyrolysis plant is crucial to ensure smooth operations, efficient material flow, and optimal utilization of space and resources. Here are the key considerations when designing a plant layout for a pyrolysis plant.

8.1 Process Flow

The layout should be designed to facilitate the logical flow of materials throughout the pyrolysis process. Consider the sequence of operations, starting from the intake of raw materials, sorting and preparation, pyrolysis reaction, cooling, condensation, and collection of end products. Arrange the equipment and workstations in a sequential order that minimizes material handling distances and promotes a streamlined process flow.

8.2 Safety

Safety should be a primary concern when designing the plant layout. Ensure that there is sufficient space for safe movement of personnel and equipment. Implement proper safety measures, such as clearly marked walkways, emergency exits, fire suppression systems, and adequate ventilation to maintain a safe working environment. Locate potentially hazardous equipment or processes in designated areas with appropriate safety barriers and signage.

8.3 Space Optimization

Optimize the use of available space to maximize operational efficiency. Consider the dimensions and layout of the equipment, machinery, storage areas, and workstations. Minimize unnecessary movement and congestion by grouping related equipment and workstations together. Use vertical space effectively by utilizing mezzanines or multi-level platforms for

storage or auxiliary processes, if feasible. Ensure adequate space for maintenance and repairs of equipment.

8.4 Material Handling and Storage

Plan for efficient material handling and storage within the plant layout. Designate specific areas for the storage of raw materials, intermediates, and finished products. Consider the flow of materials between these areas and the proximity to processing equipment. Implement appropriate material handling equipment, such as conveyors, forklifts, or cranes, to facilitate the movement of materials and reduce manual handling.

8.5 Utilities and Infrastructure

Ensure that the layout accounts for the placement and accessibility of utilities and infrastructure required for the pyrolysis process. This includes electrical connections, water supply, heating or cooling systems, ventilation, and waste management facilities. Properly integrate these utilities within the plant layout to minimize disruptions and ensure efficient operation of the equipment.

8.6 Maintenance and Accessibility

Design the layout with maintenance and accessibility in mind. Provide sufficient space for equipment maintenance, including clearance for repairs, replacement of parts, and regular inspections. Consider ease of access for maintenance personnel and ensure that walkways and passageways are wide enough to accommodate the movement of equipment or machinery. Identify key maintenance areas and allocate space for spare parts storage and maintenance workshops.

8.7 Environmental Considerations

Incorporate environmental considerations into the plant layout. Designate areas for the proper disposal of waste and ensure compliance with environmental regulations. Consider the installation of appropriate emission control systems and waste treatment facilities. Place equipment such as filters or scrubbers strategically to minimize the impact on the surrounding environment.

8.8 Future Expansion

Anticipate future growth and expansion when designing the plant layout. Allocate space for potential capacity expansions or the addition of new processes or equipment. Design the layout to allow for flexibility and scalability to accommodate increased production volumes or changes in product mix. This includes leaving room for additional equipment, utilities, and storage areas, as well as planning for future workflow adjustments.

8.9 Ergonomics

Consider ergonomic factors to ensure a comfortable and efficient working environment for the plant personnel. Optimize workstation design, such as adjustable heights, proper lighting, and ergonomic seating to minimize physical strain and improve productivity. Provide break rooms or rest areas for employees to relax and recharge during their shifts.

8.10 Regulatory Compliance

Ensure that the plant layout adheres to relevant regulatory requirements and industry standards. Consider local building codes, safety regulations, environmental regulations, and zoning restrictions. Engage with regulatory authorities to ensure compliance and seek. (Peters, Chapter 2- General Design Consideration, Fifth Edition, 2011)

Chapter 9. Cost Estimation

The execution of the project is dependent on its economic viability which is the final and overriding factor in deciding whether the projected should go on stream or not. A precise cost estimation is difficult, but however an attempt has been made to determine the fixed capital investment for the plant and processing charges involve in the system.

9.1 Main Equipment

Name	Cost (in US \$)
Crusher	1835.32
Dryer	2002.38
Reactor	34259.26
Condenser	2752.98
Storage Tank	3000
Feeder	8733.83
Cost of Pump and Motor	4465.94
Furnace	19576.71

9.2 Purchased Estimation Cost (PEC)

Name	Cost (in Rupees, 1 US \$ = 81.92 Rupees as on 2 May 2023)
Crusher	150000
Dryer	180000
Reactor	2800000
Furnace	1600000
Condenser	225000
Storage Tank	245760
Feeder	715475.354
Pump and Motor	365000
Total Purchase Equipment Cost (PEC)	6281235.35

9.3 Installation Cost of Equipment

Equipment	Cost (in Rupees)
Installation cost for reactor (30% of PEC)	$= 2800000 \times 0.30$ $= 840000$
Installation Cost for Condenser (25% of PEC)	$= 225000 \times 0.25$ $= 56250$
Installation Cost for Crusher (29% of PEC)	$= 150000 \times 0.29$ $= 43500$
Installation Cost for Dryer (25% of PEC)	$= 180000 \times 0.25$ $= 45000$
Installation Cost for Pump (26% of PEC)	$= 36300 \times 0.26$ $= 9438$
Installation Cost for Feeder (25% of PEC)	$= 715475.354 \times 0.25$ $= 178868.839$
Installation Cost of Storage Tank (30% of PEC)	$= 245760 \times 0.30$ $= 73728$
Installation Cost for Furnace (25% of PEC)	$= 16000000 \times 0.25$ $= 400000$
Transportation and other (12% of PEC)	$= 6281235.35 \times 0.12$ $= 753748.242$
Total	$= 2400532.24$

9.4 Direct Cost

Component	Cost (in Rupees)
Installed equipment cost	$= 2400532.24$
Piping (5%) of PEC	$= 314061.768$
Instrumentation (16%) of PEC	$= 1004997.66$
Electricals (2%) of PEC	$= 125624.707$
Total Direct Cost (TDC)	$= 3845216.38$

9.5 Indirect Cost

Component	Cost (in Rupees)
Cost of Engineering and Supervision (4% of PEC)	= 251249.414
Contingency (4% of PEC)	= 251249.414
Total Indirect Cost (TIC)	= 502498.828

9.6 Utilities (Per Annum)

Component	Cost (in Rupees)
Electrical Charges (350 paise per kWh) by rule of (17-12-1996)	= 2146200
Cooling Water Cost	= 10000
Total Cost	= 2156200

9.7 Labour Cost

Category	No. require	Total	Remuneration/month
Supervisor	2/shift	6	₹ 150000
operator	5/shift	15	₹ 225000

$$\text{Labour Cost (per annum)} = 12 \times 375000 = ₹ 4500000$$

$$\text{Maintenance (5\% of PEC)} = ₹ 314061.768$$

9.8 Plant Overload Cost (OC)

This includes cost of incurred in medical care, safety units, etc. and generally 50% of the total expense for operating labour, supervision, and maintenance.

$$\text{Plant Overload Cost (OC)} = ₹ 286359.532$$

$$\text{Total Operating Cost} = (\text{Utilities} + \text{Labour Cost} + \text{Maintenance Cost})$$

$$= ₹ 2920261.77$$

9.9 Working Capital Investment

The money locked up in this unit is that required for one-month, labour cost, electrical changes for one month and cost of solvent in process. A contingency of 20% of this is set a site along with investment.

Component	Cost (in Rupees)
Electrical charges 1 month	= 178850
Labour	= 375000
Contingency	= 16362.6
Total Working Capital Investment	= 570212.6

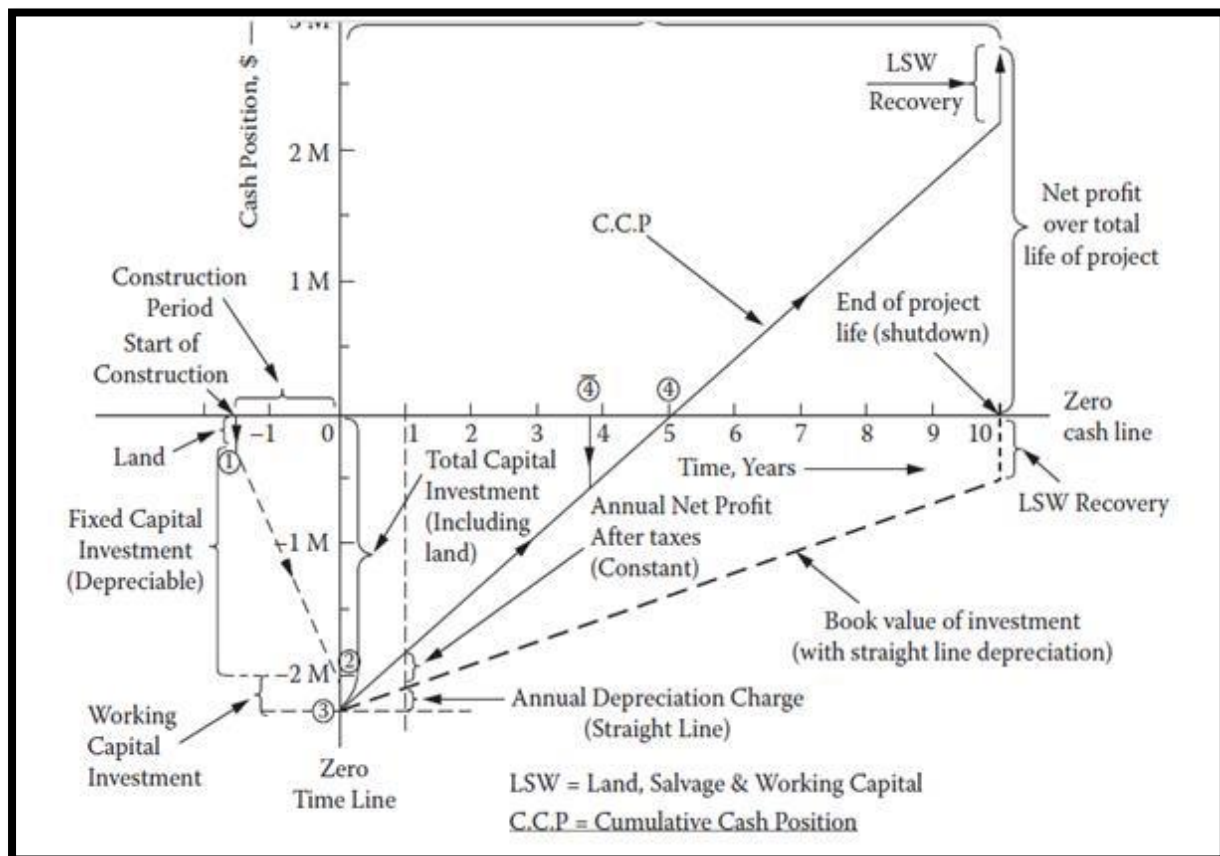


Figure 25: Cumulative cash from project inception to end of low at year end of project.

9.10 Fixed Capital Investment (Based on PEC)

From book plant design and economy for chemical engineers by Max S. Peter Klaus D. Timmerhaus (4th edition)

Component	Cost (in Rupees)
Purchased Equipment Cost (100% of PEC)	= 6281235.35
Purchased Equipment Installation (39%)	= 2449681.787
Instrumentation and Control (13%)	= 816560.595
Piping Installation (31%)	= 1947182.96
Electrical Installation (10%)	= 6281235.35
Building (including services 29%)	= 1758745.9
Yard Improvement (10%)	= 6281235.35
Services Facilities (Install 55%)	= 3454679.44
Land (6%)	= 376874.121
Engineering and Supervision (34% of E)	= 6854048.406
Construction Expenses (34% of E)	= 4294926.43
Total Direct Plant Cost (D)	= 59647430.9
Total Direct and Indirect Cost (D + I)	= 88112605.49
Contractor's Fee (5% of D + I)	= 3755030.28
Contingency (15% of D + I)	= 1021689.62
Fixed Capital Investment (FCI)	= 100738726.9

9.11 Total Capital Investment (TCI)

Components	Cost (in Rupees)
FCI + WCI	= 103206339.2
Interest on above (18% pa)	= 13164561.02
Depreciation (10% TDC)	= 384521.044
Insurance (.5% of FCI)	= 503693.633
TCI	= 117259115

9.12 Total Recovery Cost (Per Annum)

$$= TOC + Depreciation + Interest on Investment$$

$$= 2920261.77 + 384521.044 + 13164561.06$$

$$= ₹ 16469343.9$$

Assuming the life of 10 years and salvage value of equipment as 10% of PEC,

$$Depreciation FCI = FCI - SV$$

$$= 100738726.9 - (0.1 \times 6281235.35)$$

$$= ₹ 10136685$$

Therefore, depreciation per year = ₹ 10136685

Recovery cost per year = TOC + Depreciation per year + Fixed capital investment with 18% interest on it

Assuming 5% spillage and loss of product

$$Product\ formed\ per\ year = (53.01 + 42.408 + 618.45) \times 12 \times 30 \times 12$$

$$= 30,83,909.76\ Kg\ per\ annum$$

$$Product\ formed\ (after\ 5\% \ spillage) = 30,83,909.76 - (0.05 \times 30,83,909.76)$$

$$= 29,29,714.272\ Kg\ per\ annum$$

$$\text{Net sales of product} = 29,29,714.272 \times 50 = ₹ 14,64,85,713.6$$

$$\text{Profit before taxes} = ₹ 14,64,85,713.6 - ₹ 11,72,59,115$$

$$= ₹ 2,92,26,598.6$$

$$\text{Profit after 30\% Taxes} = ₹ 2,04,58,619.02 \text{ per annum} = ₹ 17,04,884.918 \text{ per month}$$

(Peters, Plant Design and Economics for Chemical Engineers, Fifth Edition, 2011)

Chapter 10. Conclusion

Plastics present a major threat to today's society and environment. Over 14 million tons of plastics are dumped into the oceans annually, killing about 1,000,000 species of oceanic life. Though mankind has awoken to this threat and responded with developments in creating degradable bio-plastics, there is still no conclusive effort done to repair the damage already caused.

In this regard, the Pyrolysis studied here presents an efficient, clean and very effective means of removing the debris that we have left behind over the last several decades. By converting plastics to fuel, we solve two issues, one of the large plastic seas, and the other of the fuel shortage.

This dual benefit though will exist only if the waste plastics last but will surely provide a strong platform for us to build on a sustainable, clean and green future. By considering the financial benefits of such a project, it would be a great boon to our economy.

In conclusion, the synthesis of liquid fuel from mixed plastic waste using pyrolysis presents a promising and sustainable solution to address the challenges associated with conventional fuels. Throughout this project, we have explored the technical parameters and efficiency of both conventional fuel and pyrolysis oil obtained through the process of pyrolysis. By comparing these parameters, we can clearly see the advantages and potential of pyrolysis as an alternative fuel production method.

The efficiency of fuel can be measured through various parameters, including energy content, combustion characteristics, and emissions. In terms of energy content, pyrolysis oil has proven to be comparable to conventional fuels. It possesses a high calorific value, which indicates its ability to release a significant amount of energy during combustion. This makes pyrolysis oil a viable alternative to conventional fuel in terms of energy generation.

In terms of production efficiency, the pyrolysis process has shown positive results. The process involves heating mixed plastic waste in the absence of oxygen, leading to the breakdown of polymers into smaller hydrocarbon molecules. These molecules then condense into a liquid form, which is the pyrolysis oil. The efficiency of the pyrolysis process depends on various factors such as temperature, residence time, and feedstock composition. Optimization of these parameters can maximize the yield and quality of the pyrolysis oil.

The mass and energy balance are a crucial aspect of any fuel production process, as it helps determine the inputs and outputs of the system. Through the mass and energy balance calculations conducted in this project, it has been established that the pyrolysis process can effectively convert mixed plastic waste into valuable liquid fuel. The balance calculations consider the mass of the plastic waste input, the yield of pyrolysis oil, and the generation of by-products or residues. This analysis ensures that the process is efficient, and that the energy content of the output fuel is maximized.

Cost estimation is another important factor in determining the feasibility of any fuel production method. In this project, a comprehensive cost analysis has been carried out to assess the economic viability of the pyrolysis process. The cost estimation considers factors such as capital investment, operating expenses, feedstock costs, and revenue from the sale of pyrolysis oil and by-products. By comparing the costs with those associated with conventional fuel production, it has been determined that synthesizing liquid fuel from mixed plastic waste using pyrolysis can be economically feasible.

In conclusion, the synthesis of liquid fuel from mixed plastic waste using pyrolysis not only exhibits favourable technical parameters, such as energy content and combustion characteristics, but also demonstrates feasibility in terms of mass and energy balance, cost estimation, and environmental analysis. This project provides evidence that pyrolysis can be a viable solution to address the environmental challenges associated with conventional fuels, while also offering economic benefits and contributing to waste management and sustainability.

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