JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

FACULTY OF MECHANICAL ENGINEERING

THERMAL SYSTEMS ENGINEERING

Design, Manufacturing, and testing of small scale plastic pyrolysis plant (Case study: Jimma town)

A Thesis Research Submitted to the School of Post graduate Studies in Partial Fulfillment of the Requirements for the Degree of Master of Science in Thermal Systems Engineering at Jimma Institute of Technology, Jimma University.

By: Tesfahun Meshesha

June, 2020

Jimma, Ethiopia

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Advisor: **Balewgize A. Zeru** (*Assistant Professor of Faculty of Mechanical Engineering at Jimma Institute of Technology, Jimma University*)

Co - Advisor: **Eyuel Abate** (*Instructor of Faculty of Mechanical Engineering at Jimma Institute of Technology, Jimma University*)

Declaration

I, the undersigned declare that this thesis research entitled "*Design manufacturing and testing of small scale plastic pyrolysis plant (Case study: Jimma town)*" for partial fulfilment of the degree of MSc. in thermal systems engineering at Jimma university, Jimma institute of technology is my original work, and has not been presented in any university for the award of degree.

By: Tesfahun Meshesha

________________ Date: 13/08/2020

Advisors and board of examination committee

1. Advisor: Balewgize A. Zeru (Assistant professor)

________________ Date: 13th Aug 2020

2. Co – advisor: Eyuel Abate(MSc)

________________ Date: 13/08/2020

3. External examiner: Dr.-Ing. Getachew S. Tibba (PhD)

________________ Date: 11/08/2020

4. Internal examiner: Ali Seid (MSc)

________________ Date: 13/08/2020

5. Chairman: Fikadu Kifle(MSc)

________________ Date: ________________

Fikadu Kifle
Chair, Thermal System Engineering /
Faculty of Mechanical Engineering

Abstract

Plastics are non-biodegradable synthetic organic materials produced by polymerization. Since its very synthesis in 1900s, plastics have substituted many types of materials such as wood, metals, and ceramics in production of goods, as they are light, durable, resistant to corrosion, diversity of applications, ease of processing and low cost. Since many plastic waste can be generated daily, it appears difficult for plastic waste management. Recycling, incineration, and thermal or catalytic cracking are the basic mechanism implemented by the world to manage plastic waste. Since it is most environmental friendly, this research is all about using thermal cracking as a method of plastic waste management in Jimma town.

There are two types of plastic waste. The first is industrial plastic waste. This type of plastic waste is easy to recycle due to its homogeneity. The other is municipal plastic waste, which is difficult to recycle because it is heterogeneous. The daily per capital waste generation of Ethiopia is 0.3kg/day, of which 2% is plastic waste (Daniel Hoornweg, 2012). *In Jimma town, the daily per capital waste generation is 0.157kg/day* (Beneberu, 2011), *of which 3.35% is plastic waste* (Dereje T., 2017). *Up on the use of thermal pyrolysis, these waste plastics can be converted to either solid, liquid, or gaseous fuel. Temperature, types of reactor, residence time, use of catalyst, pressure, particle size, and chemical composition of feedstock are the basic factors which affects the pyrolysis.*

The reactor is selected to be batch type, and designed to decompose 30liter of feedstock at a time. Counter flow shell and tube heat exchanger is selected as a primary condensation mechanism, which is designed to a length of 1.8m. The shell side pyrolysis gas is supplied at rate of 0.01103kg/s. The heat exchanger is designed to 8 number of tube, and the rate of tube side cooling water is 0.1847kg/s.

Based on the designed dimensions, both reactor and condenser are manufactured. Only using distillation cooling, test pyrolysis is conducted for polyethylene theraphthalate.

From pyrolysis of polyethylene theraphthalate 350ml of liquid fuel and 3.0105kg solid fuel is obtained. The liquid fuels obtained have a heating value of 37.86MJ/kg and viscosity of $2.7mm^2/s$*. The solid fuel have 67.096%wt carbon content and calorific value of 25.887MJ/kg.*

Key words: *Polymerization, incineration, thermal pyrolysis, municipal plastic waste, industrial plastic waste, polyethylene theraphthalate.*

Acknowledgements

First of all, I would like to thank ‘Almighty GOD’, who always helped me throughout my life. I am thankful to my advisor Balewgize A. Zeru (Assistant professor of school of Mechanical Engineering at JiT) for his lion share of contribution to my research from the very beginning till the final documentation.

I am also grateful to my co-advisor Eyuel Abate and Amanuel Tesfaye for their support in facilitating the required materials for the test pyrolysis and conducting laboratory test for the fuels obtained.

Finally, I would like to forward my special thanks to all my friends who contributed directly and indirectly for the accomplishment of this research.

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Acronyms

PET	Polyethylene theraphthalate
HDPE	High density polyethylene
LDPE	Low density polyethylene
PVC	Polyvinyl chloride
PP	Polypropylene
PS	Polystyrene
WPO	Waste plastic oil
Wt	Weight
Wt%	Weight percentage
ml	milliliters
mv	millivolt
g	gram
^{0}C	Degree Celsius
Kg	kilograms
V	volume
h	height
r	radius
D	diameter
ρ	Density
LMTD	Logarithmic mean temperature
Re	Reynolds number
TEMA	Tubular equipment manufacturers association

CHAPTER ONE

1. INTRODUCTION

1.1. Background

Raw material for plastic production is naphtha which is a fraction of crude oil. Plastics are non-biodegradable synthetic organic materials produced by polymerization (Anene, 2017). Crude oil is first fractionally distilled to naphtha which is then heated and cracked to yield substances with low molecular weight such as ethylene and propylene. These low molecular substances are then polymerized according to the requirement of properties to form substances like polyethylene and polypropylene. These substances are then melted and formed into pellets because of the difficulty in handling them in their powder or bulk form. Further processing of these pellets enables us to produce plastics of various forms and shapes.

Since its very synthesis in 1900s, plastics have substituted many types of materials such as wood, metals, and ceramics in production of goods, as they are light, durable, resistant to corrosion, diversity of applications, ease of processing and low cost (Asgedom, 2012). As most plastic products are single purpose, it appears difficult for plastic waste management because many plastic waste can be generated daily. There are a number of methods by which waste plastics are managed. These includes recycling, incineration, and thermal or catalytic cracking.

Recycling is one of the method for reducing the quantity of plastic waste by recapturing selected items for additional productive uses. Incineration is the other plastic waste management technique, which becomes an increasingly attractive disposal option for many communities, especially those facing dwindling landfill capacity and rapidly increasing tipping fees, but incineration at present limits the potential of waste plastic to energy technologies as it produce greenhouse gases and some highly toxic pollutants such as polychlorinated dibenzo para dioxins and polychlorinated dibenzo furans. Thermal cracking as a waste management option which implies the decomposition of waste plastics by using some sort of heat sources. Because, plastics are composed of hydrocarbon originally, up on pyrolysis they are converted into fuel oil and some other important gases.

If plastic waste are not changed in to useful resources, the last chance what we can do and doing right now the most is land filling and dumping in to water bodies.

Of all the methods mentioned above to plastic waste managements, the most environmentally sound method is Thermal cracking, or pyrolysis. Pyrolysis is the method of converting waste plastic wastes in to useful resources. As discussed above plastic is formed by polymerization of low molecular substances, such as ethylene, and propylene. Up on heating in oxygen deficient reactor, cracking of long chain polymer in to monomer takes place. Since the cracking takes place at high temperature, the monomer exist at gaseous state, and posse high latent heat of vaporization. These highly energetic gaseous monomer is free to move. Therefore it is possible to provide a pipe at the top of reactor and carry the gaseous monomer in to a condenser, where in it will be converted in to liquid state due to the fact that it releases its latent heat to the cooling water.

Based on the feeding, and construction of bed there are different types of reactors, thus I selected fixed bed batch reactor. In batch reactor the feedstock is fed in small batch at the start of the process and feeding will be repeated when all the material in the reactor is completely processed. Batch type reactor is used for research purpose. In fixed bed type reactor, the pyrolysis takes place in fixed bed. Fixed bed reactor is easier to design and operate at large temperature gradient in batch type reactor. Shell and tube heat exchanger is used as a condenser, for it is highly efficient to work on liquid and gas phase streams, require small area, and convenient to carry energy rich uncondensed gas in to secondary condensation.

1.2. Problem statement

Jimma is originated at 1830. Even though the city is one of the oldest town in Ethiopia, it is not that much clean as recently originated towns like Hawassa. One of the basic factor that results with these is poor plastic waste management. There are many circumstances by which plastic waste are generated in the town each day. One of the source of plastic waste in Jimma is that, most peoples in the town chew *Khat* every day and along with consumes plastic packed water or soft drinks. With this and other source of plastic waste such as plastic bags, the town dump many plastic waste in to the environment. From the observation made in the town, the ditches are highly clogged by plastic bottles and plastic bag. There are two rivers namely Awetu and Kito crossing the town. These rivers are also highly polluted due to enormous amount of plastic bottles dumped in to them.

In Jimma city there are no researches conducted either to recycle or pyrolyse waste plastic. Measures taken as the plastic waste management are either landfilling or incineration, which are not environmentally safe methods of plastic waste managements.

In this research the most environmentally safe method of plastic waste management techniques is used, which is pyrolysis of waste plastic to convert plastic wastes in to useful resources especially liquid fuel. With this it will be possible to minimize environmental pollution.

1.3. Objective

1.3.1.General objective

The objective of the research is design, manufacturing, and testing of small scale plastic pyrolysis plant, for the purpose of pyrolysing waste plastic in Jimma town.

1.3.2.Specific objective

Specifically the research works on;

- Design of fixed bed batch reactor to crack polymers to monomer.
- Design of shell and tube heat exchanger.
- Manufacturing of model reactor.
- Manufacturing of model heat exchanger.
- A test production and characterization of fuel.

1.4. Research Questions

- What are the size of reactor?
- What are the size of heat exchanger?
- How to manufacture model reactor?
- How to manufacture model heat exchanger?
- Can we produce fuel using the final assembly?

1.5. Beneficiaries of the research

- I selected to work on pyrolysis of plastic waste, because plastic takes long period to be degraded naturally. Being accumulated in the environment, plastic emerges as a source of environmental pollution. As pyrolysis is environmentally friendly method of waste plastic management, everyone is beneficial from the research.
- The ditches and water bodies in Jimma town are highly polluted by plastic waste. Since it is the work of Municipality to take care of the cleanly of any town, Jimma town

Municipality will be beneficial from this research, because it will minimize the amount of waste plastic to be simply dumped in to the environment.

- It is small scale waste plastic pyrolysis plant, and requires a smaller capital to be established. Therefore the local government can use it as a means of creating job opportunity.

1.6. Scope of the research

In this research the analysis of waste plastic generated in Jimma town is done. The research also works on design, model development, and manufacturing of the basic components (i.e. reactor and heat exchanger) of the small scale pyrolysis plant. After assembling of the components of the entire system, the final thing this research have gone through includes a test production of fuel. Finally the fuels produced are experimentally checked for fuel properties, alcoholic content, proximate analysis, and heating value.

1.7. Limitation of the research

- Time and financial constraints
- Lack of experience to manufacturing of components

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Generals

Plastic waste conversion into fuel requires feedstock which are combustible and non-hazardous. Plastics wastes may have a different composition as some plastics contains additives, sulphur and other hazardous substances which are disastrous to humans and the environment.

The cracking temperature, quality of liquid fuel produced, pretreatment needed, energy consumption since the process is endothermic, and the composition of flue gas depends on the types of plastics under pyrolysis. As discussed under chapter one, there are many methods of waste plastics managements. However, these research works on pyrolysis to manage the waste plastics.

2.1.1. Types of Plastics

Depending on how the plastics react to heat, they can be divided into two main groups. These groups are thermosets and thermoplastics (Muhammad, 2017).

A. Thermoplastic

Thermoplastic made of long side chains. The bond between thermoplastics molecules are weak, so they can be soften and harden through heating and cooling process repeatedly (Rana, 2012). Thermoplastic can be recycled after use. Most of the plastics products are made from thermoplastics. When thermoplastics are heated, they are susceptible to molecular motion. This important property of thermosetting plastics is responsible for their widespread use which enables them to be molded into a variety of shapes through heating and cooling. PET, HDPE, LDPE, PVC, PP, and, PS are examples of thermoplastics.

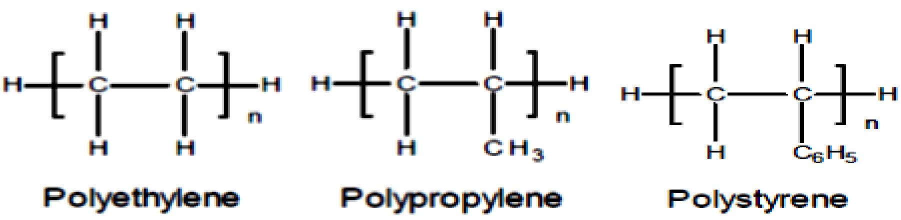


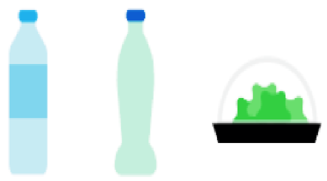
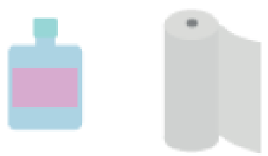
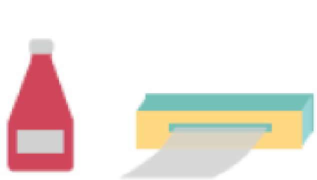
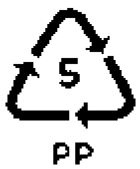
Figure 2-1: Types of Thermoplastics (Anene, 2017)

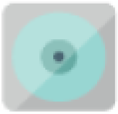
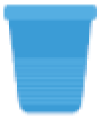
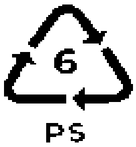
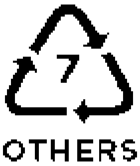
B. Thermosets

On the other hand thermosets are plastics that can only be shaped into a different product just once. Heat treatment of these plastics after solidification is not right as they requires the application of excess heat. Melamine formaldehyde, phenol formaldehyde, epoxy, and urea formaldehyde are examples of thermosets plastics (Rana, 2012).

The Society of the Plastics Industry (SPI) established a classification system in 1988 to allow consumers and recyclers to identify different types of plastic. Plastic types, resin numbers, and application areas are shown in the following table (Achyut Kumar Panda, 2011).

Table 2-1: Plastic type, Resin number and application areas

Plastic type	**Resin number**	**Application areas**
		It sometimes absorbs odour and flavour from foods and drinks that are stored in them. Items made from this plastic are **commonly recycled.** PET commonly is used to make many household items like beverage bottles, medicine jars, rope, clothing and carpet fiber.
		They are very safe and are not known to transmit any chemicals into foods or drinks. HDPE products are **commonly recycled**. Items made from this plastic include containers for milk, motor oil, shampoos and conditioners, soap bottles, and detergents.
		Is **sometimes recycled**. PVC is used for all kinds of pipes and tiles, but is most commonly found in plumbing pipes.
		Is **sometimes recycled**. It is a very healthy plastic that tends to be both durable and flexible. Items such as cling-film, sandwich bags, squeezable bottles, and plastic grocery bags are LDPE
		Is **occasionally recycled.** PP is strong and can withstand a higher temperatures. It is used to make lunch boxes, margarine containers, yogurt

	pots, syrup bottles, prescription bottles. Plastic bottle caps are often made from PP
  	**Commonly recycled**, but is difficult to do. Items such as coffee cups, plastic food boxes, plastic cutlery and packing foam are made from PS.
 	Code 7 is used to designate miscellaneous types of plastic not defined by the other six codes. These types of plastics are **difficult to recycle**. CD, Flexible films, and toothpaste tubes are some examples.

2.1.2. Plastic as a waste

Plastic wastes are divided into two main types: industrial plastic waste (IPW) and municipal plastic wastes (MPW). These wastes have different properties, qualities, and different management approach (Achyut Kumar Panda, 2011).

A. Industrial plastic waste

Industrial plastic waste are the waste product of plastic packaging, manufacturing and processing industries. Industrial plastic waste can be recycled easily by remolding and pelletization because of their homogeneity.

B. Municipal plastic waste

Municipal plastic wastes are collected as household wastes as they are a major component of municipal solid waste (MSW). Municipal plastic wastes are heterogeneous as they contain different materials, such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS), polyethylene terephthalate (PET), polypropylene (PP), and polyvinyl chloride (PVC). MPW obtained from MSW includes food containers, feed bags, carbonated drink bottles, electronic equipment, plumbing pipes, thermal insulation foams, wire, cable, and disposable cups.

Recycling of MPW involves separation of the plastics from other household wastes. Sorting of waste at home is the most encouraged and efficient method for separation of plastic waste from MSW before disposal.

2.1.3. Plastic Waste in Ethiopia

The increase of amount of plastic waste is related with urbanization. Thus a highly urbanized cities produce larger amount of waste. According to World Bank report (Daniel Hoornweg, 2012), United state produce a total of 624,700ton of MSW per a day. Forecasting to a year 2025, United States is expected to produce 1,397,755ton of MSW per a day.

This report reveals that, urban population of Ethiopia is 12,566,942, and a total of 3,781ton of MSW produced per a day, in the year 2025 this figure will be 19, 690ton of MSW per a day. The daily per capita MSW generation of Ethiopia is 0.3kg per a day. Of the MSW generated in Ethiopia, 2%wt is composed of Plastic.

The daily per capital waste generation in Jimma town is 0.157kg/person per a day (Beneberu, 2011). Of the amount of waste generated in the town, the plastic waste covers 3.35%wt (Dereje T., 2017). Thus the moisture contents of plastic waste produced in Jimma town is 0.95% (Dereje T., 2017). The annual population growth rate of Jimma town is 4.9% (Dereje T., 2017). Taking current estimated population in to account 1.362, 9.537, 40.8738, and 497.298 tone of plastic waste will be dumped into the environment daily, weekly, monthly, and annually.

2.2. Pyrolysis

Pyrolysis is the degradation of long-chain polymer molecules into smaller molecules by intense heating in the absence of oxygen. Pyrolysis process produces a broad range of product (gas and liquid hydrocarbon fuel) which can be used as fuel and sources of chemicals. The products produced from plastic pyrolysis are very similar to fossil fuels. This is because plastics are essentially polymers with chemical additives that are used to orient and engineer their use towards desired applications by customers (Al-Salem et al., 2017). Pyrolysis process is an endothermic process, gases obtained with high heating value (HHV) during pyrolysis can be utilized in the process to reduce the energy input, thereby making it a self-sustained process. Pyrolysis can be thermal, catalytic, or hydrocracking (RTI, 2012).

2.2.1. Thermal pyrolysis

Thermal pyrolysis is the thermal degradation of plastics in the oxygen/air deficient environment. It is an endothermic process that does not use catalyst. This process involves heating of the polymers to high temperatures (300-900^{o}C), to break their macromolecules to smaller molecules. The thermal cracking process can be of two types: first is pyrolysis at low temperatures to obtain more yield of waxes and reduced yield of oil and gases; secondly, pyrolysis at higher temperatures (e.g. 700^{o}C) to get a higher yield of gases and reduced yield of waxes and oil.

2.2.2. Catalytic pyrolysis

This process involves the use of a catalyst. Catalytic pyrolysis produces liquid oil of higher quality at lower residence time and temperature compared to thermal pyrolysis (RTI, 2012). There are two types of catalyst that are used for pyrolysis of plastic wastes; homogeneous and heterogeneous (alumina, zeolites, silica-alumina, mesostructured catalyst (e.g. MCM-41), and nanocrystalline zeolites (e.g. HZSM-5)) (Feng, 2010). Heterogeneous catalysts are more favourable, because of ease of separation and recovery at the end of the reaction than homogeneous catalysts (Feng, 2010). This method can be used to process a variety of plastic feedstocks, including low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), and polystyrene (PS).

2.2.3. Hydrocracking

Is also known as hydrogenation. The feedstock is reacted with hydrogen and a catalyst. The process occurs under moderate temperatures and pressures (e.g., 150–400 °C and 30–100 bar hydrogen). Most research on this method has involved generating gasoline fuels from various waste feedstock, including MSW plastics, plastics mixed with coal, plastics mixed with refinery oils, and scrap tires.

2.3. Factors affecting pyrolysis

In plastic pyrolysis, process parameters determine product yield and composition. These parameters affect the products (liquid oil, gaseous and char) obtained during pyrolysis of plastic. The critical parameters that affect pyrolysis are temperature, type of reactors, residence time, catalyst, pressure, particle size, and feedstock composition (Feng, 2010). In depth discussions of various parameters that affect pyrolysis is presented here under.

2.3.1. Temperature

Temperature is one of the most significant operating parameters in pyrolysis since it controls the cracking reaction of the polymer chain. Molecules are attracted together by Van der Waals force and this prevents the molecules from getting collapsed. When temperature in the system increases, the vibration of molecules inside the system will be greater and molecules tend to evaporate away from the surface of the object. This happens when the energy induced by Van der Waals force along the polymer chains is greater than the enthalpy of the C – C bond in the chain, resulted in the broken carbon chain (Feng, 2010).

The quality and quantity of liquid fuel product of pyrolysis will be improved up on the increase in temperature. Even an increase in temperature enhanced the liquid yield, conducting the pyrolysis at a very higher temperature will decrease the liquid yield. This is because further increase in critical decomposition temperature results in secondary decomposition, which produce more gaseous product by reducing liquid yield.

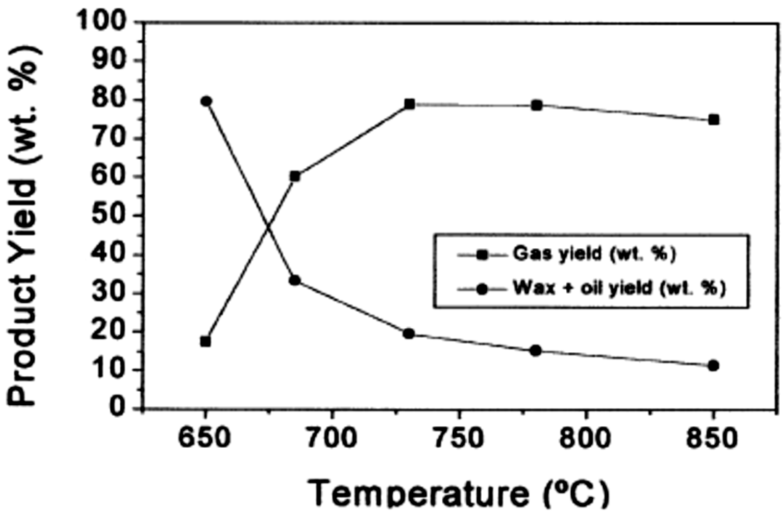


Figure 2-2: The effect of pyrolysis temperature on product yield (Feng, 2010)

Therefore it can be concluded that, temperature has the greatest impact on reaction rate that may influence product composition of liquid, gaseous and char for all plastics. The operating temperature required relies strongly on the product preference. If gaseous or char product was preferred, higher temperature more than 500^{0}C was suggested. If liquid was preferred instead, lower temperature in the range of 300 – 500 ^{0}C was recommended and this condition is applicable for all plastics.

2.3.2. Type of reactor

The type of reactor used determines mainly the quality of heat transfer, mixing, gas and liquid phase residence times, and the escape of primary products. The reactor geometry will determine the escape dynamics of primary decomposition products and thus different reactors give variable product quality and quantity (Chomba, 2018). On the basis of feeding and product removal process or construction of bed, there are two categories of reactors being used in pyrolysis of plastics. Typical reactors that have been used in the pyrolysis of waste plastics research includes:

2.3.2.1. On the basis of feeding and product removal

i. Batch reactor

In these reactors, feedstock are fed in batches into the reactor at the start of the pyrolysis process. When the process is complete, the reactor is emptied of products as well as residues and prepared for another batch (Chomba, 2018). In this reactor there is no feedstock feeding or product removal simultaneously with pyrolysis process running.

ii. Semi – batch 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. Some semi-batch process uses inert carrier gas to help remove the pyrolysis products. Thus the reactor is either pressurized before the start or continuously supplied with an inert gas in order to help the product removal (Chomba, 2018). Advantage of semi-batch reactor over batch reactor is that some reactions and phenomenon such as secondary pyrolysis is possible in semi-batch reactors.

iii. Continuous reactor

In continuous reactor, the material is constantly fed from input side of the reactor whereas products get out from the output side of the reactor (Chomba, 2018). Batch and semi-batch reactors are mostly used for research purposes whereas continuous reactors are used for industrial purposes.

2.3.2.2. On the basis of construction of bed

Reactor's construction has enormous effects on the heat transfer. The following are the type of reactors based on the construction of reactors bed.

i. Fixed bed reactor

In fixed bed reactors, pyrolysis is carried out on fixed bed. Advantage of this type of reactor is that it is easy to design and operate.

ii. Fluidized bed reactor

In fluidized bed reactors, gaseous products flow through feedstock resulting in better heat and mass transfer rates. The key parameter affecting the pyrolysis and products in this type of reactor is dimensions and material of the bed.

iii. Screw kiln reactor

In recent years, a new reaction system named screw kiln reactor has been widely applied for plastic processing. In this type of reactor, there is an extruder to screw the feedstock from a feeder in an oxygen free environment. The extruder is heated by external heat sources. Solid residues and pyrolysis products are separated and collected from the other end of the extruder. Melted plastic or even plastic solid particles can be fed into this reactor. The small diameter of the extruder and good mixing of the materials make the radial temperature gradient negligible. The process is relatively stable and does not use bed material as in the fluidized bed reactor. The feeding rate is controlled by adjusting the rotation speed of the extruder, which also determines the residence time of pyrolysis.

2.3.3. Residence time

The definition of residence time is different for different pyrolysis methods. In fast or continuous pyrolysis, residence time is the amount of time during which plastic was in contact with hot surface within the reactor. In slow or batch pyrolysis, residence time is defined as the time for which feedstock start to be heated to the removal of products. To yield more thermally stable products such as light weight hydrocarbons and non-condensable petroleum gases, longer residence times are require.

2.3.4. Use of Catalyst

The use of catalyst optimize the pyrolysis of plastics and also modify the pyrolysis product distribution. Catalyst can be used in research and industrial pyrolysis process. Thermal pyrolysis produce low quality liquid oil and requires both high temperature and retention time (R. Miandad et al., 2016). Using catalyst in plastic pyrolysis lower the temperature and residence time. For example, catalytic pyrolysis of HDPE with HZSM-5 at 450 ◦C produced 35wt% liquid oil with 65wt% gases, while using same catalyst and feedstock at 500 ◦C, liquid oil was decreased to 4.4wt% with 86.1wt% gases production (R. Miandad et al., 2016). On the other hand usage of certain catalysts such as silica–alumina (SA-2) and mesoporous silica catalysts (FSM) improved the liquid yield for both PP and HDPE slightly than the thermal pyrolysis with a small increase of around 1.0–7.0wt%.

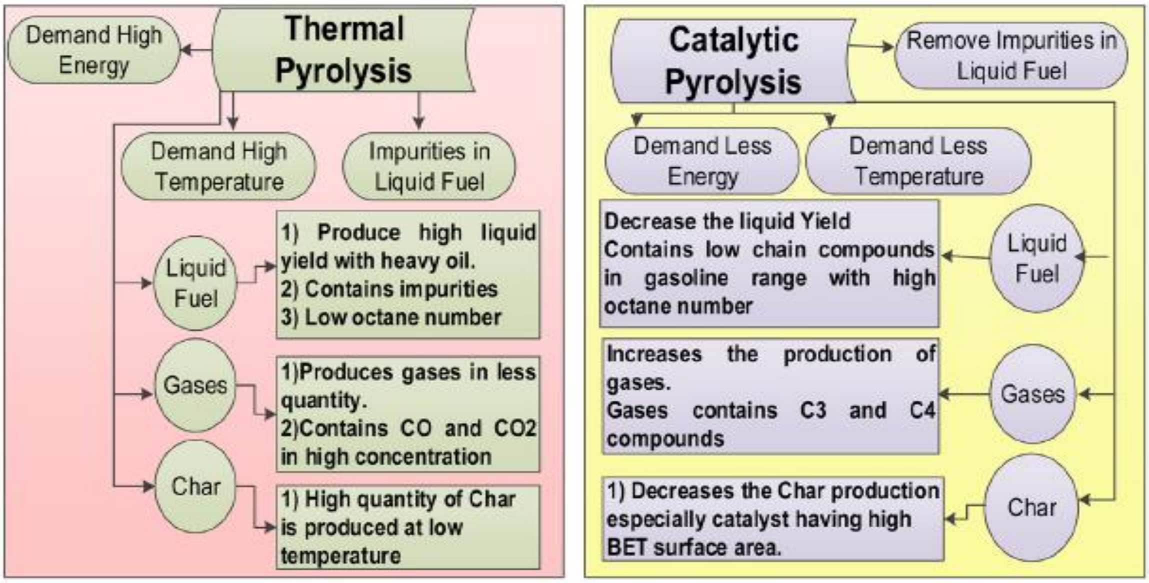


Figure 2-3: Effect of using catalyst over Thermal pyrolysis (R. Miandad et al., 2016)

Different researchers used different types of catalysts such as ZSM-5, HZSM-5, FCC, natural zeolite, activated alumina, and red mud (R. Miandad et al., 2016). Catalysts have different impacts on the pyrolysis process and its products. Some basic impacts of using catalysts are shown in the following figure.

2.3.5. Pressure

Operating pressure has significantly effect on both the pyrolysis process and the products. Pressurized pyrolysis of HDPE is studied increasing the pressure from 0.1 to 0.8MPa. In this paper the authors have seen the increase of gas yield from 6wt% to 13wt% at a temperature of 410^{0}C. This is because 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. Figure 2.4 below shows an increase of gas yield for the pyrolysis of PE due to an increase in the operating pressure.

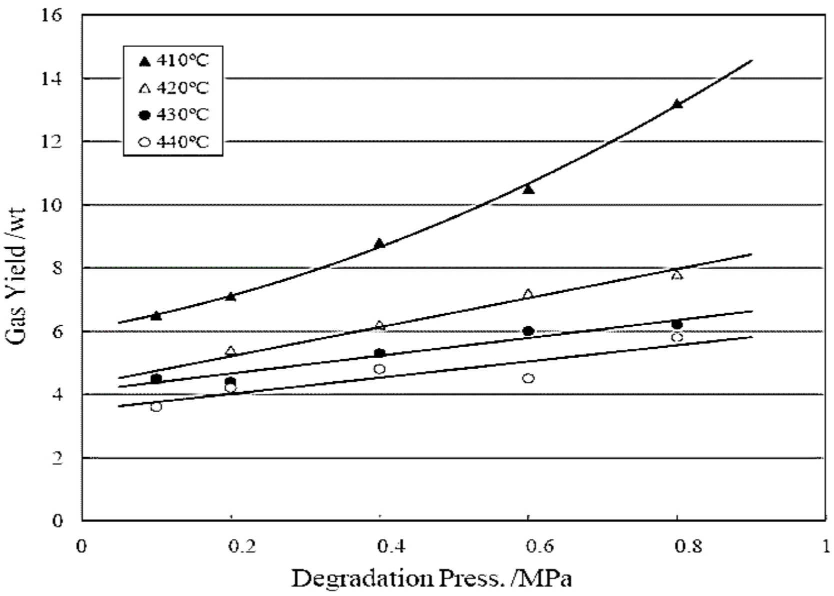


Figure 2-4: Effect of pressure on gas yield at different temperature (Feng, 2010)

2.3.6. Particle size

The size of the plastic materials fed in to the reactor influences pyrolysis product distribution, because as the size of the plastic is smaller, the heat transfer between particles is high. Fine particles are reported to offer high mass transfer rates to escaping condensable gases before they undergo secondary cracking, leading to higher liquid yields. Contrarily speaking, larger particles limit heat transfer and facilitate secondary cracking. This is partly because of high resistance they pose to the escaping primary pyrolysis products.

2.3.7. 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. Based on the structural shape, polymer molecules of plastics are classified as, linear, branched, and cross linked.

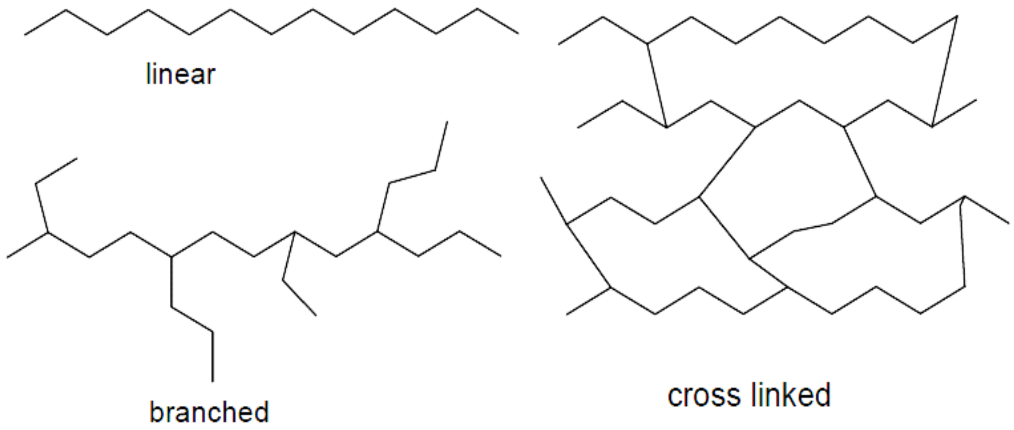


Figure 2-5: Polymer structure

The units in linear polymer are linked only to two others, one to each ends. The polymer is termed branched when branches extend beyond the main polymer chain randomly. In branched polymers, at least one of the monomers is connected to more than two functional groups due to the branching points produced from the polymerization process. The functional side group and the branch structure have significant effects on the pyrolysis product. A cross linked polymer can be described as an interconnected branched polymer with all polymer chains are linked to form a large molecule. In pyrolysis process, cross linked polymer will crack rather than melt or evaporate. This is different from the reactions of linear or branched polymers in pyrolysis process.

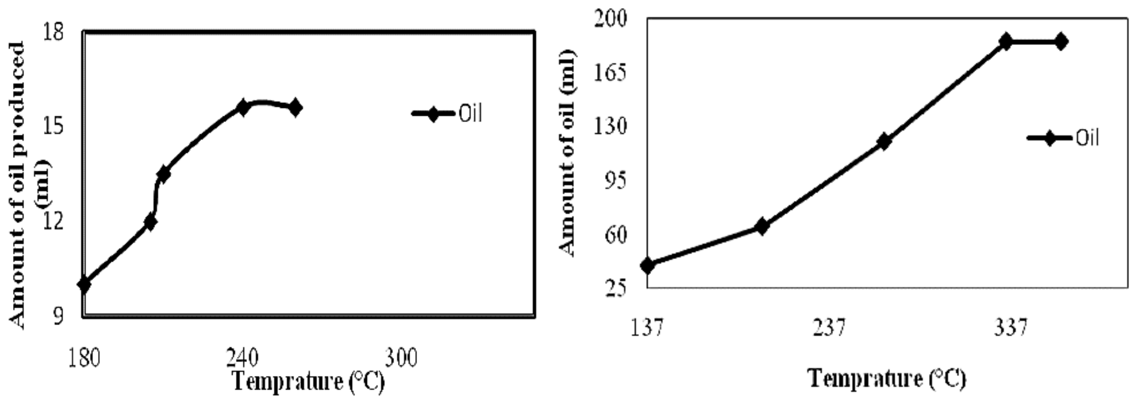


Figure 2-6: The effect of polymer structure on pyrolysis of LDPE (left) and HDPE (right) (Yasabie Abatneh, 2013)

There is significant relationship between the density and branching intensity of polymers. The PE with more branches has relatively lower density. Therefore LDPE is example of branched polymer, whereas HDPE is example of linear polymer. HDPE is a less linear and more crystalline plastic than LDPE and these aspects make LDPE more thermally unstable than HDPE. The high degree of branching in LDPE provides it with more reactive tertiary carbons leading to less thermal stability when compared to HDPE. This thermal instability of LDPE results in less amount of liquid oil product, when compared to HDPE (Yasabie Abatneh, 2013).

2.4. Theoretical review

Table 2-2: Some research conducted on plastic pyrolysis

S.N.	Author	Title	Work carried out	Validation
1	Feng Gao	Pyrolysis of Waste Plastics into Fuels	Pyrolysis of polyethylene (PE), polypropylene (PP), and polystyrene (PS)	Theoretically and Experimental investigation in a lab-scale pyrolysis reactor.
2	Yasabie Abatneh, Omprakash Sahu	Preliminary study on the conversion of different waste plastics into fuel oil	Thermal pyrolysis of different waste plastic, measurement of oil product, and compare which plastic waste produce more oil	Experimental investigation, using small scale reactor.
3	Muhammad Shoaib	Improving thermal decomposition process of recycled plastics for Sustainable gas and liquid fuel production	Review of existing methods of converting plastics into fuel. In addition, various factors which affect the conversion efficiency and product quality of plastic feedstock are evaluated.	Experimental
4	S.D. Anuar Sharuddin *et. al*.	A review on pyrolysis of plastic wastes	Review of the pyrolysis process for each type of plastics and the main process parameters that influenced the final end product such as oil, gaseous and char.	Theoretical investigation

2.5. Research gap

Many researches are recently conducted to improve the pyrolysis of plastic waste. From the results obtained, it can be said that pyrolysis of plastic waste is the best mechanism to manage plastic waste. It is impossible to convert all the feedstock in to liquid oil, there is some amount left as solid residue and the rest is non - condensable gas. But this gas is energy rich (S.D. Anuar Sharuddin et al, 2016). The most commonly adopted method of waste plastic pyrolysis is, cracking the feedstock in the reactor, condense the condensable gas in the condenser, and finally release the non-condensable gas to the environment. Thus rather than releasing the uncondensed pyrolysis gas to the environment, providing a mechanism that allows this gas to secondary pyrolysis more liquid fuel can be produced. This is done by passing back such a gas through a pipe, and condense it in a secondary condensation.

Primarily pyrolysis gas is condensed in a shell and tube heat exchanger, and uncondensed pyrolysis gas can be released in a stainless steel Flask submerged in water for secondary condensation.

CHAPTER THREE

3. ANALYTICAL DESIGN

3.1. Reactor design

3.1.1. Reactor type

The type of reactor used determines mainly the quality of heat transfer, mixing, gas and liquid phase residence times, and the escape of primary products. The reactor geometry will determine the escape dynamics of primary decomposition products and thus different reactors give variable product quality and quantity. On the basis of feeding and product removal process or construction of bed, there are two categories of reactors being used in pyrolysis of plastics. Details of typical reactors used in the pyrolysis of waste plastics research are discussed under section 2.4.2.

In this research the type of reactor to be designed is fixed bed batch reactor. Thus the bed is constructed fixed, and the feeding is chosen to be batch type, which means once the reactor is fed with plastic feedstock, all the feedstock must be cracked to make another feed.

3.1.2. Reactor Shell sizing

The pyrolysis reactor was designed to have the vertical cylindrical cross section, called a shell. Base, which is the bottom end of the reactor is chosen to be elliptical flat in order to ensure greater rate of heat transfer. The reactor was designed to operate at normal atmospheric pressure. Specific spots are provide to mount thermocouple, to connect piping for guiding vapor to the condenser, and also to discharge the residue.

If the size of reactor is chosen to be capable of processing all the plastic waste generated in Jimma town, the reactor volume appears to be larger. So the reactor vessel is selected to have a volume of 30liters.

$$V = \pi r^2 h \qquad (1)$$

From the selected volume of reactor vessel and equation (1) above, considering the height is 1.2 of the diameter, the geometry of the reactor vessel is designed to have inside diameter of 320mm and height of 400mm. The right standard diameter of reactor vessel is 324mm.

Note that the density of plastic feed stocks are (William D. Callister, 2001):

$$\left.\begin{aligned} \rho_{PET} &= 1.35\, g/cm^3 = 1350\, kg/m^3 \\ \rho_{HDPE} &= 0.959\, g/cm^3 = 959\, kg/m^3 \end{aligned}\right\} \qquad (2)$$

$$V = \frac{m}{\rho} \qquad (3)$$

Regarding the volume of reactor vessel, equations (2), and (3) above, the reactor is capable of processing 40.5kg of PET, and 29.77kg of HDPE at a time separately.

The thickness of reactor shell is designed so that it can withstand the pressure inside the reactor vessel (Robert H. Perry, 1997).

$$t_{rs} = \frac{P \times R_i}{\sigma \times E - 0.6 \times P} \qquad (4)$$

Where: P = pressure inside the reactor

R_i = inside radius of the reactor

σ = Allowable stress in construction material

E = joint efficiency

t_{rs} = thickness of reactor shell exclusive to corrosion allowance

The pressure inside reactor is equal to atmospheric pressure. Carbon steel being the material of construction for the reactor component, and butt joint without using backing strip is the type of welding to use. The allowable stress for the construction material at 450^0C is found to be 65MPa, the operating pressure equals to 101325Pa, but the design pressure is better to be 10% greater than operating pressure (Eugene F., 2001). Therefore the design pressure equals to 111,457.5Pa, and joint efficiency equals to 60% (Eugene F., 2001). Substituting all this value into equation (4), thickness of the reactor shell becomes, 0.464mm. Taking safety factor and corrosion allowance in to account, the thickness of reactor vessel becomes, 3mm. Minimum vessel thickness is standardized to be 6mm. Since the thickness is less than half of the inside radius, the design is satisfactory.

3.1.3. Reactor Cover Sizing

To make the discharge of pyrolysis gas easier, reactor head are designed to be to be torispherical in shape. Since L/r $\geq 16^{2/3}$, equation to calculate the head thickness is given by equation (5).

$$t_{rh} = \frac{0.885PL}{\sigma E + 0.8P} \qquad (5)$$

Where:

L = outside radius of the dish, equals to shell diameter

σ = Allowable stress in construction material

E = joint efficiency

t_{rh} = thickness of reactor head

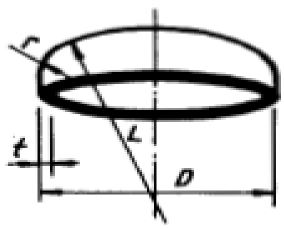


Figure 3-1Torispherical Head

Applying all the available information, the head thickness become, 0.2mm. Considering safety factor, it becomes 6mm.

3.1.4. Pyrolysis gas production rate of Reactor

Energy required to vaporize PE, $H_V = 180.46kJ/kg$

Specific heat capacity of PE, $C_p = 2300J/kg$

Average value of latent heat of fusion of PE (Andrew J. Peacock, 2000), $H_f = 121.34kJ/kg$.

Heat energy required for the pyrolysis of 1kg of PE (Feng, 2010), $Q_H = 1047.62kJ$

10kg being the amount of plastic waste under pyrolysis, and 3hr is the time for complete pyrolysis, therefore, Heat taken by10 kg solid plastics till it starts melting at 115°C,

$$Q_1 = m \times C_p \times \Delta T = 10kg \times 2.3\frac{kJ}{kg.K} \times 90K = 2070kJ$$

Heat required to completely melt 10 kg plastics at 115°C,

$$Q_2 = m \times H_f = 10kg \times 121.34\frac{kJ}{kg} = 1213.4kJ$$

Heat taken by 10kg liquid plastics till it reaches 450°C,

$$Q_3 = m \times C_p \times \Delta T = 10kg \times 2.3\frac{kJ}{kg.K} \times 335K = 7705kJ$$

Heat required for pyrolysis,

$$Q_4 = m \times Q_H = 10kg \times 1047.62kJ/kg = 10476.2kJ$$

Total heat required, is the sum of Q_1 through Q_4

$$Q = 21{,}464.6kJ$$

Take 21,500 kJ

The rate of heat transfer is equal to,

$$\dot{Q} = \frac{Total\ heat\ required}{Time\ taken} = 7166.67kJ/hr$$

Pyrolysis gas production rate:

$$\dot{m}_E = \frac{Heat\ transfer\ rate}{heat\ of\ Vaporization} = 39.72\ kg/hr = 0.01103\ kg/s$$

3.2. Design of Condenser

The condenser type to be used in this research is shell and tube heat exchanger. The design of condenser is similar to a typical shell and tube exchangers. A condenser must have a vent to carry uncondensed gas to secondary condensation. The uncondensed gas decreases the heat transfer rate. Condenser usually use a wider baffle spacing of $B = D_s$ (ID of shell) as the allowable pressure drop in shell side vapor is usually less. Vertical cut-segmental baffles are generally used in condensers for side-to-side vapor flow and not for top to bottom. An opening at the bottom of the baffles is provided to allow draining of condensate. Water cooled counter concurrent shell and tube heat exchanger is designed based on Kern's method. Since it is corrosive, water is selected to be the tube side fluid stream. Thus water enter the tube at a temperature of 25^{0}C and leaves at 45^{0}C. Similarly the pyrolysis gas, (i.e. Ethylene) is allowed to pass through shell. The main objective behind using condenser is to condense this pyrolysis gas cooling it from 450^{0}C to 50^{0}C. Design of condenser involves process and mechanical design.

3.2.1. Design Parameters

Ambient temperature, $T_a = 25°C$

Vapor inlet temperature, $T_{oi} = 450°C$

Condensate outlet temperature, $T_{oc} = 50°C$

Mass of ethylene, $\dot{m}_o = 0.01103\ kg/s$

Water inlet temperature, $T_{wi} = 25°C$

Water outlet temperature, $T_{wo} = 45°C$

Specific heat of water, $Cw = 4.18kJ/kg.K$

Latent heat of vaporization of PE, $Q_{LH} = 482.1kJ/kg$, (Appendix 1K)

Thermal conductivity of copper, $K_C = 392.8W/m$

3.2.2. Thermal design

Thermal design of shell and tube heat exchanger typically includes the determination of heat transfer area, number of tubes, tube length and diameter, tube layout, number of shell and tube passes, type of heat, tube pitch, number of baffles, its type and size, shell and tube side pressure drop.

For liquid fluid flowing at velocity less than *1m/s*, allowable pressure drop up to 35kPa. Whereas for liquid fluid of velocity *1 - 10m/s*, pressure drop of 50 - 70kPa. Similarly for gases at high vacuum operation, the allowable pressure drop is 0.4 - 0.8kPa is allowed, and 50 percent of the system pressure at 100-200kPa, and 10 percent of the system pressure above 1000kPa (J. F. Richardson, 1999).

Step 1: Obtain the required thermo physical properties of hot and cold fluids at the arithmetic mean temperature.

For cooling water

$T_{CW} = 0.5(298 + 318)K = 308K$ → arithmetic mean temperature of cooling water.

At 308K, for Water

- Viscosity

  $\mu_W = 0.7225 \times 10^{-3}\ N.s\ /m^2$

- Thermal conductivity

$k_W = 0.59\, W\ /m.K$

- Density

  $\rho_W = 995\, kg\ /m^3$

For Condensing Vapor Oil

$T_E = 0.5(723 + 323)K = 523K$, arithmetic mean temperature of condensing ethylene.

At 523K, for Vapor ethylene

- Viscosity

  $\mu_E = 0.01677 \times 10^{-3}\, N.s\ /m^2$, (Robert H. Perry, 1997)

- Thermal conductivity

  $k_E = 0.052826\, W\ /m.K$, (Robert H. Perry, 1997)

- Specific heat capacity

  $C_{p,E} = 3\, kJ\ /kg.K$, (R. K. Sinnott, 2005)

- Density

  $\rho_E = 1.261\, kg/m^3$

Step 2: Perform energy balance and find out the heat duty (Q) of the exchanger.

Heat load in the shell,

i. Sensible heat load

$q_s = (\dot{m}_O C_P \Delta T)_{gas} = (0.01103\, kg/s) \times (2.3\, kJ/kg.K) \times (400K) = 10.15\, kJ/s$

ii. Latent heat load

$q_l = \left(\dot{m}_O h_{fg}\right)_{gas} = (0.01103kg/s)(482.1kJ/kg) = 5.317kJ/s$

$where,\ h_{fg} = Latent\ heat\ absorbed\ in\ vaporization\ \equiv latent\ heat\ released\ in\ condensation$

iii. Total heat load in the shell, Q

$Q = q_s + q_l = 15.46kJ/s$

Heat load in the tube

Heat released by shell side fluid is equal to heat absorbed by tube side fluid. Therefore,

$Q = (\dot{m}_w C_P \Delta T)_{water} = 15.46\, kJ/s$

$$\dot{m}_w = \frac{Q}{(C_P \Delta T)_{water}} = \frac{15.46kJ/s}{(4.187kJ/kg.K)\times(20K)} = 0.1847\, kg/s = 664.96\, kg/hr$$

For counter flow shell and tube heat exchanger:

$\Delta T_1 = T_{h,i} - T_{c,o} = 405℃\ and\ \Delta T_2 = T_{h,o} - T_{c,i} = 25℃$

$$LMTD = \frac{(\Delta T_1 - \Delta T_2)}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} = 136.445℃$$

For single shell and single tube pass, the correction factor is given by equation (6),

For $T_a = inlet\ temperature\ of\ shell\ side\ fluid = 450℃$

$T_b = outlet\ temperature\ of\ shell\ side\ fluid = 50°C$

$t_a = inlet\ temperature\ of\ shell\ side\ fluid = 25°C$

$t_b = outlet\ temperature\ of\ tube\ side\ fluid = 45°C$

$N = number\ of\ shell\ side\ passes = 1$

$where, R = \frac{T_a - T_b}{t_b - t_a} = 20$, and $P = \frac{t_b - t_a}{T_a - t_a} = 0.047$, for $\alpha = \left(\frac{1-RP}{1-P}\right)^{1/N}$, $S = \frac{\alpha - 1}{\alpha - R}$

Note: for N = 1, S = P = 0.047

$$F_c = \frac{(\sqrt{R^2+1}) * \ln\left[\frac{1-S}{1-RS}\right]}{(R-1) * \ln\left[\frac{2-S(R+1+\sqrt{R^2+1})}{2-S(R+1-\sqrt{R^2+1})}\right]} \qquad (6)$$

Substituting the value of R and S into equation (6), correction factor becomes 0.882. This value can also be obtained from the figure in Appendix 1D. Since F_C is greater than 0.75, steady operation of the exchanger can be achieved. Therefore, corrected value of logarithmic mean temperature is found to be,

$LMTD_{cortd} = LMTD \times F_c = 136.445°C \times 0.882 = 120.34°C$

Step 3: Assume a reasonable value of overall heat transfer coefficient ($U_{assumed}$). From Appendix 1A, approximate overall heat transfer coefficient is taken to be (Robert W.Serth, 2007),

$U_A = 30 Btu/°F.ft^2.h = 170.35\, W/m^2.k$

Step 4: Calculation of heat transfer area and tube numbers, for the tube of 19.1mm outer diameter, thickness of 1.65mm 16BWG (Frank Kreith, 1999), and tube pitch is 1.25 of outer diameter. Effective length of the tube is taken to be 1.8m.

Iteration 1:

- Total Heat transfer area, A

$A = \frac{q}{U_A \times LMTD_{cortd}} = 0.75412 m^2$

- Number of tube, n_t

$A_t = \pi \times D_o \times L = 0.108 m^2$ → the heat transfer area of each tubes

$n_t = \frac{A}{A_t} = 6.9$

Choose the number of tube to be 8, and check if the assumed overall heat transfer coefficient is greater than the required value.

$U_r = \frac{q}{A_r \times LMTD_{cortd}}$, $A_r = n_t \times \pi \times d_o \times L = 0.86406 m^2$

$U_r = 148.68\, W/m^2.k$, Thus $U_A \gg U_r$

- Number of pass, n_p

$Re = \frac{4\dot{m}_w(n_p/n_t)}{\pi D_i \mu_w} = \frac{4(0.1847kg/s)(n_p)}{8\pi(17.46\times10^{-3}m)\left(0.7225\times10^{-3}\frac{N.s}{m^2}\right)} = 2{,}330.26n_p$

According to Reynolds experiment for practical importance in a pipe flow, 2000 is the Reynolds lower critical number, and the flow will change from laminar to turbulent in between Reynolds number of 2000 and 4000 (Streeter, 1962). Therefore $n_p(number\ of\ tube\ passes)$ of 1 is sufficient enough to achieve fully developed turbulent flow ($i.e.\ Re \geq 2000$).

$$n_t = a(d_b/d_o)^b \qquad (7)$$

$where, d_b = diameter\ of\ tube\ bundle, and\ d_o = outer\ diameter\ of\ the\ tube$

From Appendix 1B, a = 0.215 and b = 2.207 for single pass and square pitch. Since d_o is $19.1mm$, substituting all these values in to equation (7), the diameter of tube bundle become

$d_b = 98.3mm$

Using *fixed and U tube*, the value of clearance between the outer tubes in the bundle and the inside diameter of the shell (C_{bs}) is found to be 10mm. From this, shell inside diameter (d_s), is found to be;

$d_s = d_b + C_{bs} = 108.3mm = 4.56in$

Thus a standard shell size of 125mm is selected (Indian Standard (IS: 4864 to IS: 4870 -1968), 1993). Therefore inside shell diameter is taken as,

$d_s = 125mm$

Step 5: Determine the heat transfer coefficient

Tube-side coefficient, h_i

The water-side coefficient may now be calculated using equation (8)

$$N_u = (hd/k) = j_h Re Pr^{0.33}(\mu/\mu_s)^{-0.14} \qquad (8)$$

$Cross\ sectional\ area\ of\ one\ tube = \frac{\pi {d_i}^2}{4} = 239.156mm^2$

$Number\ of\ tube/Pass = (8/1) = 8$

Therefore,

$Tube\ side\ flow\ area, A_T = (8\times 239.156)mm^2 = 1915.44mm^2 = 0.00191544m^2$

$Mass\ velocity\ of\ water, G = \frac{\dot{m}_w}{A_T} = 96.427\ kg/m^2.s$

Since mean water density is 995kg/m^3, the velocity of water is found from equation (9),

$$\vartheta_t = \frac{\dot{m}_w/A_t}{\rho_w} = 0.0969\ m/s \qquad (9)$$

$Re = (d_i\vartheta_t\rho/\mu)_w = 2{,}330$, which is *Re>2000,* therefore this is fully developed turbulent flow.

Pr $= C_p\mu_w/k = \frac{(4.187kJ/kg.K)(0.7225\times10^{-3}N.s/m^2)}{0.59W/m.K} = 5.127$

$l/d_i = (1.8m)/(17.46 \times 10^{-3}m) = 103.1$

Now considering figure in Appendix 1E, the heat transfer factor for flow inside the tube is;

$j_h = 3.3 \times 10^{-3}$

Neglecting the viscosity term, film coefficient in tube side can be calculated from equation (11) as,

$(hd/k) = j_h RePr^{0.33}(\mu/\mu_s)^{-0.14}$

$$h_i = \frac{kj_h RePr^{0.33}}{d_i} = \frac{(0.59\times W/m.K)(3.3\times10^{-3})(2330.26)(5.127)^{0.33}}{(17.46\times10^{-3}m)} = 4445.636\, W/m^2.K$$

Shell-side coefficient, h_o

For condensers, baffle spacing will be taken equals to inside diameter of the shell, that is

$B_s = d_s = 125mm$

For the ease of mechanical cleaning and maintenance, the pitch is selected to be square pitch, and is equal to 1.25 of tube outer diameter. That is

$P_t = 1.25d_o = 1.25 \times 19.1mm = 24mm$

$$A_s = d_s B_s (C'/P_t) \qquad (10)$$

where, d_s is shell diameter, B_s is baffle spacing, and (C'/P_t) is the ratio of clearance between outside diameter of the tubes to the tube pitch.

Therefore

$A_s = 125mm \times 125mm[(24 - 19.1)/24] = 3{,}190.104mm^2 = 0.0031901m^2$

Shell side mass velocity, G_s

$$G_s = \frac{\dot{m}_E}{A_s} = \frac{0.01103kg/s}{0.0031901m^2} = 3.45767\, kg/m^2.s$$

For square pitch, the equivalent diameter of the shell is given by

$$D_e = \frac{4\left(P_t{}^2 - \frac{\pi}{4}(d_o{}^2)\right)}{\pi d_o} = \frac{1.27(24mm^2 - 0.7854(19.1mm)^2)}{19.1mm} = 19.25mm$$

$$Re = G_s D_e/\mu = \frac{(3.45767kg/m^2.s)(19.25\times10^{-3}m)}{0.01677\times10^{-3}((kg.m/s^2).s)/m^2} = 3{,}968.9,\ This\ is\ fully\ developed\ turbulent\ flow$$

$$Pr = C_p\mu/k = \frac{(3kJ/kg.K)(0.01677\times10^{-3})((kg.m/s^2).s)/m^2}{0.052826W/m.K} = 0.9524$$

From Appendix 1F, shell side heat transfer factor with segmental baffle cut at 25% is found,

$j_h = 9.2 \times 10^{-3}$

$$Nu = h_o D_e/k_f = j_h RePr^{0.33}(\mu/\mu_s)^{0.14} \qquad (11)$$

Neglecting the viscosity correction factor, shell side heat transfer coefficient can be obtained from equation (14) as,

$$h_o = \frac{k_f j_h RePr^{0.33}}{D_e} = \frac{(0.052826W/m.K)(9.2\times10^{-3})(3968.9)(0.9524)^{0.33}}{19.25\times10^{-3}m} = 98.602\, W/m^2.K$$

Step 6: Determine overall coefficient, U_D

The thermal conductivity of copper is *392.85W/m.K* (Robert W.Serth, 2007), and, from Appendix 1F, scale resistances will be taken as 0.00021 m^2K/W for the water and 0.00018 m^2K/W for the organic. Based on the outside area, the overall coefficient is given by equation (12) below.

$$\frac{1}{U_D} = \frac{1}{h_o} + R_o + \frac{x_w}{k_w} + \frac{R_i}{(d_o/d_i)} + \frac{1}{h_i}(d_o/d_i) \qquad (12)$$

$$= \frac{1}{98.602} + (0.00018\ ) + \frac{0.00165}{392.85} + \frac{0.00021}{(0.0191/0.01746)} + \frac{1}{445.632}(0.0191/0.01746)$$

$U_D = 78.24\, W/m^2K \ll U_r$, **Note safe!**

Iteration 2:

Since the first design is not safe, some correction is required. Tube side velocity is too small, and let's increase it to 0.5m/s. Similarly let's reduce the baffle spacing, into 40% of the inside shell diameter. Following the same procedure as in the first Iteration, and using these modifications, the following results are obtained.

Tube-side

$\vartheta_t = 0.5 m/s$

$Pr = 5.127$

$Re = \frac{\rho \vartheta_t d_i}{\mu} = 12{,}022.63$, turbulent flow

From Nusselt theory, for a flow in a pipe with

$\{0.6 \leq Pr \leq 16{,}700, Re \geq 10{,}000, and\ L/D \geq 10\}$,

Nusselt number N_u can be calculated from the following relation, (Theodore L. Bergman, 2011).

$N_U = (hd/k) = 0.027 Re^{4/5} Pr^{1/3} (\mu/\mu_S)^{-0.14}$

Neglecting the viscosity term, the Nusselt number is calculated to be, 85.04. From this the heat transfer coefficient can be obtained as,

$h_i = (N_u k/d) = \frac{85.503 \times 0.59}{17.46 \times 10^{-3}} = 2889.2\, W/m^2.k$

Shell-side

$B_s = 0.4 d_s = 40 mm$

$A_s = 0.00127604 m^2$

$G_s = 8.64\, kg/m^2.s$

$Re = 9{,}917.7$

$j_h = 5.8 \times 10^{-3}$

$h_o = 155.3\, W/m^2.K$

$U\ \ = 139.006\, W/m^2K < U_r$, **not safe!**

Iteration 3

Let's reduce the baffle spacing to 30% of the shell diameter. With this modification the shell side thermal design results in

$B_s = 0.3d_s = 37.5mm$

$A_s = 0.00957m^2$

$G_s = 11.52\, kg/m^2.s$

$Re = 13{,}223.6$

$j_h = 5.5 \times 10^{-3}$

$h_o = 196.399\, W/m^2.K$

$U_D = 171.04\, W/m^2K \gg U_r$, **safe!**

Step 7: Calculate the Pressure drop

Tube-side, ΔP$_t$

$$\Delta P_t = n_p\left[4j_f(l/d_i)(\mu/\mu_s)^m + 1.25\right]\left(\rho{\vartheta_t}^2\right) \quad (13)$$

From Appendix 1G at Re =12,022.63, Darcy friction factor is found to be,

$j_f = 4.6 \times 10^{-3}$

$\Delta P = 1[4(4.6 \times 10^{-3}\,)(1800mm/17.46mm) + 1.25]\left((995\, kg/m^3)(0.5\, m/s)^2\right)$

$\Delta P = 782.79Pa$

Shell side, ΔP$_s$

$$\Delta P_s = 4j_f(l/B_s)(d_s/D_e)\left(\rho{\vartheta_s}^2\right) \quad (14)$$

From Appendix 1H at Re = 13,223.6, Darcy friction factor is found to be,

$j_f = 4.8 \times 10^{-2}$

$\Delta P_s = 4(4.8 \times 10^{-2})(1800/37.5)(125/19.25)\left((1.261\, kg/m^3)(9.14\, m/s)^2\right)$

$\Delta P_s = 6.304kPa$

This is acceptable pressure drop in the shell side.

3.2.3. Mechanical Design

The structural rigidity and satisfactory service of heat exchangers depends on the appropriate mechanical design. Mechanical design is generally performed according to the design standards and codes. Some mechanical design standards used in heat exchanger design are: TEMA (United States), IS 4503-1967 (India); BS 3274 (United Kingdom) and BS 20414 (United Kingdom).

The major mechanical design components of shell and tube heat exchangers are: shell and tube end support thickness, shell cover, nozzles, gaskets, bolt, flanges, and design of supports.

3.2.3.1. Shell diameter and thickness

The shell thickness (t_s) can be calculated from the equation below based on the maximum allowable stress and corrected for joint efficiency, (Eugene F., 2001).

$$t_s = \frac{PR_s}{\sigma E - 0.6P} \quad (15)$$

P = pressure

R_s = shell inside Radius of the reactor

σ = Allowable stress in construction material

E = joint efficiency

t_s = thickness of shell exclusive to corrosion allowance

From thermal design, shell inside diameter is calculated to be 125mm. Using butt joint without backing strip is the type of welding. Joint efficiency is taken as 60%. The shell of condenser is designed for the pressure with 10% increment at the inlet, which is equal to 111,457.5Pa. The shell is made of low carbon steel (SA-106 B). The maximum allowable stress in the shell material is 8700Psi (60MPa), (Eugene F., 2001).

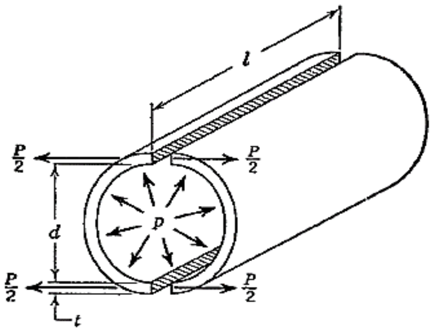


Figure 3-2: Condenser shell

$$t_s = \frac{(111{,}457.5N/m^2)(62.5\times10^{-3})}{0.6[(60\times10^6 N/m^2)-(111{,}457.5N/m^2)]} = 0.19386mm$$

Accounting the safety factor for corrosion, thickness of the shell is taken to be 3mm. Effective length of the shell is equals to the length of the tube (i.e. 1.8m). Thus effective length is the length that exclusive of the covers at the two end.

3.2.3.2. Head

Heads are used to cover the openings in both end of the shell. There are different types of head and, for the ease of construction, flat plate is used as a closure. The minimum thickness of flat plate shown in figure 3.3 is given by equation shown below, (Lioyd E. Brownell, 1959)

$$t_h = d_s\sqrt{C(P/\sigma)} \quad (16)$$

Where,

t_h = minimum thickness of head

C = constant

P = Design pressure

σ = Maximum allowable stress

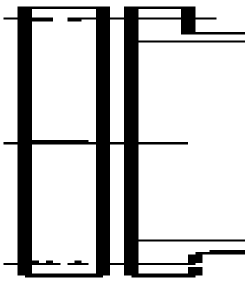


Figure 3-3: Head

The design pressure must be taken with 10% increase to the operating pressure. Therefore the design pressure is equal to 111,457.5Pa. The material of construction of head is selected to be carbon steel (SA-285

C). The maximum allowable stress in SA-285 C, at 850^0F is 8,400psi (57.91MPa). Since the head cover is flat circular plate rigidly riveted or bolted to the shell or channel as shown in figure 4.3, the constant C = 0.162, (Lioyd E. Brownell, 1959). From equation (16), the minimum thickness of the head plate is calculated to be 2.207mm. Taking corrosion allowance, thickness of the head is taken as, $t_h = 5mm$

3.2.3.3. Tube end Support

Tube end support is a circular flat plate with regular pattern drilled holes according to the tube layouts. The open end of the tubes is connected to the tube sheet. It is fixed with the shell and channel to form the main barrier for shell and tube side fluids. The tube end support is attached either by welding (called integral construction) or bolting (gasket construction) or a combination of both types. Here the tube end support is bolted with the shell and the channel. The minimum thickness (TEMA standard) to '***resist bending***' is given by:

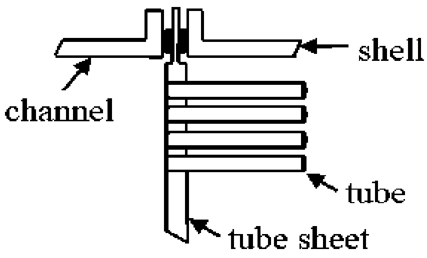


Figure 3-4: Tube end support

$$t_{ts} = \frac{FG_p}{3}\sqrt{\frac{P}{kf}} \quad (17)$$

Where,

F = 1 for fixed or floating tube end support, and 1.25 for U – Tube

G_p = diameter over which the pressure act, for fixed tube HE $G_p = d_s$

P = Design pressure

k = Mean ligament efficiency, $\left[k = 1 - \frac{0.785}{(P_t/d_o)^2}\right]$ for square pitch

σ = Allowable stress in the construction material

Construction material of tube end support is selected to be carbon steel (SA-285 C). The maximum allowable stress in SA-285 C, at 850^0F is 8,400psi (57.91MPa).

$$t_{ts} = \frac{(1)\times 125mm}{3}\sqrt{\frac{111{,}457.5(N/mm^2)}{(0.5028)\left(57.91\times 10^6(N/mm^2)\right)}} = 2.578mm$$

For the corrosion allowance, the thickness of tube end support is taken to be 5mm. since $P/\sigma < 1.6(1 - d_o/P_t)^2$, the tube sheet is not designed to resist shearing, the satisfaction of the above criteria implies, the shear formula does not control tube sheet thickness.

3.2.3.4. Baffles (Impingement plates)

Impingement plates are fixed on the tube side between the tube bundle and inlet nozzle to deflect the liquid or vapor-liquid mixture to protect the tubes from erosion. According to the IS:4503, the protection against impingement may not be required for the services involving non-corrosive, non-abrasive, single phase fluids having entrance line values of $\rho u^2 < 125$, where u is the linear velocity of the fluid in m/s and ρ is the density in g/cm^3. In all other cases, the tube bundle at the entrance against impinging fluids should be protected. Thus without using the baffles turbulent flow cannot be achieved in the shell side. Usually a metal plate about ¼ inch (6 mm) thick is used as the impingement plate.

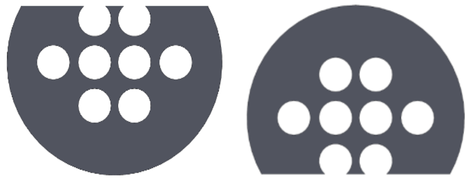


Figure 3-5: Cut segmental Baffles

3.2.3.5. Nozzles and branch pipes

The wall thickness of nozzles and other connections shall not be less than that defined for the applicable loadings, namely pressure, temperature, bending and static loads, (Indian Standard (IS:4503-1967):, 2007). Excluding the corrosion allowance, the wall thickness of ferrous piping is $(0.04d_{oc} + 2.5)$ mm, where d_{oc} is the outside diameter of the connection. From figure 3.6, d_n = diameter of nozzle, t_{rh} = thickness of reactor head, *and* t_n = thickness of nozzle. Therefore the minimum thickness of nozzle is given by equation (18).

$$t_n = \frac{Pd_n}{2\sigma E - P} + C \qquad (18)$$

There are four nozzles to be connected with the condenser shell, two for the inlet and discharge of cooling water, and also one for the inlet of pyrolysis gas, and the other for the discharge of condensate. Similarly there is a nozzle on the reactor vessel for discharging pyrolysis gas into condenser.

A. Nozzle at the discharge of reactor

Since the inside diameter of shell is in between 12inch and 17.25inch, the inside diameter of nozzle is selected to be 3inch, (Indian Standard (IS:4503-1967):, 2007). Construction material for the nozzle is carbon steel (SA-106 B). The maximum allowable stress at 850^{0}F is 8,700psi (60MPa). Joint efficiency for nozzle design is 80%. Therefore from equation (21), the thickness of nozzle is found to be,

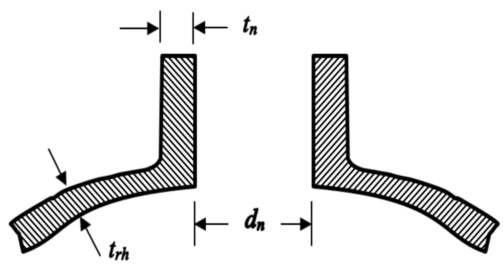


Figure 3-6: Nozzle at reactor discharge

$$t_n = \frac{Pd_n}{2\sigma E - P} + C = 6mm,$$

B. Nozzle for inlet outlet of cooling water and pyrolysis gas

Since the inside diameter of shell is less than 12inch, the inside diameter of nozzle is selected to be 2inch (Indian Standard (IS:4503-1967):, 2007). Material selected to the nozzle is carbon steel (SA-106 B). The maximum allowable stress in SA-106 B, at 850^0F is 8,700psi (60MPa). Joint efficiency for nozzle design is 80%. Therefore

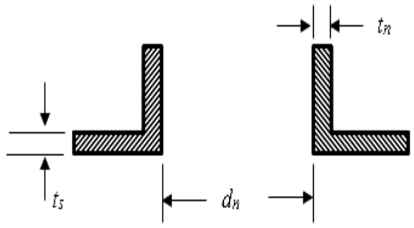


Figure 3-7: Condenser Nozzle

$$t_n = \frac{Pd_n}{2\sigma E - P} + C = 5mm$$

3.2.3.6. *Gaskets*

Leak proof metal to metal surface connections without using gaskets is difficult to achieve. Irregularities in clearances of only a few inch will permits the escape of a fluid under pressure. Gaskets are elasto-plastic materials and relatively softer than the flange materials. Deformation of gaskets under load seals the surface irregularities between metal to metal surfaces and prevents leakage of the fluid. This force required to deform the gasket material is known as *yield* or *seating force*. As shown in figure 3.8, there are three major forces acting on gasket (Lioyd E. Brownell, 1959). Internal pressure load is a force acting on the gasket from the internal working environment during operating condition. When the bolt is tightened, a seating force is applied on gasket prior to hydrostatic force which tends to separate the flange up on the application of internal pressure. Leakage will occur when hydrostatic end force is sufficiently greater than the bolt load.

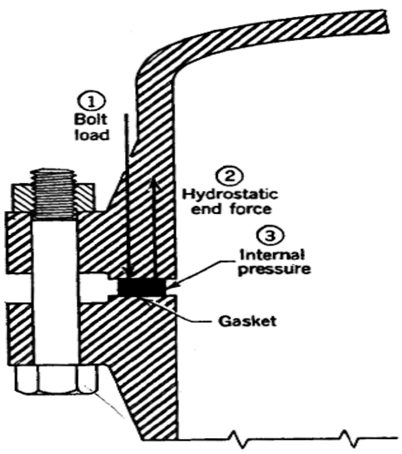


Figure 3-8: Forces acting on gasket

There is possible choice of gasket material for different application. The decisions to which gasket material should be selected is based on the required gasket width (Lioyd E. Brownell, 1959). If the gasket is too narrow, the unit pressure on it may be excessive. Similarly if the gasket is too wide, the bolt load will be unnecessarily increased. A relationship to make preliminary estimate of gasket proportion may be derived as follow (Lioyd E. Brownell, 1959).

$$\text{Gasket seating force} - \text{Hydrostatic pressure force} = \text{Residual gasket force} \quad (19)$$

The above relation can be written in the form of

$$\frac{\pi}{4}\left({d_{og}}^2 - {d_{ig}}^2\right)y - \frac{\pi {d_{og}}^2}{4}p = \frac{\pi}{4}\left({d_{og}}^2 - {d_{ig}}^2\right)pm \quad (20)$$

Rearranging equation (23), the following equation is obtained.

$$\frac{d_{og}}{d_{ig}} = \sqrt{\frac{y-pm}{y-p(m+1)}} \qquad (21)$$

Where,

d_{og} = outside diameter of gasket (mm)

d_{ig} = inside diameter of gasket (mm) = d_s +0.25

y = seating stress

m = gasket factor

p = inside pressure

Flat ring gaskets are used wherever service conditions permits because of the ease which they may be cut from flat sheet and installed (Lioyd E. Brownell, 1959). The minimum width of peripheral ring gaskets for external joints shall be 10 mm for shell sizes up to 600 mm nominal diameter and 13 mm for all larger shell sizes (Indian Standard (IS:4503-1967):, 2007). Ferrous metal gaskets can be used up to maximum temperature rating of the flange (Lioyd E. Brownell, 1959). Therefore Iron or soft steel is selected as gasket material. The gasket factor is 3.75 and minimum seating stress is 7600Psi (52.4MPa). Thus the pressure at the inlet of both stream is taken 1atm. With 10% increase, the operating pressure is taken as 0.1114575MPa. Thus gasket is required at all the flange connections present.

A. Gasket for the reactor shell – head connection

Such connection is shown in figure 3.8, with the top component as head and bottom component being the shell of reactor.

$$\frac{d_{og}}{d_{ig}} = \sqrt{\frac{52.4-(0.1114575)3.75}{52.4-(0.1114575)(3.75+1)}} = 1.01149$$

Note that the inside diameter of gasket is only 0.25 greater than the inside diameter of shell. Therefore inside diameter of gasket is 324.25mm. With this, the outside diameter of gasket is found to be 328mm. From Appendix 1I, standard outside diameter of gasket is taken as 365mm,

$$N = (d_{og} - d_{ig})/2 = 20.375mm$$

B. Gasket for the Condenser cover

The two end of the condenser shell are covered with channel. Therefore there is a channel - shell connections, wherein gasket will be used in order to avoid leakage of the fluid. For the inside diameter of gasket being 0.25mm greater than the inside diameter of the shell, inside diameter of the gasket is 125.25mm. Using Iron

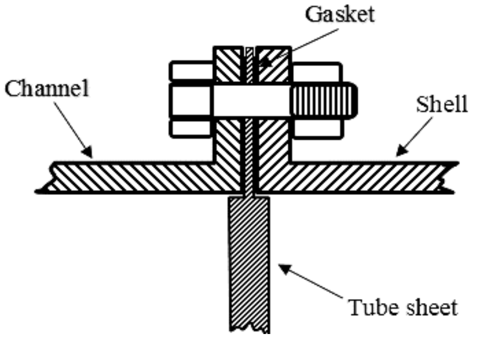


Figure 3-9: Gasket for shell - channel connection

or soft steel as a gasket material, equation (21) can be used to find the outside diameter of the gasket.

$$\frac{d_{og}}{d_{ig}} = \sqrt{\frac{52.4-(0.1114575)3.75}{52.4-(0.1114575)(3.75+1)}} = 1.01149$$

Therefore the outside diameter of gasket is 127mm, considering the minimum requirement, it is taken as 165mm (Appendix 1I).

$$N = \left(d_{og} - d_{ig}\right)/2 = 19.875mm$$

3.2.3.7. Bolt design

There are different connections which are done by using bolt. The reactor shell – head, and condenser shell – end covers are the basic bolt connections. Thus the bolts must be designed to resist different loads and create a tight connections. There are two type of bolt loads.

The first is the force developed by tightening up the bolt (W_{m1}) to exert sufficient force to produce yielding of the gasket. It is the product of bolt effective area and the gasket yield stress.

$$W_{m1} = \pi bGy \qquad (22)$$

Where

b = the effective gasket seating width, $b = b_o$ for b_o < 6mm, and $b = 0.5\sqrt{b_o}$ for b_o > 6mm

b_o = basic gasket seating width, $b_o = N/2$ for flat flange

G = mean diameter of the gasket $(D_{og} + D_{ig})/2$

y = gasket seating stress

The other is minimum initial bolt load (W_{m2}) at atmospheric pressure and temperature. This load is consists of the force necessary to resist internal pressure, and the force necessary to keep the gasket tight during operation. The internal pressure produces an end force, H is equal to;

$$H = \frac{\pi}{4} G^2 p \qquad (23)$$

The force that is required to keep the gasket from leaking, H_p is given by;

$$H_p = 2b\pi Gmp \qquad (24)$$

Therefore,

$$W_{m2} = H + H_p = \frac{\pi}{4} G^2 p + 2b\pi Gmp \qquad (25)$$

Note: *the value of W_{m1} must be greater than that of W_{m2}.*

For the operating condition, the minimum bolting area is given by;

$$A_m = \frac{W_{m1}}{\sigma_b} \qquad (26)$$

Where: σ_b= *allowable bolt stress at design temperature*

For bolting condition, the minimum bolting area is given by;

$$A_m = \frac{W_{m2}}{\sigma_a} \quad (27)$$

Where: σ_a= *allowable bolt stress at ambient condition*

3.2.3.8. Bolt design for shell - head connection of Reactor

y = 52.4N/mm^2

m = 3.75

$$G = \frac{d_{ig}+d_{og}}{2} = 344.625mm$$

$$b_o = \frac{N}{2} = 10.1875mm$$

Since $b_o > 6mm, b = 0.5\sqrt{b_o} = 1.59mm$

$$p = 0.1114575N/mm^2$$

From equation (22), the bolt load due to gasket reaction under atmospheric conditions calculated to be;

$$W_{m1} = 90{,}203.8N$$

From equation (25), the bolt load under operating condition is calculated as;

$$W_{m2} = 11{,}835.64N$$

The bolt material is selected to be alloy steel, SA-193 B7 (Eugene F., 2001). At operating temperature of 850°F, the allowable stress for SA-193 B7 is 17,000Psi (117.211N/mm^2). From equation (26), the minimum bolt cross sectional area is found to be;

$$A_m = \frac{W_{m1}}{\sigma_b} = \frac{90{,}203.8N}{117.211N/mm^2} = 769.5mm^2$$

The bolt is selected to, nominal thread diameter of M20, bolt circle diameter (d_{bc}) of 395 mm, number of bolts 12, and bolt root diameter (d_{br}) of 22 mm, (Indian Standard (IS: 4864 to IS: 4870 -1968), 1993).

The corresponding actual bolt cross sectional area, A_b is calculated as;

$$A_b = \frac{\pi}{4}\left({d_{br}}^2\right)n, \quad n = Number\ of\ blot$$

$$A_b = 4{,}561.59mm^2$$

Since $A_b > A_m$, the selected bolt is suitable. The actual bolt area exceeds the minimum required bolt area, this is because an integral number usually, a multiple of four is used.

Minimum gasket width is calculated as;

$$N_{min} = \frac{A_b\sigma_b}{2\pi yG} = 4.71mm,$$

$$N > N_{min} \gg \textbf{Safe}!$$

3.2.3.9. Bolt design for shell - head connection of condenser

y = 52.4N/mm^2

m = 3.75

$G = \frac{d_{ig}+d_{og}}{2} = 145.125mm$

$b_o = \frac{N}{2} = 9.9375mm$, Since $b_o > 6mm, b = 0.5\sqrt{b_o}$

$b = 1.576mm$

$p = 0.1114575N/mm^2$

From equation (22), the bolt load due to gasket reaction under atmospheric conditions calculated to be;

$W_{m1} = 37{,}651.27N$

From equation (25), the bolt load under operating condition is calculated as;

$W_{m2} = 2{,}003.84N$

The bolt material is selected to be alloy steel, SA-193 B7 (Eugene F., 2001). At operating temperature of 850°F, the allowable stress for SA-193 B7 is 17,000Psi (117.211N/mm^2). From equation (26), the minimum bolt cross sectional area is found to be;

$A_m = \frac{W_{m1}}{\sigma_b} = \frac{37{,}651.27N}{117.211N/mm^2} = 321.226mm^2$

The bolt is selected to, nominal thread diameter of M16, bolt circle diameter (d_{bc}) of 200 mm, number of bolts 8, and bolt root diameter (d_{br}) of 18 mm, (Appendix 1I). The corresponding actual bolt cross sectional area, A_b is calculated as;

$A_b = \frac{\pi}{4}\left(d_{br}{}^2\right)n, \quad n = Number\ of\ blot$

$A_b = 2035.75mm^2$

Since $A_b > A_m$, the selected bolt is suitable. The actual bolt area exceeds the minimum required bolt area, this is because an integral number usually, a multiple of four is used.

Minimum gasket width is calculated as;

$N_{min} = \frac{A_b\sigma_b}{2\pi yG} = 3.168mm,$

$N > N_{min}$ ↠ Safe!

3.2.3.10. Design of flange

Flanges are used in the shell of a vessel, to permit disassembly and removal for cleaning of internal parts. Flanges are also used for making connections for piping and nozzle attachments of openings greater than 1.5inch nominal pipe size, (Lioyd E. Brownell, 1959).

Because of their simplicity or ease of fabrications, ring (loose type) flanges, are widely used, (Lioyd E. Brownell, 1959). Here also ring type of flange is used. As discussed above under *section 3.2.4.8*, the actual bolt area is in excess of minimum required area of the bolt. However these excessive bolt area results in overstressing of the flange in bolting up conditions. To provide a safety margins in such overstressing, the code specifies that the design load, W for bolting condition must be based on, the average of minimum, and actual bolting areas.

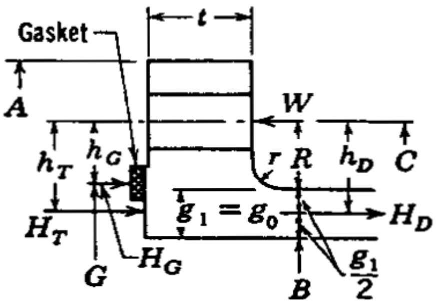


Figure 3-10: Flange forces and Moment arm

$$W = \left(\frac{A_m + A_b}{2}\right)\sigma_a \quad (28)$$

For operating conditions,

$$W = W_{m1} \quad (29)$$

Flange forces: (Lioyd E. Brownell, 1959)

Hydrostatic end force on the area inside of the flange;

$$H_D = 0.785B^2p \quad (30)$$

Pressure force on the flange;

$$H_T = H - H_D \quad (31)$$

Gasket load under operating condition;

$$H_G = W - H \quad (32)$$

For gasket seating condition;

$$H_G = W \quad (33)$$

Flange moment: (Lioyd E. Brownell, 1959)

Various axial forces acting on the flange creates a bending moment. The summation of moment is taken about the bolting axis.

$$M_o = M_D + M_T + M_G \quad (34)$$

For loose type flange, the flange directly bears on the gasket, the force H_D is considered to act on the inside diameter of the flange, and the gasket load at the center line of the gasket face. Therefore the lever arm for such flange is given by;

$$\left.\begin{aligned} h_D &= \frac{d_{bc} - B}{2} \\ h_G &= \frac{d_{bc} - G}{2} \\ h_T &= \frac{h_D + h_G}{2} \end{aligned}\right\} \quad (35)$$

Moment = Force x lever arm

$$\left.\begin{aligned} M_D &= H_D \times h_d \\ M_G &= H_G \times h_G \\ M_T &= H_T \times h_T \end{aligned}\right\} \quad (36)$$

The minimum flange thickness is calculated by;

$$t_f = \sqrt{(YM_{max})/(\sigma B)} \quad (37)$$

3.2.3.11. Flange design for shell - head connection of Reactor

Flange material is selected to be carbon steel (SA-285 C). The maximum allowable stress in SA-285 C, at 850^0F is 8,400psi (57.91MPa). The value of *B*, (the inside diameter of the flange, which is equal to the diameter of reactor vessel), is 324mm. The value of *A*, (**d_{bc} + 2*E*** - *See figure 3.10 and 3.11*), is 440mm, (Indian Standard (IS: 4864 to IS: 4870 -1968), 1993).

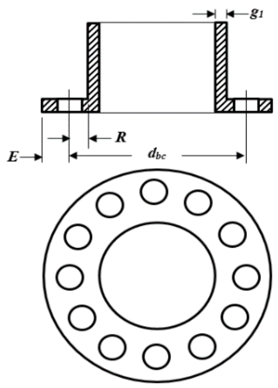


Figure 3-11: Reactor Flange

From equation (31), the load for bolting condition is found to be, *W* = 312,431.2N.

From equation (30), hydrostatic end force is found to be, H_D = 9184.78N

From equation (31), pressure force is found to be, H_T = 1,204.85N

From equation (32), gasket load under operation condition is found to be, H_G = 78,374.6N

From equation (35), lever arms are found to be, h_D = 35.5mm, h_G = 25.2mm, and h_T = 30.34mm

From equation (36), bending moment lever arms are found to be,

M_D = 326,059.69N-mm, M_G = 1,974,060.328N-mm, and M_T = 36,555.15N-mm

From equation (34), maximum bending moment is found to be, M_O = 2,336,675.078N-mm

For *A* = 440mm, and *B* = 324mm, *K* (i.e. A/B) = 1.35. From Appendix 1I, at *K* = 1.35, *Y* = 6.6

From equation (37), flange thickness found to be, *t* = 28.6mm

3.2.3.12. Flange design for shell - head connection of Condenser

Flange material is selected to be carbon steel (SA-285 C). The maximum allowable stress in SA-285 C, at 850^0F is 8,400psi (57.91MPa). The inside diameter of the flange, which is equal to the diameter of reactor vessel), is 125mm. The value of *A* is 240mm, (Appendix 1I).

From equation (28), the load for bolting condition is found to be, *W* = 68,247.22N.

From equation (30), hydrostatic end force is found to be, H_D = 1,367.1N

From equation (31), pressure force is found to be, H_T = 476.572N

From equation (32), gasket load under operation condition is found to be, H_G = 66,403.55N

From equation (35), lever arms are found to be,

h_D = 37.5mm, h_G = 27.44mm, and h_T = 32.468mm

From equation (36), bending moment lever arms are found to be,

M_D = 51,266.23N-mm, M_G = 1,822,113.412N-mm, and M_T = 15,473.34N-mm

From equation (34), maximum bending moment is found to be, M_O = 1,888,852.98N-mm

For *A* = 240mm, and *B* = 125mm, *K* (i.e. A/B) = 1.92. From Appendix 1J, at *K* = 1.92, *Y* = 3.2

From equation (37), flange thickness found to be, *t* = 28.5mm

CHAPTER FOUR

4. MATERIAL AND METHODS

4.1. Material and Tools

Once the analytical design of the research is completed, the next task is model development and testing. But to achieve this objective different materials are needed. This chapter discusses different materials and methods for component development and test.

4.1.1. Material

Materials that are used in this research includes

- Plate metals of different thickness
- Steel pipes of half inch
- Pipes (different diameter)
- Gate valves
- Bolt and nut
- Gasket

4.1.2. Tools

Tools that are used in this research includes

- Thermocouples
- Graduated Flask
- Cutting, rolling, drilling, and welding machines
- Electrodes
- Hammer
- Meter

4.2. Methodology

Here the methodologies used to construct components of entire research skeleton are discussed. In addition, test methodology and laboratory experiment method are discussed.

4.2.1. Construction methodology

Using the materials and tools mentioned under section 4.1.1 and 4.1.2, components of small scale plastic pyrolysis plant are constructed.

Reactor: The reactor shell is cylindrical in shape, with a flange welded at its top edge. The flange has 12 holes for the bolt connection. The bottom end of reactor shell is of elliptical in shape with a hole provided at the center for residue removal.

Similarly the reactor cover is elliptical in shape provided with a hole at the center to allow pyrolysis gas flow to the condenser. A flange having 12 holes is welded at the edge of cover. Thus the reactor cover also provided with small vent for thermocouple mounting.

*Condenser***:** Condenser shell, cover, and tube bundle are main constituents of the condenser. Condenser covers are used to direct the supply and the discharge of cooling water through tubes.

Condenser shell is made to handle tube bundle inside it, and is provided with two holes one as intake of pyrolysis gas and the other as discharge of condensate. At the top of discharge end a vent is provided, so that uncondensed gas is carried through it to the distillation for secondary condensation.

Tube bundle: is made of tubes and baffles arranged along the tube length at equal interval. Thus the tubes are used to carry the cooling water, and 25% segmental cut baffles are arranged one with the segmental cut at the top and the next with segmental cut at the bottom, so that the flow of pyrolysis gas becomes up and down. Such arrangement of the baffles gives the fluids enough time to exchange heat.

*Furnace***:** Furnace is made of brick wall with openings for oxygen supply. The need for using brick as a wall material is that, once it is heated the reactor will have long lasting heat source. This is because brick do have small thermal conductivity. Therefore the amount of heat lost to the surrounding is highly reduced, by which fuel cost is saved.

4.2.2. Test Methodology

Here under methodology followed while conducting a test pyrolysis for liquid fuel production from waste plastic are discussed. Decomposition of waste plastic in the reactor and condensing the pyrolysis gas obtained are the basic tasks that this research have gone through to come up with fuel from waste plastic.

4.2.2.1.Working Principle

Plastic waste collected from the Jimma town is categorized, cleaned, chopped into pieces, and fed in to the reactor heated with a heat from furnace. The condensation process is done in two stage. The primary condensation is done in shell and tube heat exchanger and the uncondensed gas from the heat exchanger is condensed in secondary condensation using distillation cooling. The decomposed pyrolysis gas is taken in to the condenser through a tube provided at the top of reactor. The condenser is made to be counter flow type shell and tube heat exchanger. Thus the pyrolysis gas is supplied into the condenser shell at one end, and condensate is discharged on the other end.

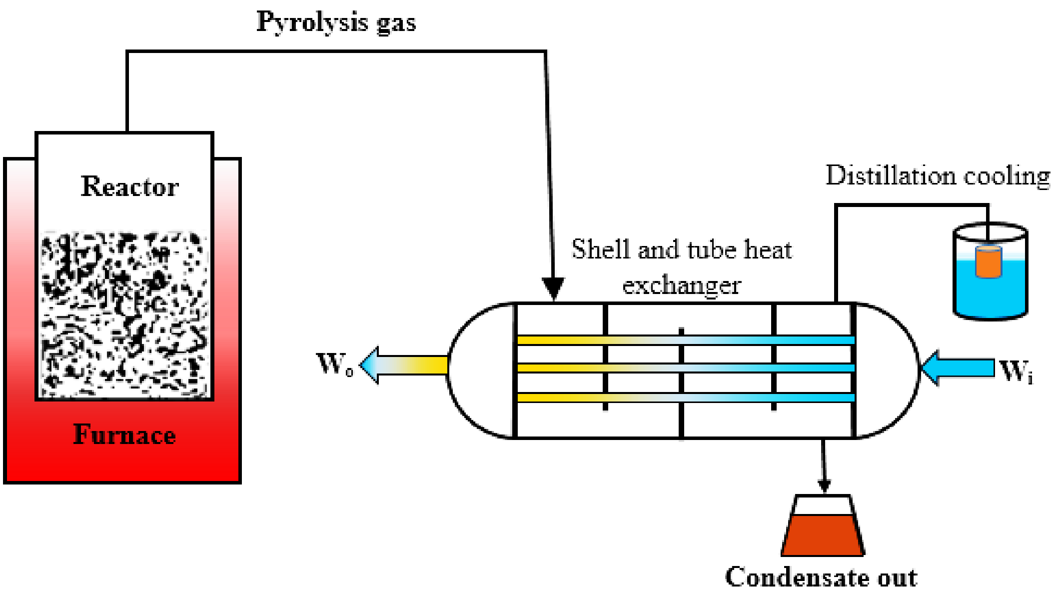


Figure 4-1: Schematic of small scale plastic pyrolysis plant

On the other hand cooling water is supplied through tubes from one end against flow direction of pyrolysis gas and discharged on the other end of the tube. A vent is provided in the top side of condensate discharge to carry uncondensed gas in to distillation cooling for secondary condensation. Once the thermal decomposition is over, the reactor is left for cooling. After some time, the residue is checked for solid fuel if any.

4.2.2.2.Test control

i. Temperature

Temperature is one of the factor that determine the state of fuel produced from pyrolysis of waste plastic. Therefore to analyze the pyrolysis products, the pyrolysis temperature must be known first. To do so K – type Thermocouple is used.

A thermocouple configuration, shown in Figure 4.2, consists of two wires of dissimilar metals joined together at one end, called the *measurement* ("hot") junction depicted by T_j. The other end, where the wires are not joined, is connected to the signal conditioning circuitry traces, typically made of copper, which is depicted by T_t.

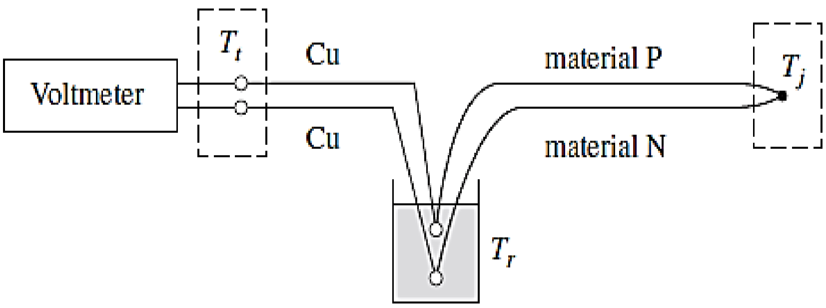


Figure 4-2: Schematic of temperature measurement using K- type Thermocouple

This junction between the thermocouple metals and the copper traces is called the *reference* ("cold") junction, T_r (Matthew Duff and Joseph, 2010). The voltage produced at the reference junction depends on the temperatures at both the measurement junction and the reference junction. Since the thermocouple is a differential device rather than an absolute temperature measurement device, the reference junction temperature must be known to get an accurate absolute temperature reading. This process is known as reference junction compensation (cold junction compensation).

Here the measurement junction is kept inside reactor, and the reference junction is created using ice bath. Copper wire is used as a wiring circuitry to the voltmeter. Thus the system temperature is obtained using the voltage reading in voltmeter. This is one method of cold junction compensation, and the other and most popular method is to identify the room temperature and add the Emf at that temperature to the voltmeter reading obtained at measurement junction.

For this research the second method is used to measure temperature at measurement junction. For temperature measurement using thermocouples, the voltage reading obtained using voltmeter should be converted to temperature. The room temperature while conducting the pyrolysis process is recorded. The Emf value at room temperature is obtained from Appendix 1L. This value is added to each voltmeter reading a time *t*. Finally using Appendix 1L, the pyrolysis temperature is obtained at the new voltmeter reading.

4.2.3.Fuel characterization method

The product of waste plastic pyrolysis could be either solid, liquid, or gaseous. Depending up on the pyrolysis product obtained, properties of the fuel is characterized. For liquid fuel products, the alcoholic content is determined by using Alcoholometer. For solid fuels obtained the proximate analysis is made by using Thermo gravimeter analyzer. In addition, the heating value of the fuels obtained, are tested according to ASTM D 5865, by using bomb calorimeter. Thus the heating value for char (solid residue) could also be calculated from the following relation (O.A. Sotannde et al., 2010).

$$HV = 2.326(147.6FC + 144V) \quad (38)$$

According to ASTM D445, Kinematic viscosity of liquid fuels are calculated from equations (39), as first formulated by Higgins (J. C. Cragg, 1943). Thus the sample is introduced in to viscometer and allowed to be heated to the test temperature inside the oil bath.

$$v_f = A.t - \frac{B}{t} \quad (39)$$

Where v_f stands for kinematic viscosity, t is saybolt time that is taken by the fluid to fill standard jar, A and B are constants equals to 0.0026 and 1.715. According ASTM D2161-19, 1mm^2/s is equals to 1centistroke.

Similarly the heating value for liquid fuels is calculated from equation (40), (Yasabie Abatneh, 2013).

$$HHV = 0.0137v_f + 38.053 \quad (40)$$

Where HHV stands for higher heating value, and v_f is kinematic viscosity of liquid fuels.

CHAPTER FIVE

5. MODEL DEVELOPMENT, MANUFACTURING AND TEST

5.1. Model Development

Model of each components are developed up on the designed dimensions. Solidworks 2016 x64 edition is used to model each components.

5.1.1. Reactor Shell

The reactor has two basic components. The reactor shell is one of these components, and designed with cylindrical shape.

D = *324mm*

h = *400mm*

t = *3mm*

The shell is modeled along with flange. The flange is designed to be bolted using M22.

Number of bolt = *12*

Bolt circle diameter = *395mm*

Outside diameter of the flange = *440mm*

Flange thickness = *14.3mm*

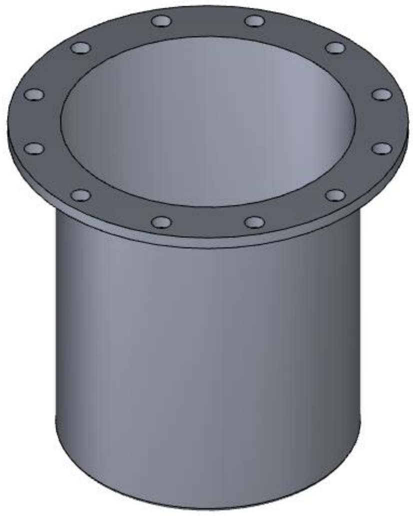


Figure 5-1: Reactor Shell

5.1.2. Reactor Head

The reactor head is the other basic component of the reactor, which is designed to be Torispherical shape. Thus the head is also designed along with flange. The flange here has dimensions similar to that of flange modeled with the reactor shell.

D = *324mm*

t = *6mm*

To allow pyrolysis gas into condenser, small opening is provided on the top center of the head. This opening is flanged with the pipe passage using the smaller flange shown in figure 5.7.

Bolt selection = *M10*.

Number of bolt = *4*

Bolt circle diameter = *130mm*

Outside diameter of the flange = 160*mm*

Figure 5-2: Reactor Cover

5.1.3. Condenser shell

Condenser shell is the basic component of heat exchanging medium, which encircles the tube bundles and baffles. Thus the hot side fluids enters at the left top side, and condensate is collected at the right bottom corner of the shell. The model shown on figure 5.3 is developed with the dimensions obtained from thermal and mechanical design.

Inside diameter of shell = *125mm*

Thickness = *3mm*

Length = *1800mm*

Inside diameter of inlet/outlet nozzle = *50.8mm*

The condenser shell is modeled along with the flange that is;

Flange type = *Flat ring*

Flange thickness = *14.3mm*

Outside diameter of flange = *240mm*

Bolt Specification = *M16*

Number of bolt = *8*

Root diameter of the bolt = *18mm*

Bolt circle diameter = *200mm*

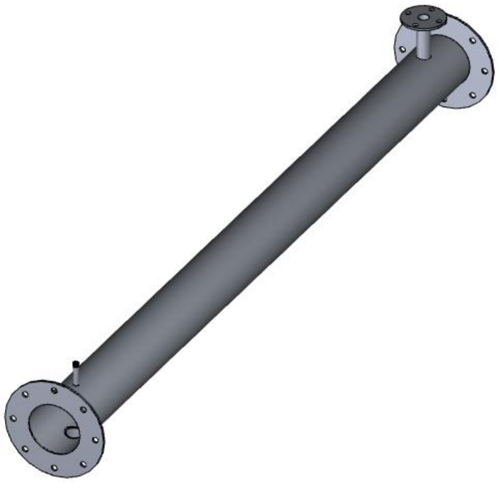


Figure 5-3: Condenser Shell

5.1.4. Condenser Cover

Condenser shell is covered at both end using condenser cover. The cover provides inlet/outlet flow of the cold side fluid. Since the condenser is selected to be counter concurrent, the cooling water is supplied from the right end and discharged at the left end cover.

Here also a flange that have similar dimension to that modeled with the condenser shell is modeled along with the covers at both end of the condenser.

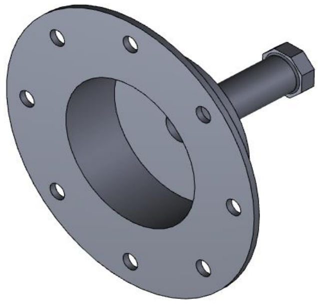


Figure 5-4: Condenser Cover

5.1.5. Tube bundle

The tube bundle is the other basic component of condenser. It is composed of a bunch of tubes through which cold side fluid flow.

Types of the tube = 16BWG

Outside diameter of the tube = 19.1mm

Thickness = *1.65mm*

Length = *1800mm*

Number of tubes = *8*

Tube bundle diameter = 98.3*mm*

Tube pitch = *24mm, (Square)*

Thus the tube bundle is modeled with the baffles. Baffles are used to hold the tubes together, and also used to create turbulence in the shell side flow.

Baffle type = *25% segmental cut*

Number of baffles = *37*

Baffle thickness = *5mm*

Baffle spacing = *37.5mm*

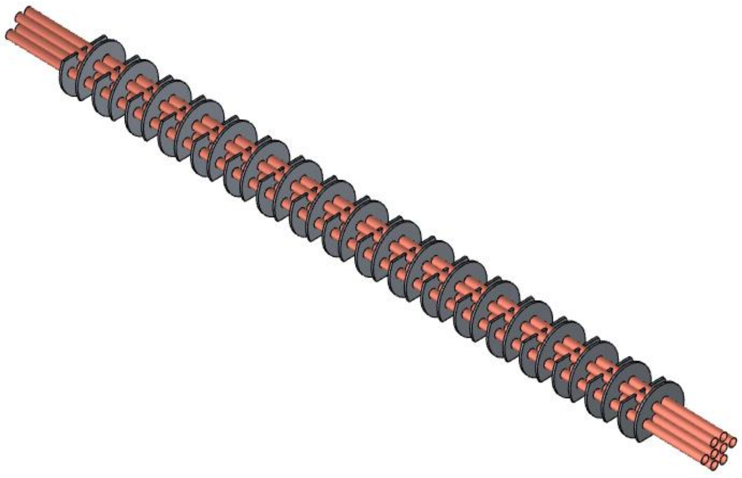


Figure 5-5: Tube Bundle

5.1.6. Connecting Tubes

Connecting tubes are used to carry pyrolysis gas from the reactor to the condenser, and also exchange cold fluids between the reservoir and condenser. These tubes are designed based on the flow rate of hot and cold fluids. Three tubes are connected one after the other to carry pyrolysis gas from reactor to condenser.

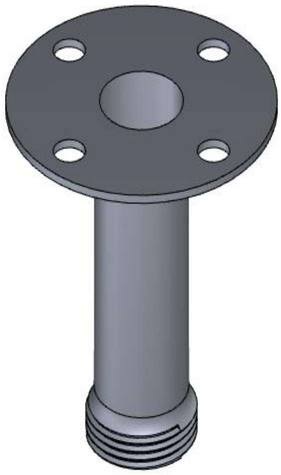


Figure 5-7: Socket Tube

Thus the tube system to carry pyrolysis gas is connected with reactor using a small socket tube shown in figure 5.7. The first is pyrolysis gas tube reactor end, which is shown in figure 5.6. There is bolt connection between socket tube and pyrolysis gas tube reactor end. The other is pyrolysis gas tube bend, shown in figure 5.8. Pyrolysis gas tube reactor end and pyrolysis gas tube bend are connected using elbow, shown in figure 5.9. The third tube is pyrolysis as tube condenser end, shown in figure 5.10. It is connected with condenser shell using bolt connection.

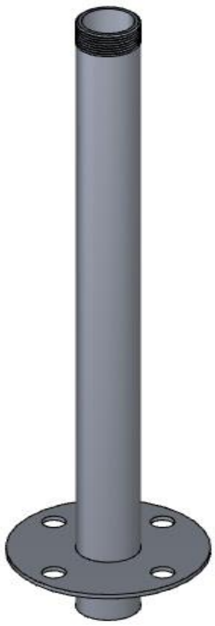


Figure 5-6: Pyrolysis gas tube Reactor end

Figure 5-8: Pyrolysis gas tube bend

Figure 5-9: Elbow

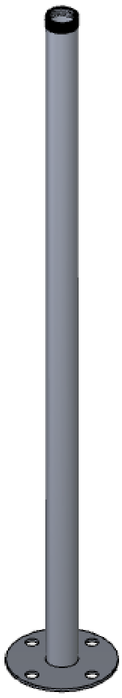


Figure 5-10: Pyrolysis gas tube Condenser

The pipe system to carry cooling water to and from condenser are modeled with right and left condenser covers respectively.

5.1.7. Furnace

The furnace is where the entire system get the heat supply. To come up with cost effective system, it is better to save fuel. The furnace wall is made of concentric sheet metal. The annulus is filled with sand. These is because, sand have small thermal conductivity. Therefore the heat generated from a unit mass of fuel will not be quickly dissipated from the furnace, rather it serve to heat the system. Due to such property, using sand as insulation material for the furnace enables us to save fuel cost.

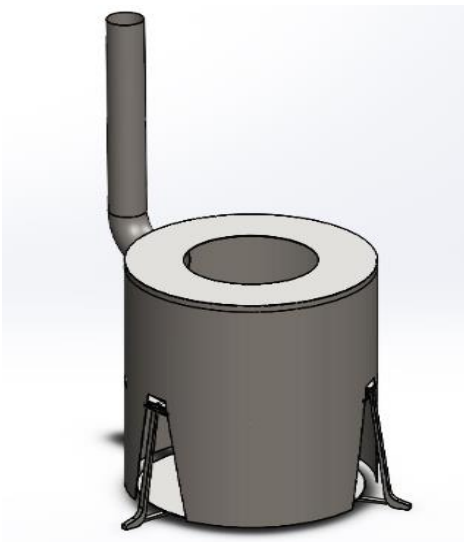


Figure 5-11: Furnace

The furnace is modeled in such a way that most portion of reactor wall can be kept inside it. With such arrangement the reactor could also be supplied with heat through its wall, and this enables us to achieve constant temperature operation early. For better heat flow, chimney is provided near the top of furnace.

5.1.8. Model assembly

Assembly of model components developed using Solidworks software is shown in figure 5.12.

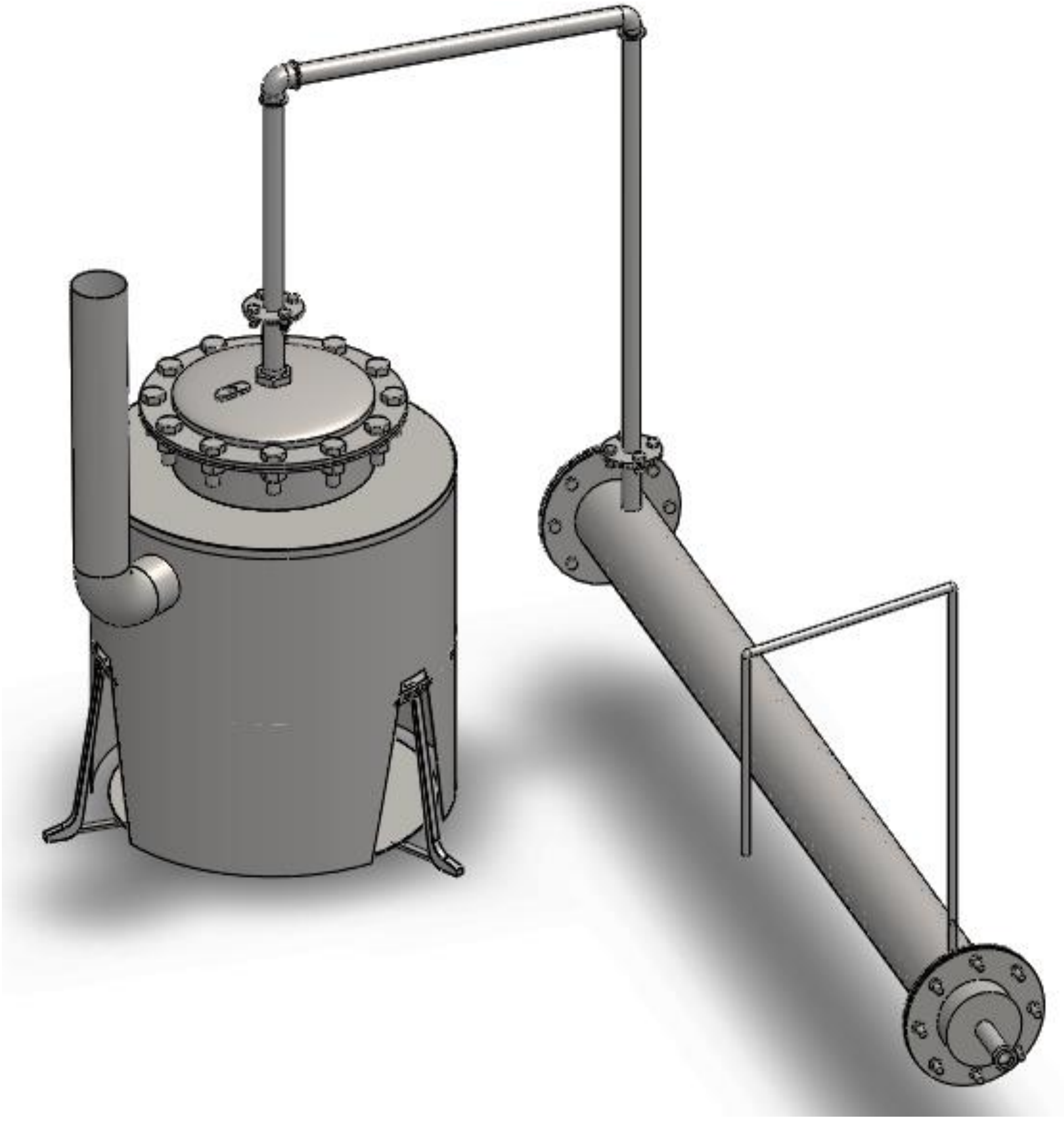


Figure 5-12: Assembly of model small scale plastic pyrolysis plant

5.2. Manufacturing of Model Components

Based on the designed dimension and software aided developed models, each of the model components are manufactured. Hereunder the sub assembly of basic system components are discussed. Reactor, condenser, tube bundle, connecting tube system, and furnace are the basic components of small scale plastic pyrolysis plant.

5.2.1. Reactor Assembly

Reactor is consisted of reactor shell, reactor cover and residue discharge pin. Figure 5.13 below shows the assembled reactor from fabricated components.

Threaded type temporary connection is used to mate the reactor shell with the residue discharge pin. Whereas bolted type temporary connection is used to couple the reactor shell with the reactor cover.

(Photo by Tesfahun Mesheha)

Figure 5-13: Fabricated Reactor

5.2.2. Condenser assembly

Condenser shell, condenser cover, and tube end support are the basic constituent of condenser. Figure 5.14 shows, the assembled condenser from fabricated components.

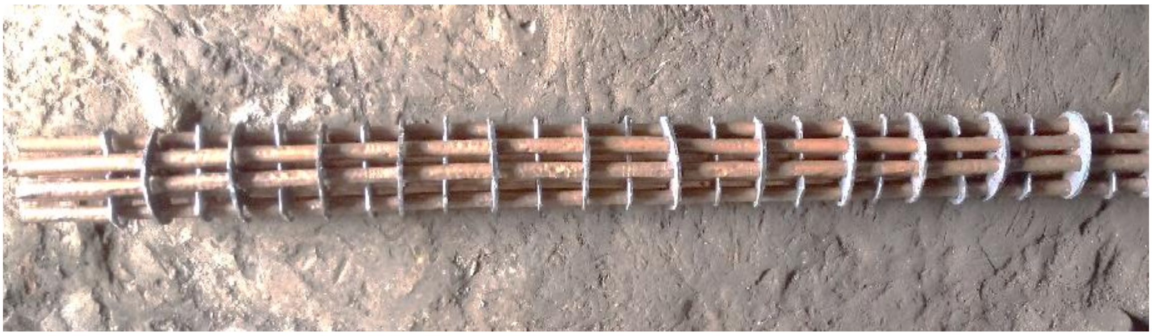
Condenser cover and tube end support are mounted at the right and left end of condenser shell. Condenser covers at the left and right side are respectively used to hold and direct the supply and discharge of cooling water. The two tube end supports are used to avoid mixing of the two fluid stream. Thus bolt connection is used to couple both condenser cover and tube end support to condenser shell.

(Photo by Tesfahun Mesheha)

Figure 5-14: Fabricated Condenser Assembly

5.2.3. Tube bundle

The two basic constituents of tube bundle are baffle and copper tube. As shown in Figure 5.15, there are 8 copper tubes hold together with the help of 36 baffles. There is a loose connection between the baffles and each tubes.



(Photo by Tesfahun Meshesha)

Figure 5-15: Fabricated tube Bundle

5.2.4. Connecting Tube system

Because the tubes for the supply and discharge of cooling water are welded with the condenser covers, connecting tube system here only refers to the tube series that carry pyrolysis gas from the reactor to condenser. The tube system is connected with reactor and condenser using bolt connection. Similarly tube series in the tube system are connected using threaded connection.

(Photo by Tesfahun Meshesha)

Figure 5-16: Connecting Tube

5.2.5. Furnace

Furnace is constructed to have combustion chamber and chimney as basic components. Since it is built in such a way that the reactor shell wall is submerged in the chamber, chimney is provided at the top end of the furnace wall to discharge smoke.

(Photo by Tesfahun Meshesha)

Figure 5-17: Furnace assembly

5.2.6. Overall assembly

Finally the assembly of all the components manufactured is shown in figure 5.18 below.

(Photo by Tesfahun Meshesha)

Figure 5-18: Assembled small scale plastic pyrolysis plant for manufactured components

5.3. Testing

5.3.1. Test for PET

PET as a waste plastic will be collected, cleaned and shredded before supplied to the reactor. Condensation for Pyrolysis of PET is designed to be made in two stage, the primary condensation in heat exchanger and secondary condensation in distillation cooling. In order

(Photo by Tesfahun Meshesha)

Figure 5-19: Preparation of PET

to conduct the primary cooling we need a pump to circulate the cooling water. After design, modelling and manufacturing of shell and tube heat exchanger for the purpose of primary condensation, it is not possible to find a pump and conducted the condensation of pyrolysis gas using only distillation cooling. To conduct a pyrolysis test for PET, a total of 5kg PET have been supplied in to the pyrolysis reactor for decomposition. As sown in figure 5.19, PET as a waste plastic will be collected, cleaned and shredded before supplied to the reactor. Figure 5.20 below shows the setup for the test pyrolysis of PET.

(Photo by Tesfahun Meshesha)

Figure 5-20: Pyrolysis setup for PET

5.3.2. Proximate Analysis

Proximate analysis is used to determine the proximate composition of a certain solid fuels. Thus the proximate composition includes,

Moisture content: it is the water vapor that is released up on heating the sample inside oven for 2 to 3hour at 105^{0}C.

Volatile matter: is the constituent of the fuel that is released up on heating the sample in oxygen free system for 7 minutes at 950^{0}C.

Ash content: is the amount that is left heating the sample in oxygenated environment at 600 to 900^{0}C.

Fixed carbon: is difference between initial sample weight and weight of moisture content, volatile matter, and ash content.

For its ability to record weight as the sample is heated over a temperature range, and changing the samples environmental atmosphere from inert to oxidizing, proximate analysis is done by using PerkinElmer STA 4000, simultaneous thermal analyzer. Figure 5.23 shows laboratory setup used for proximate analysis.

Photo by: Tesfahun Meshesha

Figure 5-21: Laboratory setup for proximate analysis using PerkinElmer STA 4000

Fine grained solid fuel is added to a crucible and weighs 35.408mg. The analysis is set to be heated at inert gas atmosphere from 30^0C to 800^0C, and oxidizing atmosphere between 800^0C and 900^0C. Throughout the process, heating rate is 40^0C/min.

5.3.3. Measuring heating value

To check the heating value of fuels obtained from pyrolysis of waste plastic materials, calorimeter is used. Figure below shows laboratory set up to check the heating value of solid and liquid fuels.

As shown in figure 5.22(right), 1gram of fuel is held in the crucible and sealed in a combustion chamber. The chamber is filled with oxygen at 30bar, and immersed in a bucket filled with 2liter of water. Before combustion, temperature of water in the bucket is always equals to room temperature. Immediately after combustion, bucket temperature increase because of heat inside combustion chamber. Thus the temperature increase must be 2.5 to 3.5^{0}C. If the temperature increase is not within this range, accurate heating value can't be obtained.

(Photo by Tesfahun Meshesha)

Figure 5-22: Bomb Calorimeter

5.3.4.Alcoholic Strength of liquid fuel

Alcoholic strength refers to the alcoholic content of liquid fuels. The tendency of a fuel to combust is directly related with the alcoholic strength. For any liquid fuels obtained here, the alcoholic strength is measured using Alcoholometer. Before using the Alcoholometer, it has been calibrated by using Ethanol of 97% alcoholic content.

Photo by: Tesfahun Meshesha

Figure 5-23: Alcoholometer

As suggested by ASTM D445, The viscosity of the liquid fuel was measured by utilizing the Saybolt - Redwood viscometer coupled with equation (39).

The liquid fuel along with its container is submerged in a standard oil bath to be heated to the required temperature, then the liquid fuel is allowed to flow, and the time taken to fill 60ml glass jar is recorded. Thus the time required to fill 60mml glass jar is 6second.

Figure 5-24: Viscometer

CHAPTER SIX

6. RESULT AND DISCUSSION

6.1. Criterion

A quality gasoline fuels to be used for different application has lower heating value of 43.3MJ/kg and density of 735kg/m^3 at 15^{0}C (Jhon Bacha, 2007). Similarly chars obtained from pyrolysis of waste plastic has a heating value of 18.83MJ/kg and density of 1.59g/cm^3 (Jindaporn Jamradloedluck, 2014).

6.2. PET

At the beginning of pyrolysis the reactor is loaded with 5kg of PET plastic waste. The decomposition takes place for 3hours. As shown in figure 6.1 a) and b), 350ml liquid fuel and 3.0105kg of char is obtained.

(Photo by Tesfahun Meshesha)

a) b)

Figure 6.1: Pyrolysis products for PET

The room temperature while conducting pyrolysis of PET is 30^{0}C. Thus at the start of pyrolysis temperature is the same to the environmental temperature. As heat is supplied, the temperature inside reactor increase with time.

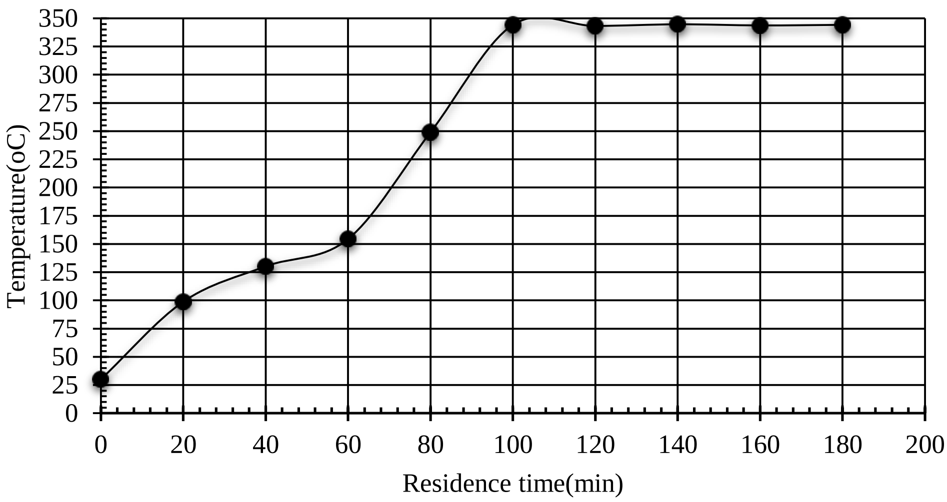


Figure 6.2: Temperature gradient for pyrolysis of PET

Figure 6.2 shows that the maximum temperature of reactor is achieved after constantly heating the system for100min. Thus the decomposition temperature remain varying between 343.24^{0}C and 344.73^{0}C.

6.3. Fuel Characterization

Up on pyrolysis of PET, liquid and solid fuel are obtained. Thus the liquid fuel is analyzed for its alcoholic content, and it is 88% alcoholic by volume. Up on the use of laboratory setup shown in figure 5.22, the calorific value of liquid fuel from PET is 38.2MJ/Kg.

Table 6-1: Comparison between characteristics of liquid fuel from pyrolysis of PET and conventional fuel

Property	PET	Gasoline
Calorific value, (MJ/kg)	37.86 (*)	45.6 (**)
Viscosity @ 40°C, (mm^2/s)	2.7 (*)	0.6 (***)

*(This research) ** (Ramli Thahir, 2019) *** (www.geotechenv.com - July 24 /2020)

According to equation (3), the heating value of liquid fuel obtained from pyrolysis of waste PET is found to be 38.1MJ.kg^{-1}

Proximate analysis is made for the solid fuel using laboratory setup shown in figure 5.21. In figure 6.3, black line represents percent weight loss as the temperature increase. From this graph we can read the percent weight of moisture content, volatile matter, fixed carbon, and ash content of the fuel.

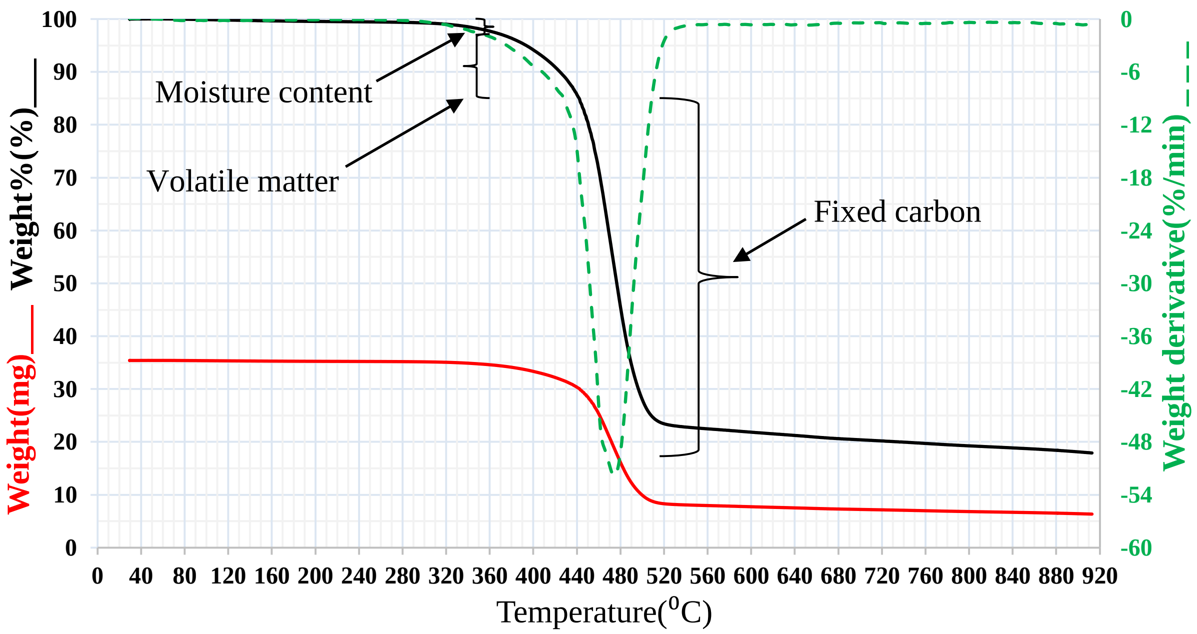


Figure 6.3: Weight loss with temperature

There are three weight loss phase, the first is loss of moisture content. Thus 1.99%wt is the weight of moisture content.

The next percent weight loss due to release of volatile matter. Volatile matter is the weight which is released up on heating the fuel in oxygen deficient environment. In other word volatile matter stands for pyrolysis gas. Since the solid fuel for which this proximate analysis being conducted is obtained by decomposing polymers and condensing the pyrolysis gas, the solid fuel left will not have much volatile matter. Thus the volatile matter of the fuel is found to be 13.01%wt.

Once the moisture content and volatile matters are released, the proximate component to be released next is the fixed carbon. After releasing fixed carbon, finally we left with ash content. As shown in the graph ash content of this fuel is equal to 17.904%wt.

Since carbon content is mass difference between total sample and moisture content, ash content, and volatile matter, carbon content of solid fuel is equal to 67.096%wt. Derivative weight loss shows the point at which maximum weight lost occurs. From the graph, 474.27^{0}C is the point at which maximum weight is lost.

From laboratory setup shown in Figure 5.22, calorific value of solid fuel is found to be 25.887MJ.kg^{-1}. According to equation (1), the calorific value of solid fuel becomes 27.39MJ.kg^{-1}.

Table 6-2: Comparison between characteristics of char obtained from pyrolysis of PET, waste plastic, and Coffee Husk

Property	PET(*)	Waste plastic(**)	Coffee husk(***)
Proximate analysis(%wt)			
◦ Moisture content	1.99	2.41 ± 0.36	6.3 ± 0.5
◦ Volatile matter	13.01	51.40 ± 0.28	22.97 ± 3.42
◦ Fixed Carbon	67.096	46.03 ± 0.32	58.33 ± 2.605
◦ Ash Content	17.04	0.16 ±0.23	12.33 ± 1.1
Calorific value(MJ/Kg)	25.887	18.829	21.1

* (This research)   ** (Jindaporn Jamradloedluck, 2014)   *** (Esayas Alemayehu, 2014)

6.4. Conversion Efficiency

Out of 5kg of PET fed in to the reactor for pyrolysis, 350ml of liquid fuel and 3.0109kg of solid char is produced. The energy content of liquid fuel is 37.86MJ.kg^{-1}, and the energy content of solid char is 25.887MJ.kg^{-1}. Thus a total of 87.67323MJ of energy is produced.

Energy required for the pyrolysis of 1kg of polyethylene is equals to 1.0476MJ.kg^{-1}, (Feng, 2010). For the pyrolysis of 5kg PET, 5.238MJ of energy will be consumed.

For the actual test pyrolysis of this research, 2.5kg charcoal made from soft wood having HHV 23.6MJ.kg^{-1} is used. Therefore a total of 59MJ of energy is consumed to produce 87.67323MJ energy. Thus the conversion efficiency of the pyrolysis looks positive and productive, but more can be produced by using more confined heating system which can reduce fuel consumption.

CONCLUSION

Design, modelling, manufacturing, and testing are the specific objectives set to be accomplished in this research. Up on the accomplishment of these specific objectives, it is expected to extract some useful fuels from waste plastic materials. The general working principles behind achieving these goal are thermal decomposition of plastic materials inside reactor, and condensation of pyrolysis gas obtained in two stage, primary condensation in shell and tube heat exchanger and secondary condensation in distillation cooling.

In primary condensation, pyrolysis gas is allowed to flow in the shell side and cooling water is selected to be tube side fluid stream. Thus to circulate cooling water, pump is required. Due to lack of water pump, condensation of pyrolysis gas is done only using secondary condensation.

For the test purpose, 5kg PET are the sample waste plastics materials used. Conducting the test separately, Out of 5kg of PET, 350ml liquid fuel and 3.0109kg solid fuel is obtained from pyrolysis of PET. Proximate analysis of solid fuel shows that it have fixed carbon content 67.096%wt. This result implies that solid fuels obtained from pyrolysis of PET comparatively have a good carbon content comparable to that of wood charcoal produced from wood species named Kautaballi using earth kiln, which is 65.6%wt (FAO, 1985). In addition, the solid fuel obtained from pyrolysis of PET have calorific value of 25.887$MJ.kg^{-1}$. This result reveals that solid fuel from waste plastic have higher heating value than coffee husk briquette which is 21.1$MJ.kg^{-1}$ (Esayas Alemayehu, 2014). Similarly liquid fuels obtained from pyrolysis of PET have heating value of 37.86 $MJ.kg^{-1}$.

Thus from test pyrolysis using PET as a feedstock 87.67323MJ of energy is produced by using 59MJ of fuel energy.

RECOMMENDATION

Based on the result obtained in this research, the following recommendations are made to aid fellow researchers get better result in the future on this and related topics.

- Leakage of tube side flow is one of the problem encountered during testing of the system components. So it is better to fabricate the flanges on the shell to cover connecter of shell and tube heat exchanger using casting.
- Once the plastic feedstock melt and if any temperature drop happens for a while, the plastic gel will start to be baked. This will creates a barrier to the gases from reaching condenser. In addition to the purpose of creating uniform temperature inside reactor, a stirrer allows free flow of pyrolysis gas. So it is highly recommended to use a stirrer inside reactor.
- For a better heat transfer rate, shell and tube heat exchangers should be used with a fluids of less fouling tendency. Since higher amount of tar is created from pyrolysis of PET, distillation cooling is preferable during pyrolysis of PET.
- For the applicability of this research in rural areas, a mechanism by which cooling system circulates water naturally by gravity should be developed.
- The chemical composition of liquid fuels produced from plastic pyrolysis is not known, therefore ultimate analysis should be done before consuming.
- The solid fuel produced from the pyrolysis of PET can also be used as alternative to asphalt bitumen.

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APPENDIX ONE

Tables and Graphs

A. Typical heat transfer coefficients in tubular heat exchangers

U = Btu/(°F · ft² · h)

Shell side	Tube side	Design U	Includes total dirt
Liquid-liquid media			
Aroclor 1248	Jet fuels	100–150	0.0015
Cutback asphalt	Water	10–20	.01
Demineralized water	Water	300–500	.001
Ethanol amine (MEA or DEA) 10–25% solutions	Water or DEA, or MEA solutions	140–200	.003
Fuel oil	Water	15–25	.007
Fuel oil	Oil	10–15	.008
Gasoline	Water	60–100	.003
Heavy oils	Heavy oils	10–40	.004
Heavy oils	Water	15–50	.005
Hydrogen-rich reformer stream	Hydrogen-rich reformer stream	90–120	.002
Kerosene or gas oil	Water	25–50	.005
Kerosene or gas oil	Oil	20–35	.005
Kerosene or jet fuels	Trichlorethylene	40–50	.0015
Jacket water	Water	230–300	.002
Lube oil (low viscosity)	Water	25–50	.002
Lube oil (high viscosity)	Water	40–80	.003
Lube oil	Oil	11–20	.006
Naphtha	Water	50–70	.005
Naphtha	Oil	25–35	.005
Organic solvents	Water	50–150	.003
Organic solvents	Brine	35–90	.003
Organic solvents	Organic solvents	20–60	.002
Tall oil derivatives, vegetable oil, etc.	Water	20–50	.004
Water	Caustic soda solutions (10–30%)	100–250	.003
Water	Water	200–250	.003
Wax distillate	Water	15–25	.005
Wax distillate	Oil	13–23	.005
Condensing vapor-liquid media			
Alcohol vapor	Water	100–200	.002
Asphalt (450°F.)	Dowtherm vapor	40–60	.006
Dowtherm vapor	Tall oil and derivatives	60–80	.004

Shell side	Tube side	Design U	Includes total dirt
Dowtherm vapor	Dowtherm liquid	80–120	.0015
Gas-plant tar	Steam	40–50	.0055
High-boiling hydrocarbons V	Water	20–50	.003
Low-boiling hydrocarbons A	Water	80–200	.003
Hydrocarbon vapors (partial condenser)	Oil	25–40	.004
Organic solvents A	Water	100–200	.003
Organic solvents high NC, A	Water or brine	20–60	.003
Organic solvents low NC, V	Water or brine	50–120	.003
Kerosene	Water	30–65	.004
Kerosene	Oil	20–30	.005
Naphtha	Water	50–75	.005
Naphtha	Oil	20–30	.005
Stabilizer reflux vapors	Water	80–120	.003
Steam	Feed water	400–1000	.0005
Steam	No. 6 fuel oil	15–25	.0055
Steam	No. 2 fuel oil	60–90	.0025
Sulfur dioxide	Water	150–200	.003
Tall-oil derivatives, vegetable oils (vapor)	Water	20–50	.004
Water	Aromatic vapor-stream azeotrope	40–80	.005
Gas-liquid media			
Air, N_2, etc. (compressed)	Water or brine	40–80	.005
Air, N_2, etc., A	Water or brine	10–50	.005
Water or brine	Air, N_2 (compressed)	20–40	.005
Water or brine	Air, N_2, etc., A	5–20	.005
Water	Hydrogen containing natural-gas mixtures	80–125	.003
Vaporizers			
Anhydrous ammonia	Steam condensing	150–300	.0015
Chlorine	Steam condensing	150–300	.0015
Chlorine	Light heat-transfer oil	40–60	.0015
Propane, butane, etc.	Steam condensing	200–300	.0015
Water	Steam condensing	250–400	.0015

NC = noncondensable gas present.
V = vacuum.
A = atmospheric pressure.
Dirt (or fouling factor) units are (h · ft² · °F)/Btu.
To convert British thermal units per hour-square foot-degrees Fahrenheit to joules per square meter-second-kelvins, multiply by 5.6783; to convert hours per square foot-degree Fahrenheit-British thermal units to square meters per second-kelvin-joules, multiply by 0.1761.

B. Constants *a* and *b* to be used with equation 7

Table 9.13. Constants for use with equation 9.211.

Number of passes		1	2	4	6	8
Triangular pitch*	a	0.319	0.249	0.175	0.0743	0.0365
	b	2.142	2.207	2.285	2.499	2.675
Square pitch*	a	0.215	0.156	0.158	0.0402	0.0331
	b	2.207	2.291	2.263	1.617	2.643

*Pitch = $1.25d_o$

C. Graph to find clearance between tube bundle and shell inside diameter

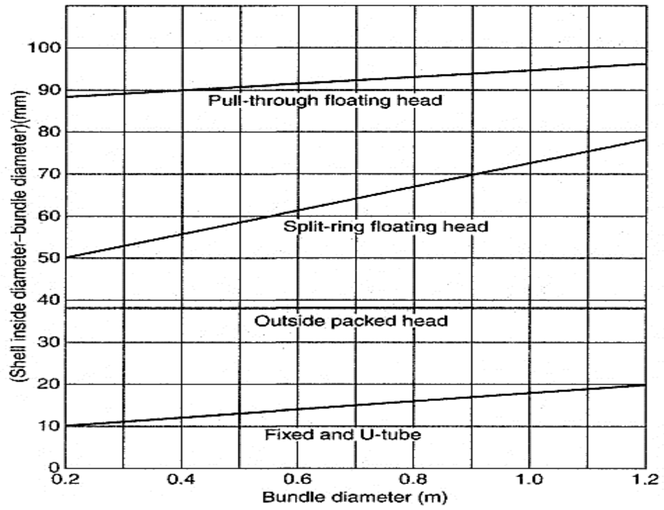
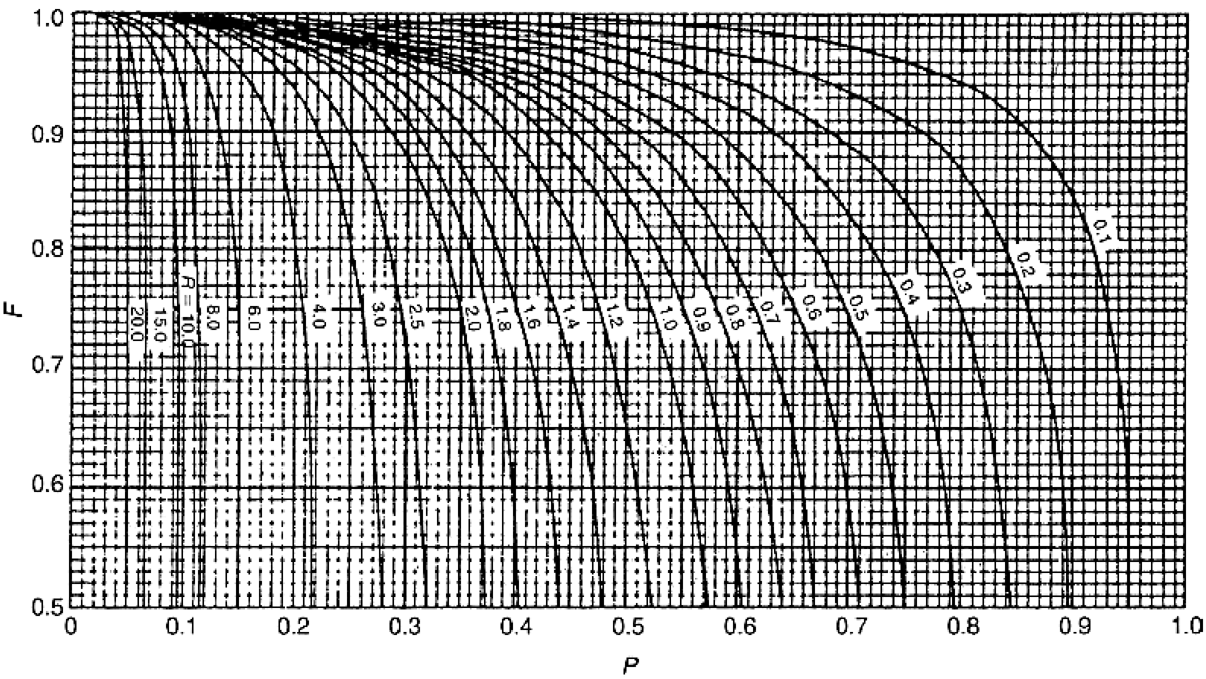
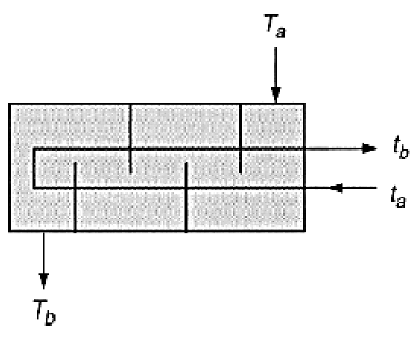


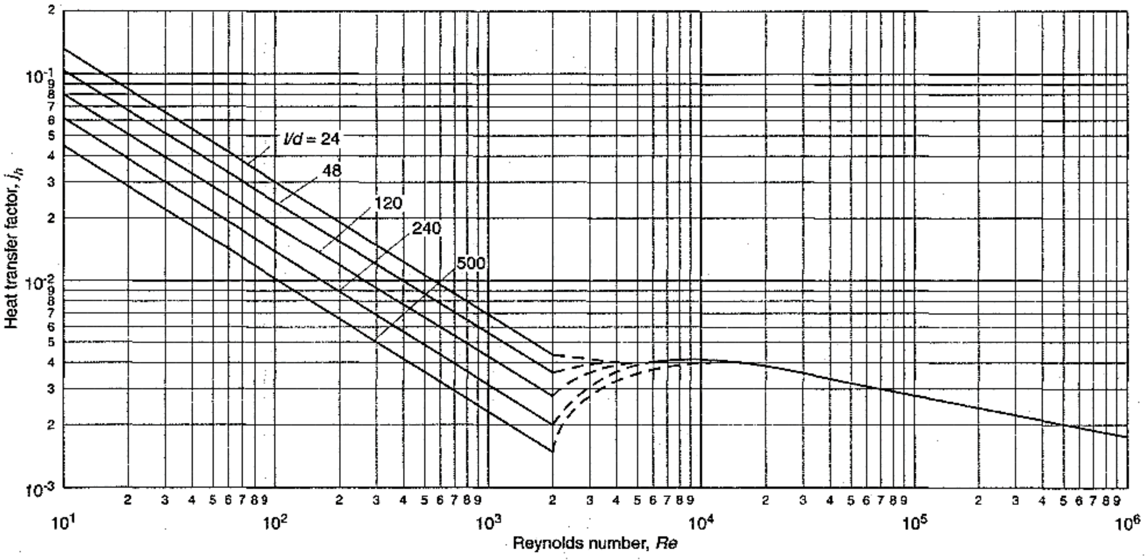
Figure 9.68. Shell-bundle clearance

D. Graph to find correction factor for logarithmic mean temperature difference

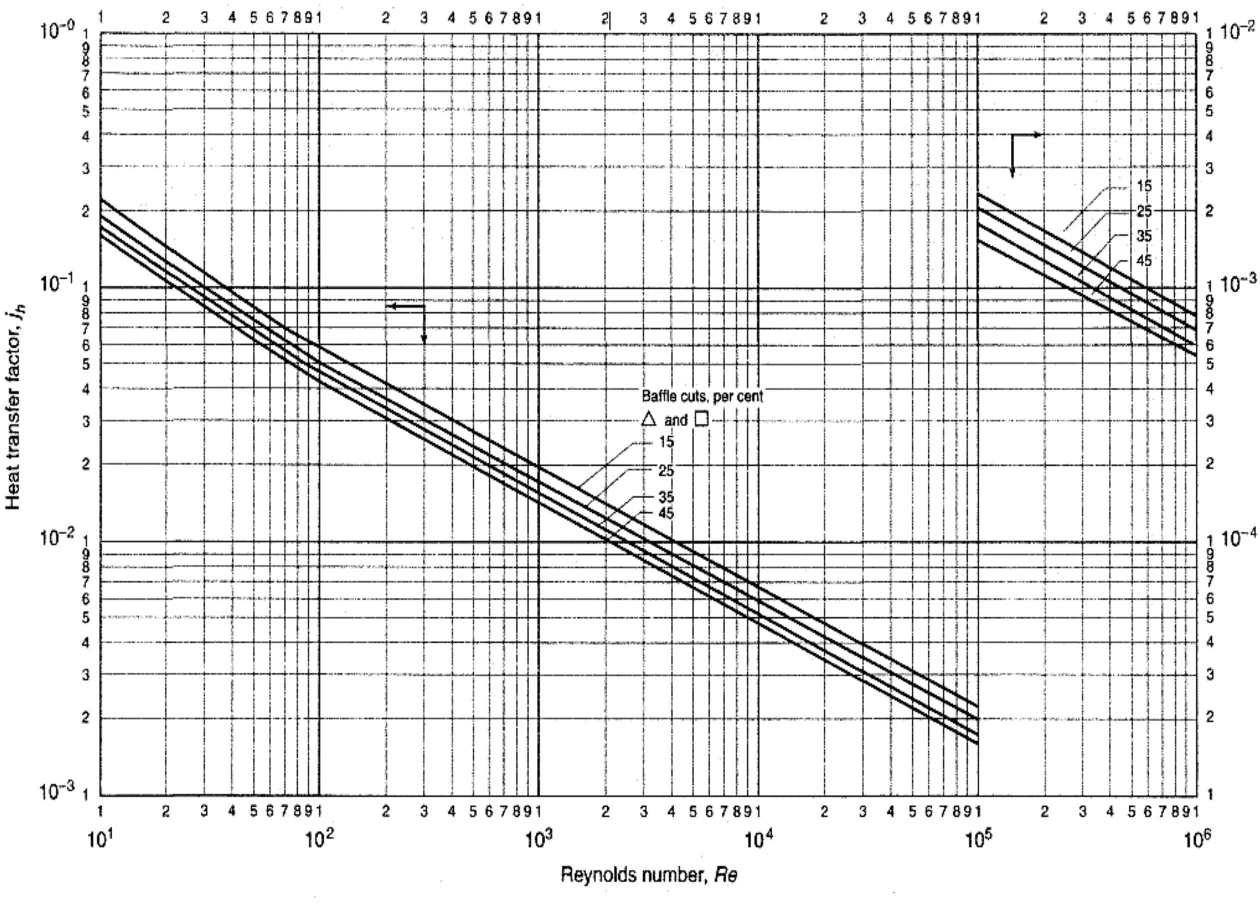




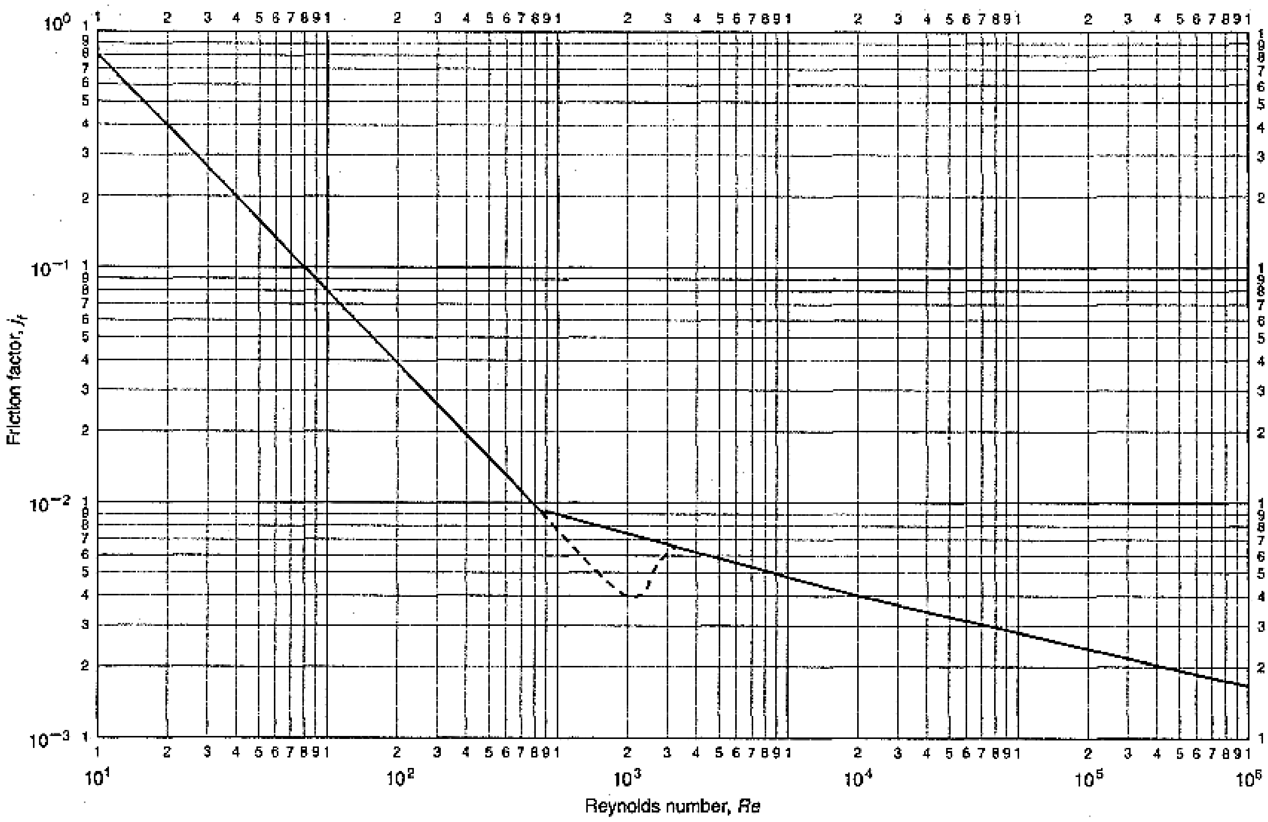
E. Heat transfer factor for flow inside tubes



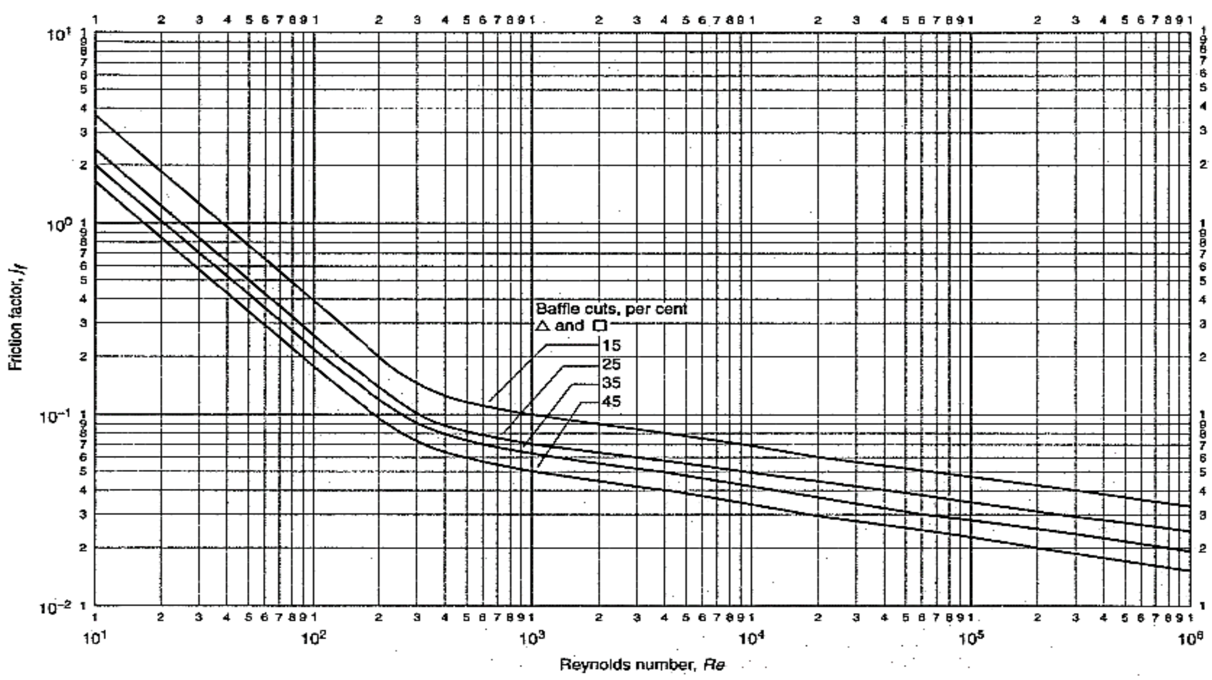
F. Heat transfer factor with segmental baffles



G. Tube side friction factor



H. Shell side friction factor with segmental baffles



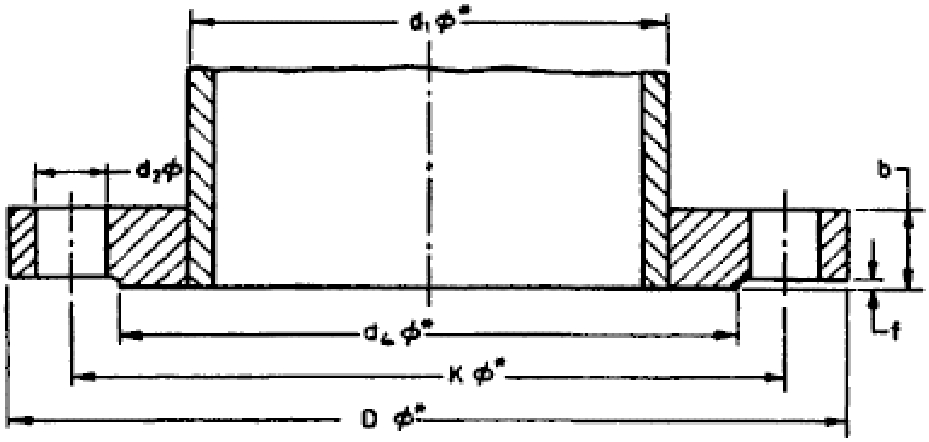
I. Indian Standard - Flange dimensions

TABLE 5 PLATE FLANGES FOR WELDING

(*Clauses* 4.1 *and* 5.1)

Nominal pressure 0·60 N/mm².

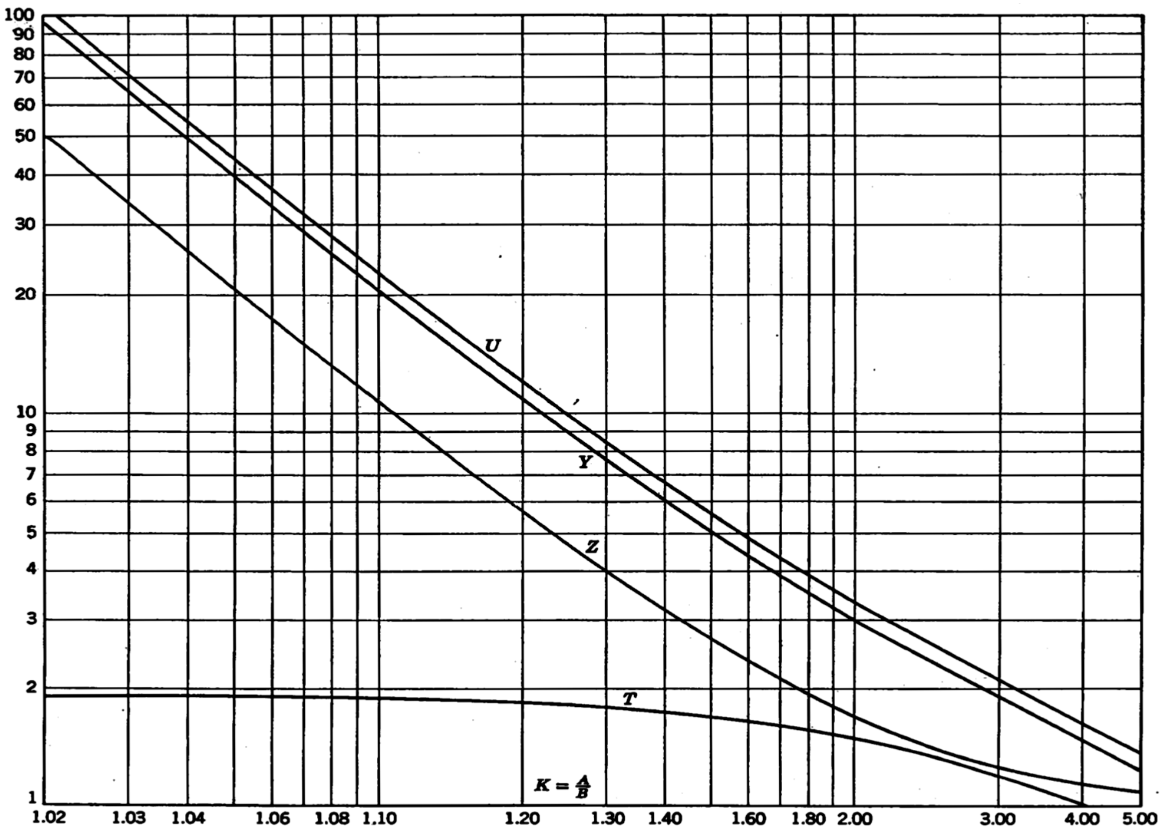
All dimensions in millimetres.



*These dimensions are not to scale.

Nom Size	Pipe o. d. d_1	Flange D	Flange b	Raised Face d_4	Raised Face f	Bolting	Drilling No.	Drilling d_2	Drilling k
10	17·2	75	12	35	2	M10	4	11	50
15	21·3	80	12	40	2	M10	4	11	55
20	26·9	90	14	50	2	M10	4	11	65
25	33·7	100	14	60	2	M10	4	11	75
32	42·4	120	16	70	2	M12	4	14	90
40	48·3	130	16	80	3	M12	4	14	100
50	60·3	140	16	90	3	M12	4	14	110
65	76·1	160	16	110	3	M12	4	14	130
80	88·9	190	18	120	3	M16	4	18	150
100	114·3	210	18	148	3	M16	4	18	170
125	139·7	240	20	178	3	M16	8	18	200
150	168·3	265	20	202	3	M16	8	18	225
200	219·1	320	22	258	3	M16	8	18	280
250	273	375	24	312	3	M16	12	18	335
300	323·9	440	24	365	4	M20	12	22	395
350	355·6	493	26	415	4	M20	12	22	445
400	406·4	540	28	465	4	M20	16	22	495
500	508	645	30	570	4	M20	20	22	600
600	609·6	755	32	670	5	M24	20	26	705
700	711·2	860	34	775	5	M24	24	26	810
800	812·8	975	38	880	5	M27	24	30	920
900	914·4	1 075	42	980	5	M27	24	30	1 020
1 000	1 016	1 175	46	1 080	5	M27	28	30	1 120
1 200	1 220	1 405	56	1 295	5	M30	32	33	1 340
1 400	1 420	1 630	66	1 510	5	M33	36	36	1 560
1 600	1 620	1 830	74	1 710	5	M33	40	36	1 760
1 800	1 820	2 045	84	1 920	5	M36	44	39	1 970
2 000	2 020	2 265	92	2 125	5	M39	48	42	2 180

J. Constants to be used with equation 37



K. Thermodynamic property of saturated ethylene

TABLE 2-257 Saturated Ethylene (Ethene—R1150)

Temperature, K	Pressure, bar	v_f, m³/kg	v_g, m³/kg	h_f, kJ/kg	h_g, kJ/kg	s_f, kJ/(kg·K)	s_g, kJ/(kg·K)	c_{pf}, kJ/(kg·K)
104.0[t]	0.00123	0.001 527	251.36	−323.81	244.36	−1.9901	3.4730	2.497
110	0.00334	0.001 545	97.57	−309.54	251.47	−1.8571	3.2431	2.500
120	0.01380	0.001 576	25.75	−284.17	263.23	−1.6362	2.9255	2.539
130	0.04456	0.001 609	8.62	−259.13	274.87	−1.4358	2.6717	2.465
140	0.1191	0.001 644	3.46	−234.80	286.28	−1.2554	2.4663	2.405
150	0.2747	0.001 681	1.5977	−210.90	297.37	−1.0908	2.2977	2.377
160	0.5636	0.001 721	0.8232	−187.12	308.00	−0.9378	2.1566	2.377
170	1.0526	0.001 763	0.4625	−163.23	318.04	−0.7935	2.0375	2.395
180	1.8207	0.001 810	0.2784	−139.05	327.35	−0.6559	1.9352	2.427
190	2.9574	0.001 861	0.1770	−114.46	335.79	−0.5244	1.7812	2.472
200	4.560	0.001 918	0.1177	−89.33	343.21	−0.3967	1.7659	2.531
210	6.730	0.001 981	0.0810	−63.52	349.41	−0.2730	1.6932	2.608
220	9.575	0.002 054	0.0573	−36.84	354.18	−0.1515	1.6258	2.711
230	13.206	0.002 139	0.0413	−9.04	357.17	−0.0314	1.5609	2.852
240	17.742	0.002 241	0.0302	20.23	357.90	0.0088	1.4957	3.055
250	23.307	0.002 369	0.02222	51.55	355.37	0.2114	1.4276	3.372
260	30.046	0.002 541	0.01624	85.91	348.68	0.3397	1.3503	3.945
270	38.132	0.002 804	0.01152	125.79	333.71	0.4819	1.3054	5.40
280	47.834	0.003 442	0.00720	183.40	292.83	0.6803	1.0711	20.0
282.3[c]	50.403	0.004 669	0.00467	234.55	234.55	0.8585	0.8585	

t = triple point; c = critical point. $h_f = s_f = 0$ at 233.15 K = −40°C.

L. K - type thermocouple Tables

Type K Thermocouple Table

Nickel-Chromium/Nickel-Aluminium, Electromotive Force as a function of temperature, E/µV
As per Standard ASTM E231

t90/°C	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	t90/°C
-270	-6458										-270
-260	-6441	-6444	-6446	-6448	-6450	-5452	-6453	-6455	-6456	-6457	-260
-250	-6404	-6408	-6413	-6417	-6421	-5425	-6429	-6432	-6435	-6438	-250
-240	-6344	-6351	-6358	-6364	-6370	-6377	-6382	-6388	-6393	-6399	-240
-230	-6262	-6271	-6280	-6289	-6297	-6306	-6314	-6322	-6329	-6337	-230
-220	-6158	-6170	-6181	-6192	-6202	-6213	-6223	-6233	-6243	-6252	-220
-210	-6035	-6048	-6061	-6074	-6087	-6099	-6111	-6123	-6135	-6147	-210
-200	-5891	-5907	-5922	-5936	-5951	-5965	-5980	-5994	-6007	-6021	-200
-190	-5730	-5747	-5763	-5780	-5797	-5813	-5829	-5845	-5861	-5876	-190
-180	-5550	-5569	-5588	-5606	-5624	-5642	-5660	-5678	-5695	-5713	-180
-170	-5354	-5374	-5395	-5415	-5435	-5454	-5474	-5493	-5512	-5531	-170
-160	-5141	-5163	-5185	-5207	-5228	-5250	-5271	-5292	-5313	-5333	-160
-150	-4913	-4936	-4960	-4983	-5006	-5029	-5052	-5074	-5097	-5119	-150
-140	-4669	-4694	-4719	-4744	-4768	-4793	-4817	-4841	-4865	-4889	-140
-130	-4411	-4437	4463	-4490	-4516	-4542	-4567	-4593	-4618	-4644	-130
-120	-4138	-4166	-4194	-4221	-4249	-4276	-4303	-4330	-4357	-4384	-120
-110	-3852	-3882	-3911	-3939	-3968	-3997	-4025	-4054	-4082	-4110	-110
-100	-3554	-3584	-3614	-3645	-3675	-3705	-3734	-3764	-3794	-3823	-100
-90	-3243	-3274	-3306	-3337	-3368	-3400	-3431	-3462	-3492	-3523	-90
-80	-2920	-2953	-2986	-3018	-3050	-3083	-3115	-3147	-3179	-3211	-80
-70	-2587	-2620	-2654	-2688	-2721	-2755	-2788	-2821	-2854	-2887	-70
-60	-2243	-2278	-2312	-2347	-2382	-2416	-2450	-2485	-2519	-2553	-60
-50	-1889	-1925	-1961	-1996	-2032	-2067	-2103	-2138	-2173	-2208	-50
-40	-1527	-1564	-1600	-1637	-1673	-1709	-1745	-1782	-1818	-1854	-40
-30	-1156	-1194	-1231	-1268	-1305	-1343	-1380	-1417	-1453	-1490	-30
-20	-778	-816	-854	-892	-930	-968	-1006	-1043	-1081	-1119	-20
-10	-392	-431	-470	-508	-547	-586	-624	-663	-701	-739	-10
0	0	-39	-79	-118	-157	-197	-236	-275	-314	-353	0
t90/°C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**t90/°C**
0	0	39	79	119	158	198	238	277	317	357	0
10	397	437	477	517	557	597	637	677	718	758	10
20	798	838	879	919	960	1000	1041	1081	1122	1163	20
30	1203	1244	1285	1326	1366	1407	1448	1489	1530	1571	30
40	1612	1653	1694	1735	1776	1817	1858	1899	1941	1982	40
50	2023	2064	2106	2147	2188	2230	2271	2312	2354	2397	50
60	2436	2478	2519	2561	2602	2644	2685	2727	2768	2810	60
70	2851	2893	2934	2976	3017	3059	3100	3142	3184	3225	70
80	3267	3308	3350	3391	3433	3474	3516	3557	3599	3640	80
90	3682	3723	3765	3806	3848	3889	3931	3972	4013	4055	90
100	4096	4138	4179	4220	4262	4303	4344	4385	4427	4468	100
110	4509	4550	4561	4633	4674	4715	4756	4797	4838	4879	110
120	4920	4961	5002	5043	5084	5124	5165	5206	5247	5288	120
130	5328	5369	5410	5450	5491	5532	5572	5613	5653	5694	130
140	5735	5775	5815	5856	5896	5937	5977	6017	6058	6098	140
150	6138	6179	6219	6259	6299	6339	6380	6420	6460	6500	150
160	6540	6580	6620	6660	6701	6741	6781	6821	6861	6901	160
170	6941	6981	6620	7060	7100	7140	7180	7220	7260	7300	170
180	7340	7380	7021	7460	7500	7540	7579	7619	7659	7699	180
190	7739	7779	7420	7859	7899	7939	7979	8019	8059	8099	190
200	8138	8178	7819	8258	8298	8338	8378	8418	8458	8499	200
210	8539	8579	8218	8659	8699	8739	8779	8819	8860	8900	210
220	8940	8980	8619	9061	9101	9141	9181	9222	9262	9302	220
230	9343	9383	9020	9464	9504	9545	9585	9626	9666	9707	230
240	9747	9788	9828	9869	9909	9950	9991	10031	10072	10113	240
250	10153	10194	10235	10276	10316	10357	10398	10439	10480	10520	250
260	10561	10602	10643	10684	10725	10766	10807	10848	10889	10930	260
270	10971	11012	11053	11094	11135	11176	11217	11259	11300	11341	270
280	11382	11423	11465	11506	11547	11588	11630	11671	11712	11753	280

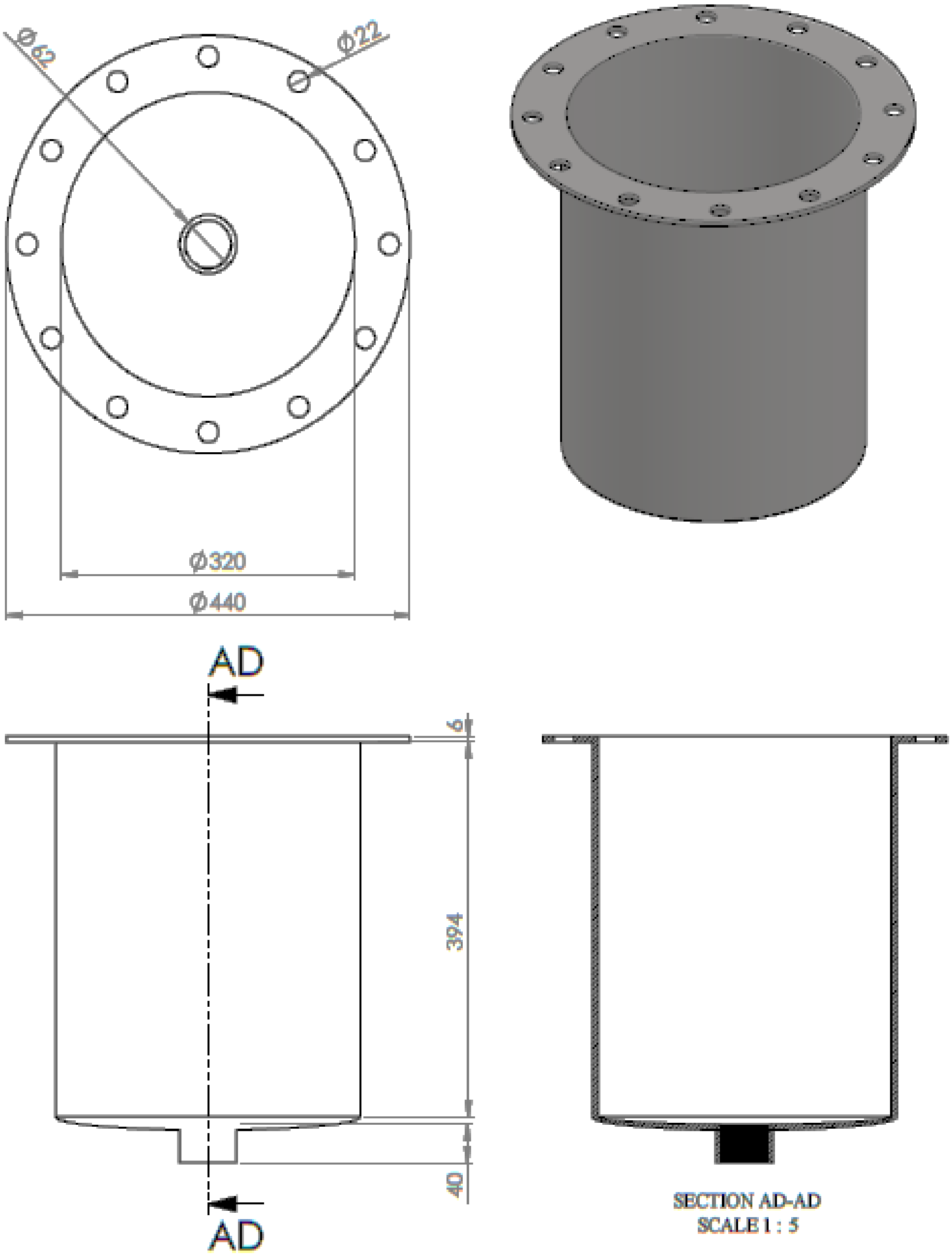
Type K Thermocouple Table

Nickel-Chromium/Nickel-Aluminium, Electromotive Force as a function of temperature, E/μV
As per Standard ASTM E231

t90/°C	0	1	2	3	4	5	6	7	8	9	t90/°C
290	11795	11836	11877	11919	11960	12001	12043	12084	12126	12167	290
300	12209	12250	12291	12333	12374	12416	12457	12499	12540	12582	300
310	12624	12665	12707	12748	12790	12831	12873	12915	12956	12998	310
320	13040	13081	13123	13165	13206	13248	13290	13331	13373	13415	320
330	13457	13498	13540	13582	13624	13665	13707	13749	13791	13833	330
340	13874	13916	13958	14000	14042	14084	14126	14167	14209	14251	340
350	14293	14335	14377	14419	14461	14503	14545	14587	14629	14671	350
360	14713	14755	14797	14839	14881	14923	14965	15007	15049	15091	360
370	15133	15175	15217	15259	15301	15343	15385	15427	15469	15511	370
380	15554	15596	15638	15680	15722	15764	15806	15849	15891	15933	380
390	15975	16017	16059	16102	16144	16186	16228	16270	16313	16355	390
400	16397	16439	16482	16524	16566	16608	16651	16693	16735	16778	400
410	16820	16862	16904	16947	16989	17031	17074	17116	17158	17201	410
420	17243	17285	17328	17370	17413	17455	17497	17540	17582	17624	420
430	17667	17709	17752	17794	17837	17879	17921	17964	18006	18049	430
440	18091	18134	18176	18218	18261	18303	18346	18388	18431	18473	440
450	18516	18558	18601	18643	18686	18728	18771	18813	18856	18898	450
460	18941	18983	19026	19068	19111	19154	19196	19239	19281	19324	460
470	19366	19409	19451	19494	19537	19579	19622	19664	19707	19750	470
480	19792	19835	19877	19920	19962	20005	20048	20090	20133	20175	480
490	20218	20261	20303	20346	20389	20431	20474	20516	20559	20605	490
500	20644	20687	20730	20772	20815	20857	20900	20943	20985	21028	500
510	21071	21113	21156	21199	21241	21284	21326	21369	21412	21454	510
520	21497	21540	21582	21625	21668	21710	21753	21796	21838	21881	520
530	21924	21966	22009	22052	22094	22137	22179	22222	22265	22307	530
540	22350	22393	22435	22478	22521	22563	22606	22649	22691	22734	540
550	22776	22819	22862	22904	22947	22990	23032	23075	23117	23160	550
560	23203	23245	23288	23331	23373	23416	23458	23501	23544	23586	560
570	23629	23671	23714	23757	23799	23842	23884	23927	23970	24012	570
580	24055	24097	24140	24182	24225	24267	24310	24353	24395	24438	580
590	24480	24523	24565	24608	24650	24693	24735	24778	24820	24863	590
600	24905	24948	24990	25033	25075	25118	25160	25203	25245	25288	600
610	25330	25373	25415	25458	25500	25543	25585	25627	25670	25712	610
620	25755	25797	25840	25882	25924	25967	26009	26052	26094	26136	620
630	26179	26221	26263	26306	26348	26390	26433	26475	26517	26560	630
640	26602	26644	26687	26729	26771	26814	26856	26898	26940	26983	640
650	27025	27067	27109	27152	27194	27236	27278	27320	27363	27405	650
660	27447	27489	27531	27574	27616	27658	27700	27742	27784	27826	660
670	27869	27911	27953	27995	28037	28079	28121	28163	28205	28247	670
680	28289	28332	28374	28416	28458	28500	28542	28584	28626	28668	680
690	28710	28752	28794	28835	28877	28919	28961	29003	29045	29087	690
700	29129	29171	29213	29255	29297	29338	29380	29422	29464	29506	700
710	29548	29589	29631	29673	29715	29757	29798	29840	29882	29924	710
720	29965	30007	30049	30090	30132	30174	30216	30257	30299	30341	720
730	30382	30424	30466	30507	30549	30590	30632	30674	30715	30757	730
740	30798	30840	30881	30923	30964	31006	31047	31089	31130	31172	740
750	31213	31255	31296	31338	31379	31421	31462	31504	31545	31586	750
760	31628	31669	31710	31752	31793	31834	31876	31917	31958	32000	760
770	32041	32082	32124	32165	32206	32247	32289	32330	32371	32412	770
780	32453	32495	32536	32577	32618	32659	32700	32742	32783	32824	780
790	32865	32906	32947	32988	33029	33070	33111	33152	33193	33234	790
800	33275	33316	33357	33398	33439	33480	33521	33562	33603	33644	800
810	33685	33726	33767	33808	33848	33889	33930	33971	34012	34053	810
820	34093	34134	34175	34216	34257	34297	34338	34379	34420	34460	820
830	34501	34542	34582	34623	34664	34704	34745	34786	34826	34867	830
840	34908	34948	34989	35029	35070	34110	35151	35192	35232	35273	840
850	35313	35354	35394	35435	35475	35516	35556	35596	35637	35677	850
860	35718	35758	35798	35839	35879	35920	35960	36000	36041	36081	860
870	36121	36162	36202	36242	36282	36323	36363	36403	36443	36484	870

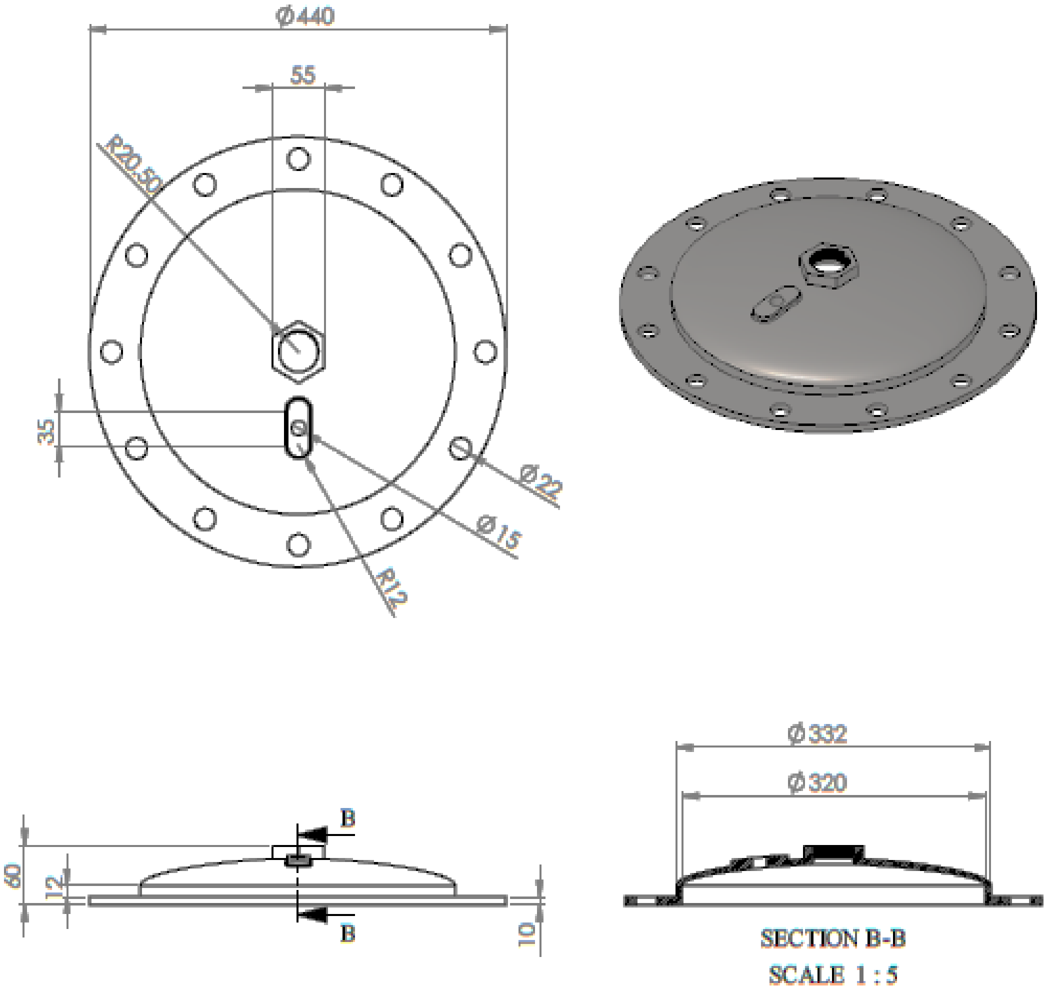
APPENDIX TWO

Detail Drawings



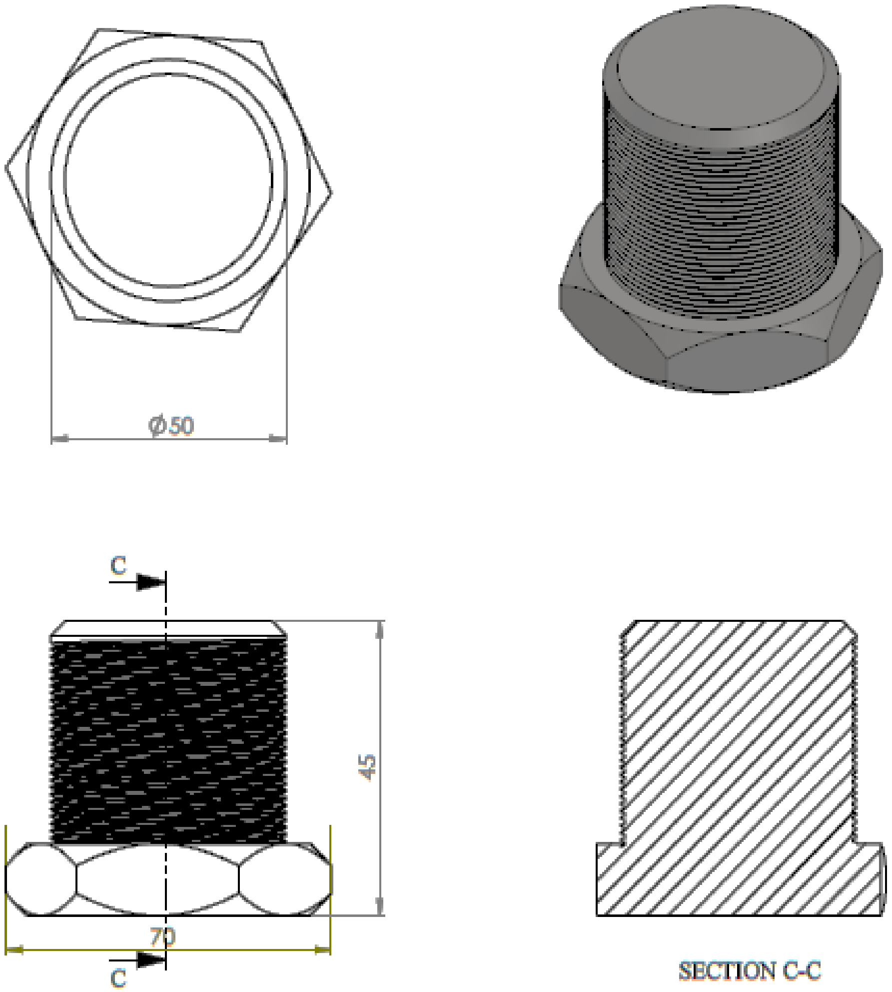
All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Reactor shell**	Drawing No 1
Checked by	Eyouel Abate		Scale 1:5
Approved by	Balewgize Amare		



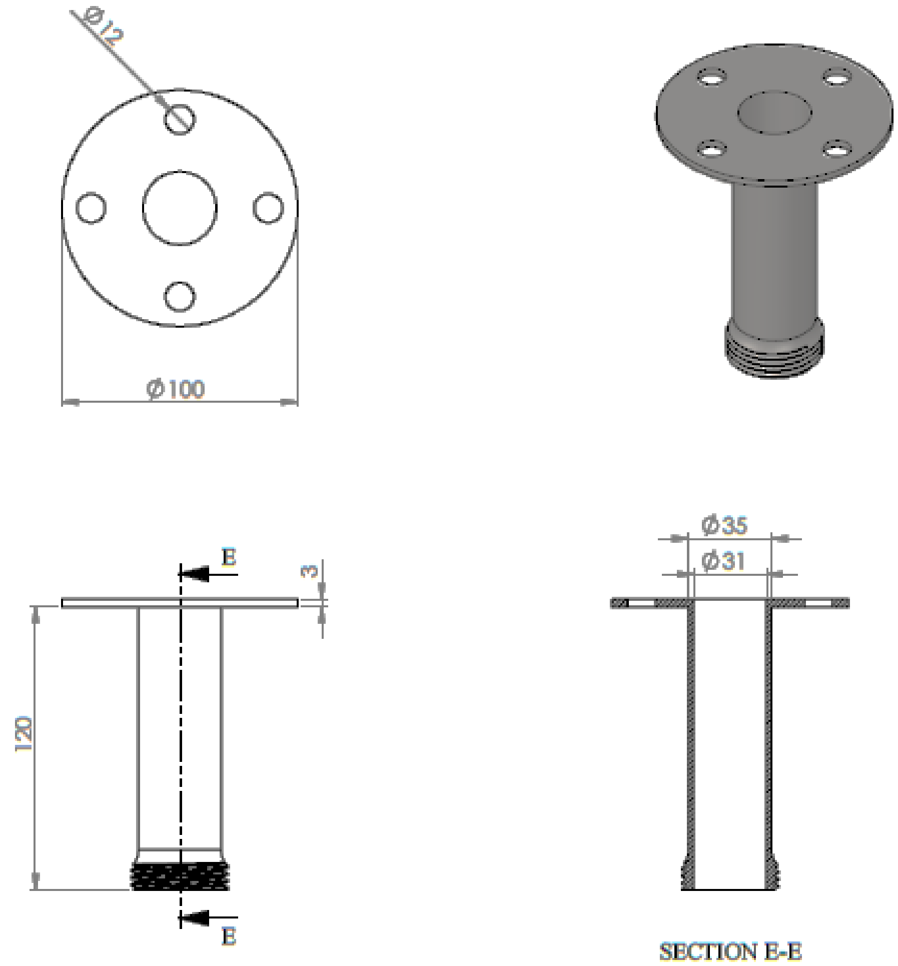
All dimensions are in mm

Drawn by	Tesfahun Meshesha	Reactor Cover	Drawing No 2
Checked by	Eyouel Abate		Scale 1:5
Approved by	Balewgize Amare		

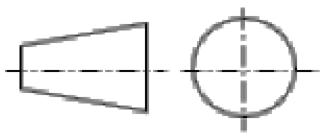


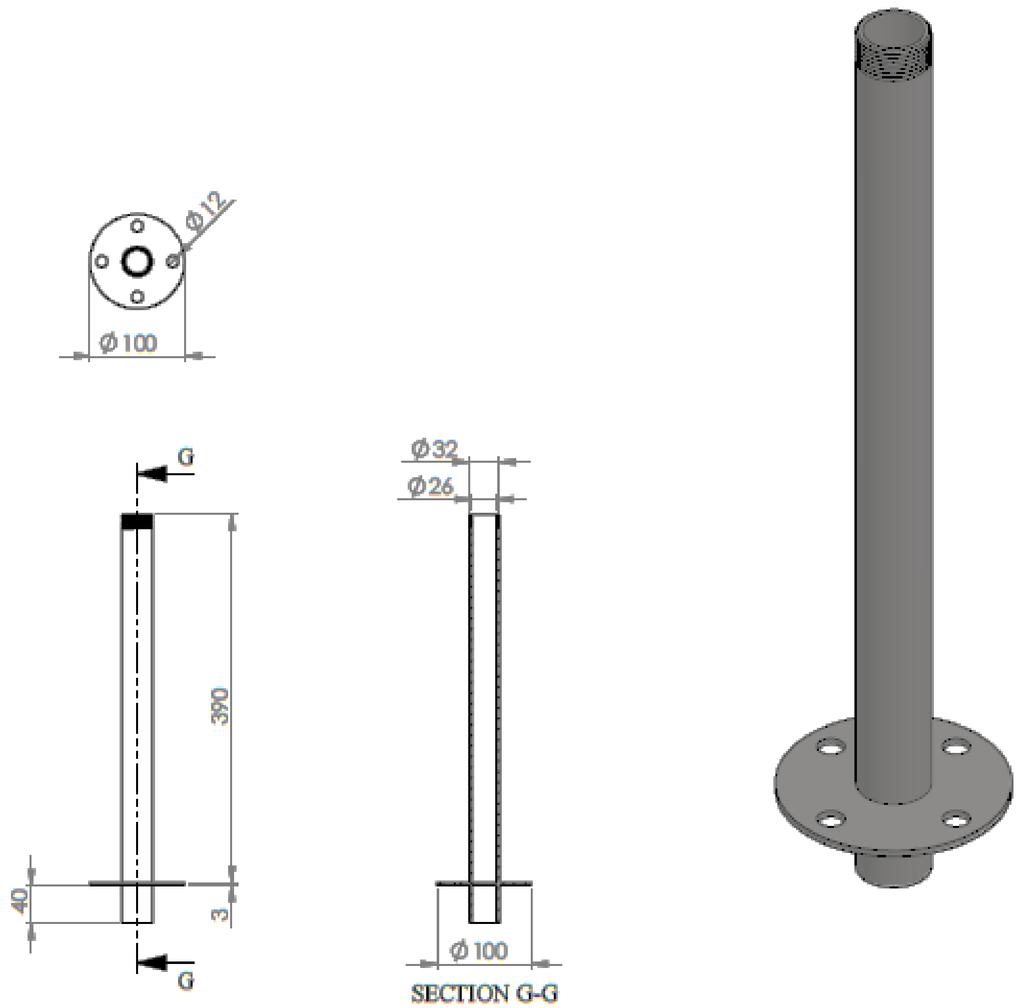
All dimensions are in mm

Drawn by	Tesfahun Meshesha	Residue discharge pin	Drawing No 3
Checked by	Eyouel Abate		Scale 1:1
Approved by	Balewgize Amare		



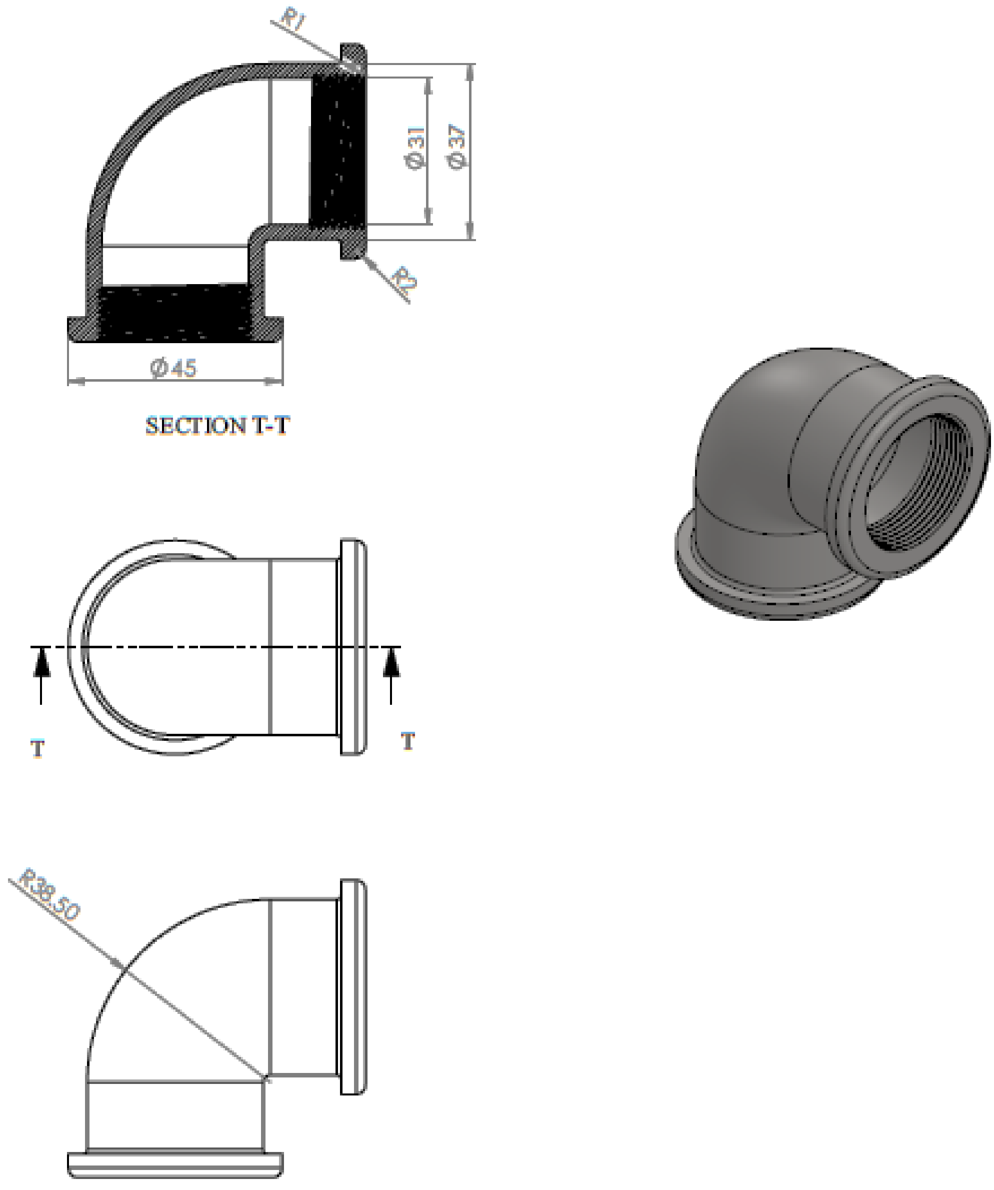
All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Socket tube on reactor**	Drawing No 4
Checked by	Eyouel Abate		Scale 1:1
Approved by	Balewgize Amare		

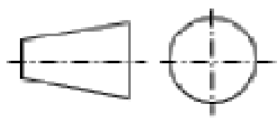


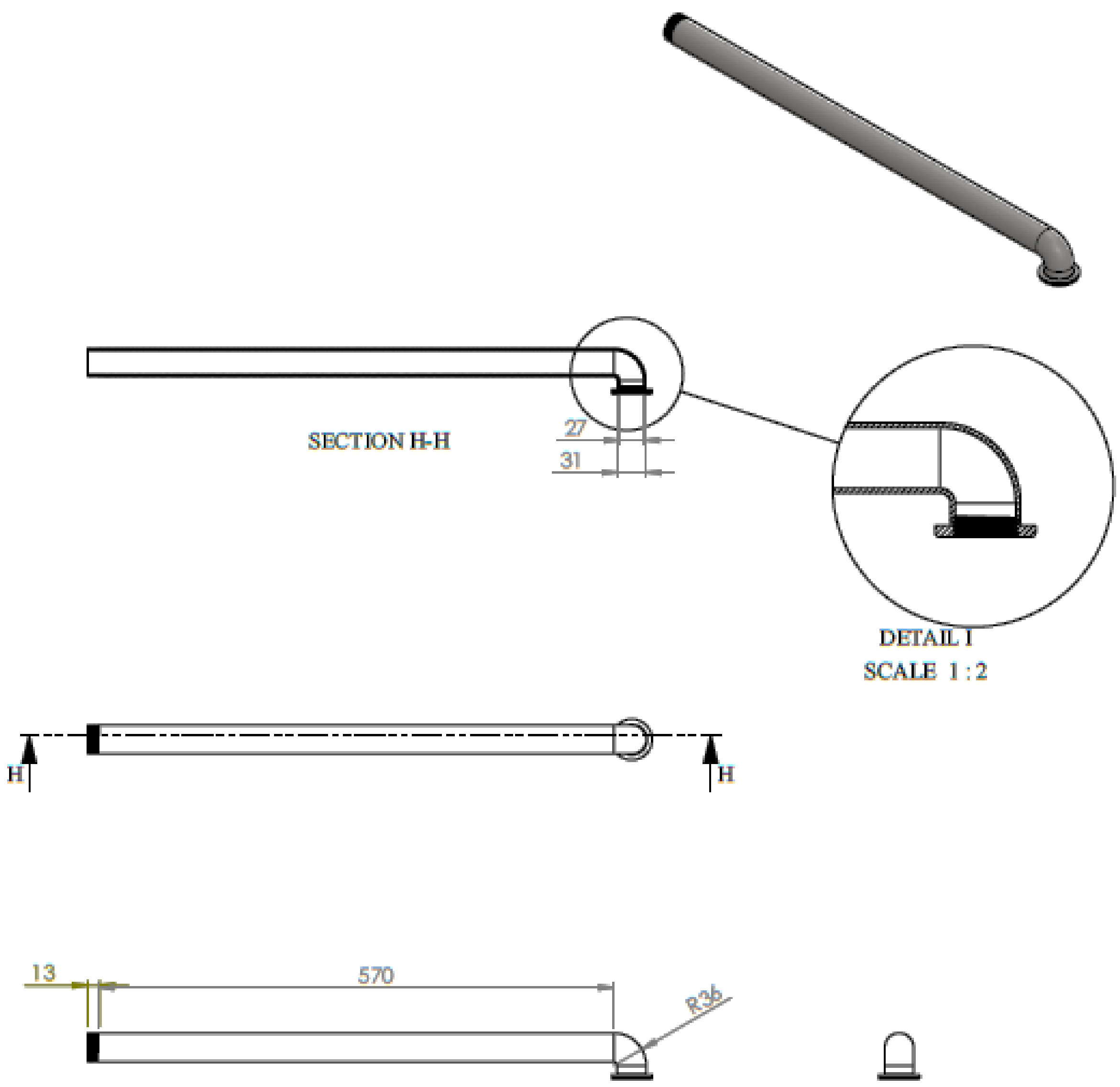
All dimensions are in mm

Drawn by	Tesfahun Meshesha	Pyrolysis gas tube reactor end	Drawing No 5
Checked by	Eyouel Abate		Scale 1:5
Approved by	Balewgize Amare		



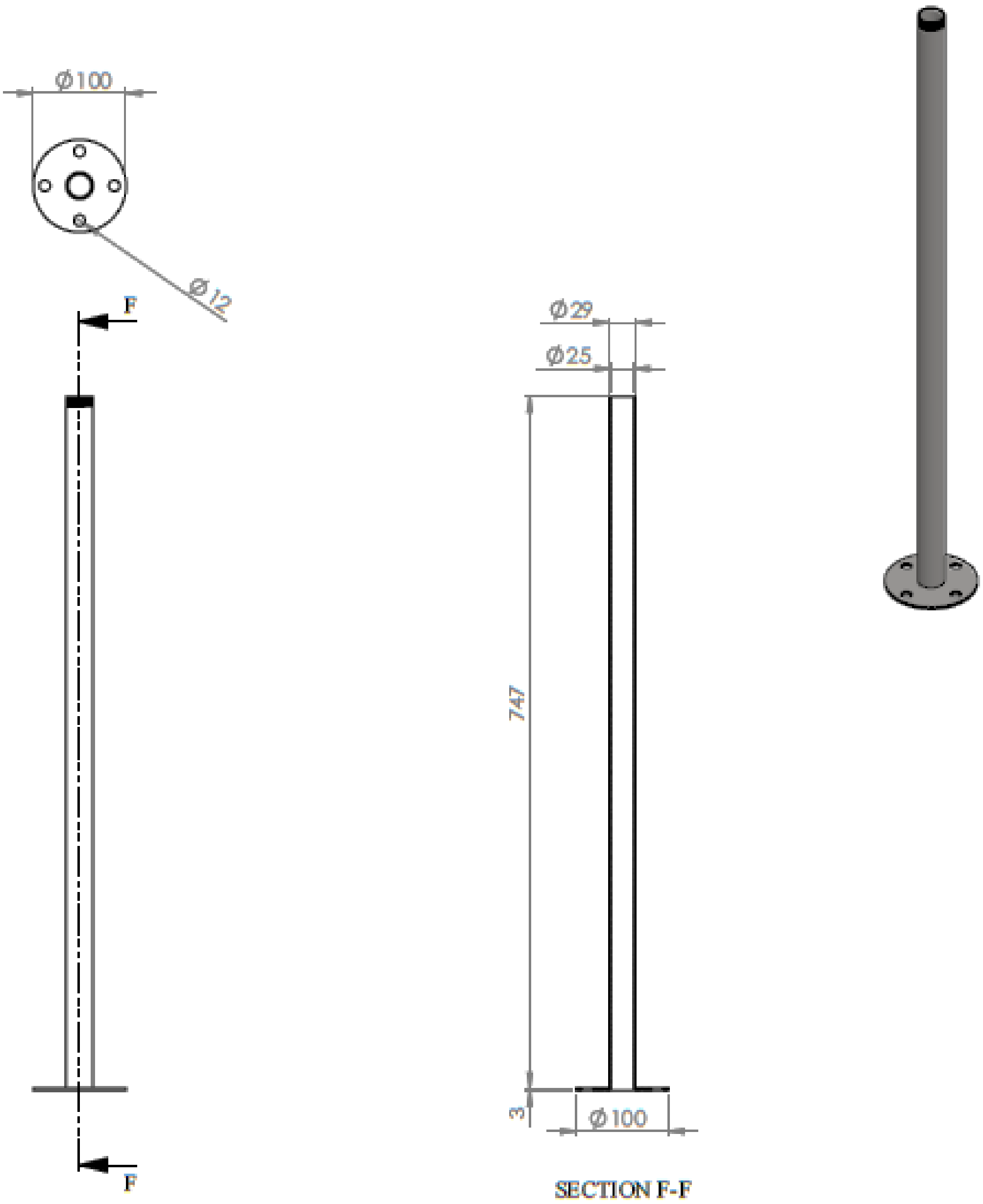
All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Elbow**	Drawing No 6
Checked by	Eyouel Abate		Scale 1:1
Approved by	Balewgize Amare		



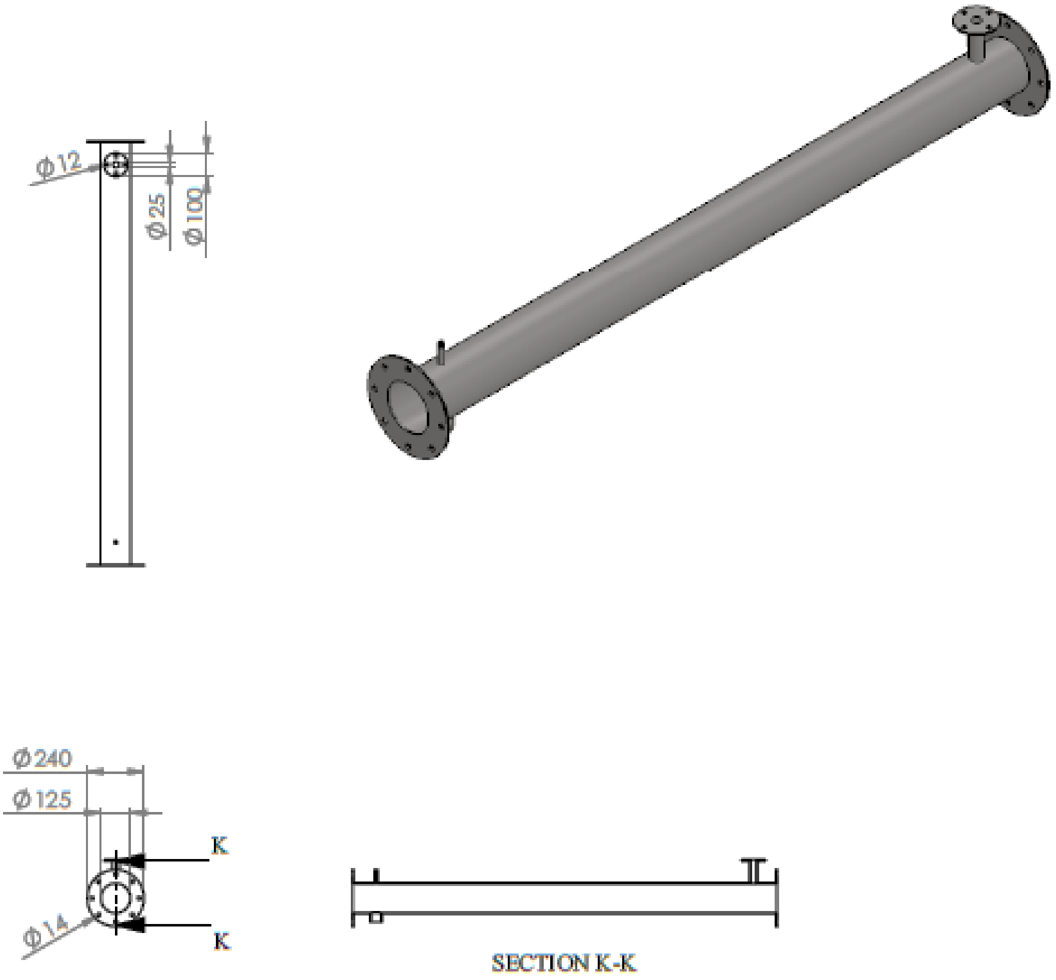
All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Pyrolysis gas tube bend**	Drawing No 7
Checked by	Eyouel Abate		Scale 1:2
Approved by	Balewgize Amare		



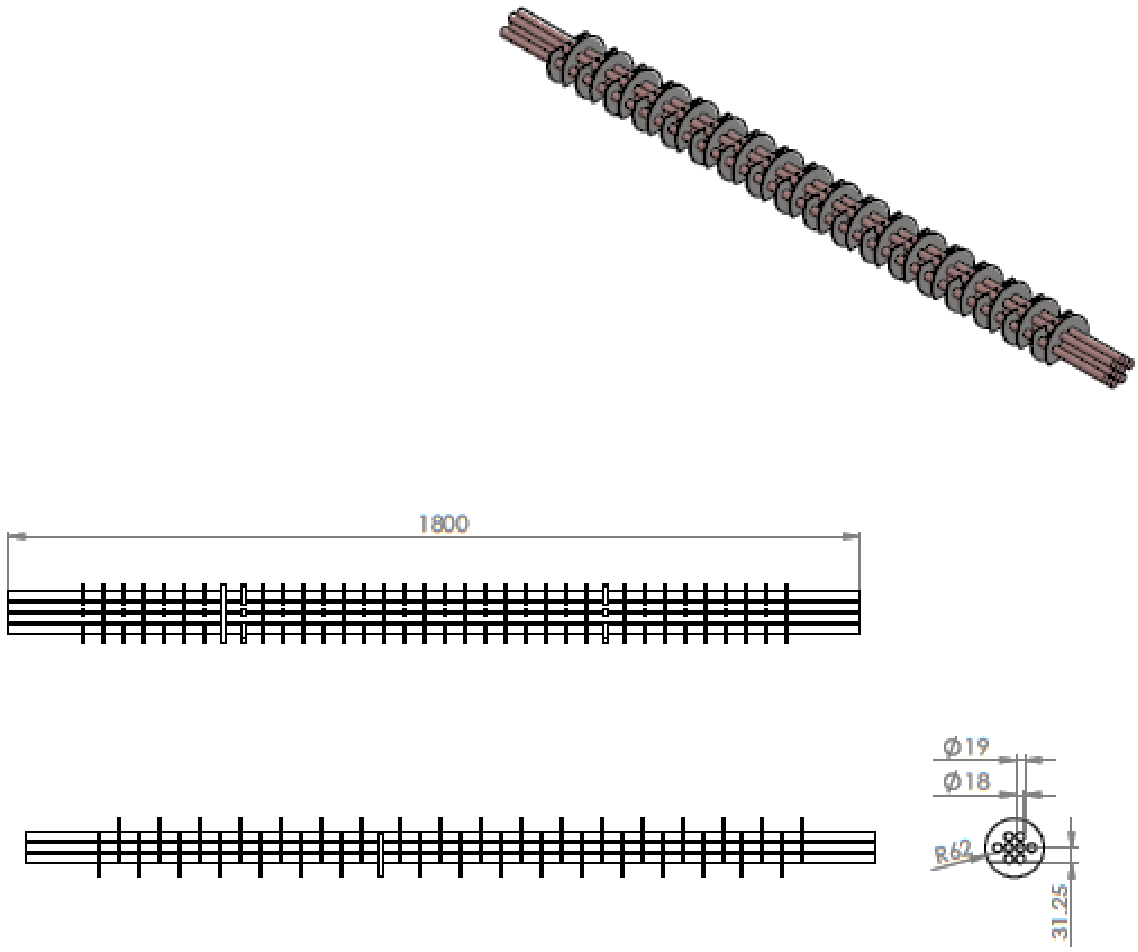
All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Pyrolysis gas tube condenser end**	Drawing No 8
Checked by	Eyouel Abate		Scale 1: 5
Approved by	Balewgize Amare		



All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Condenser shell**	Drawing No 9
Checked by	Eyouel Abate		Scale 1:20
Approved by	Balewgize Amare		

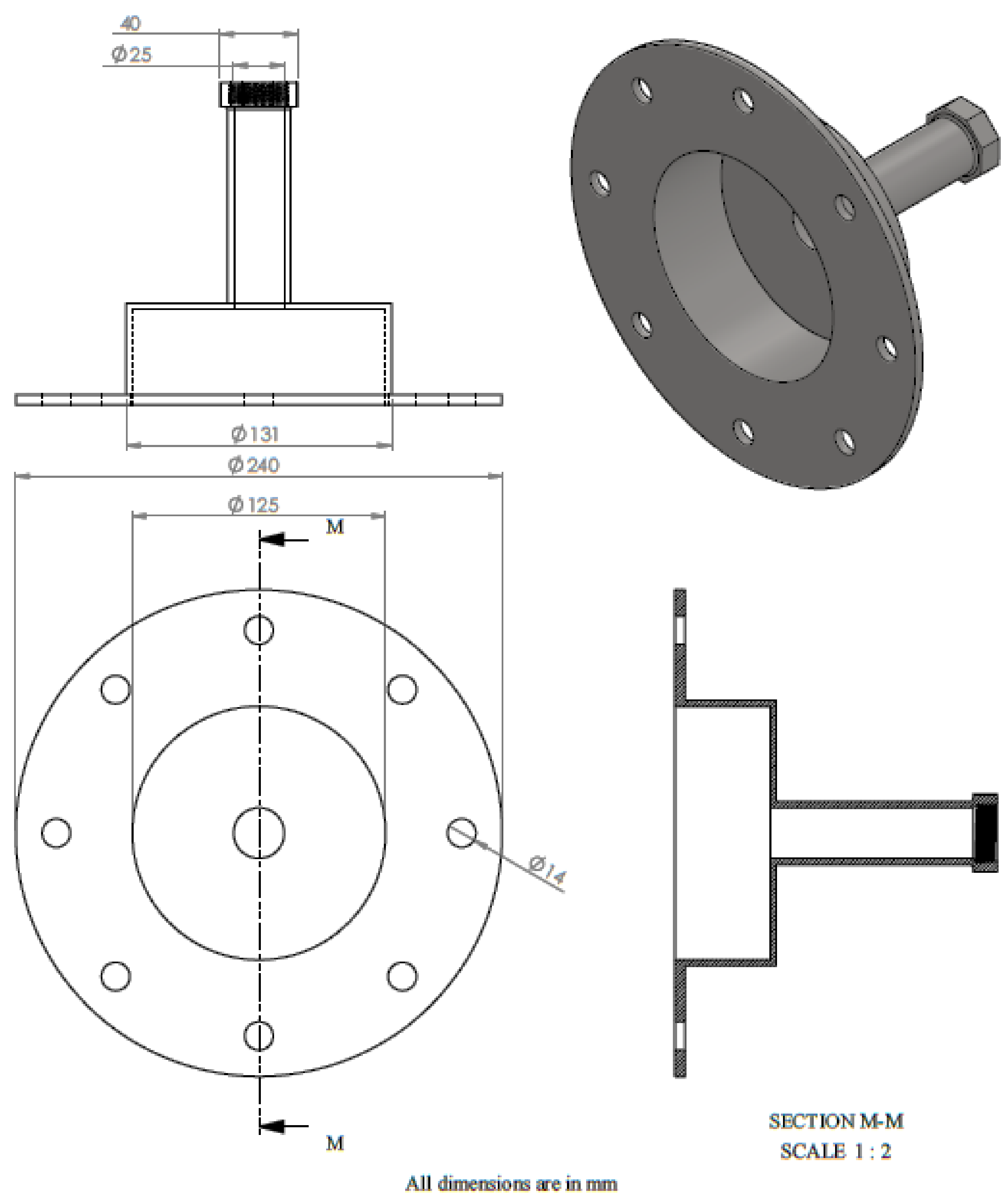


Note:

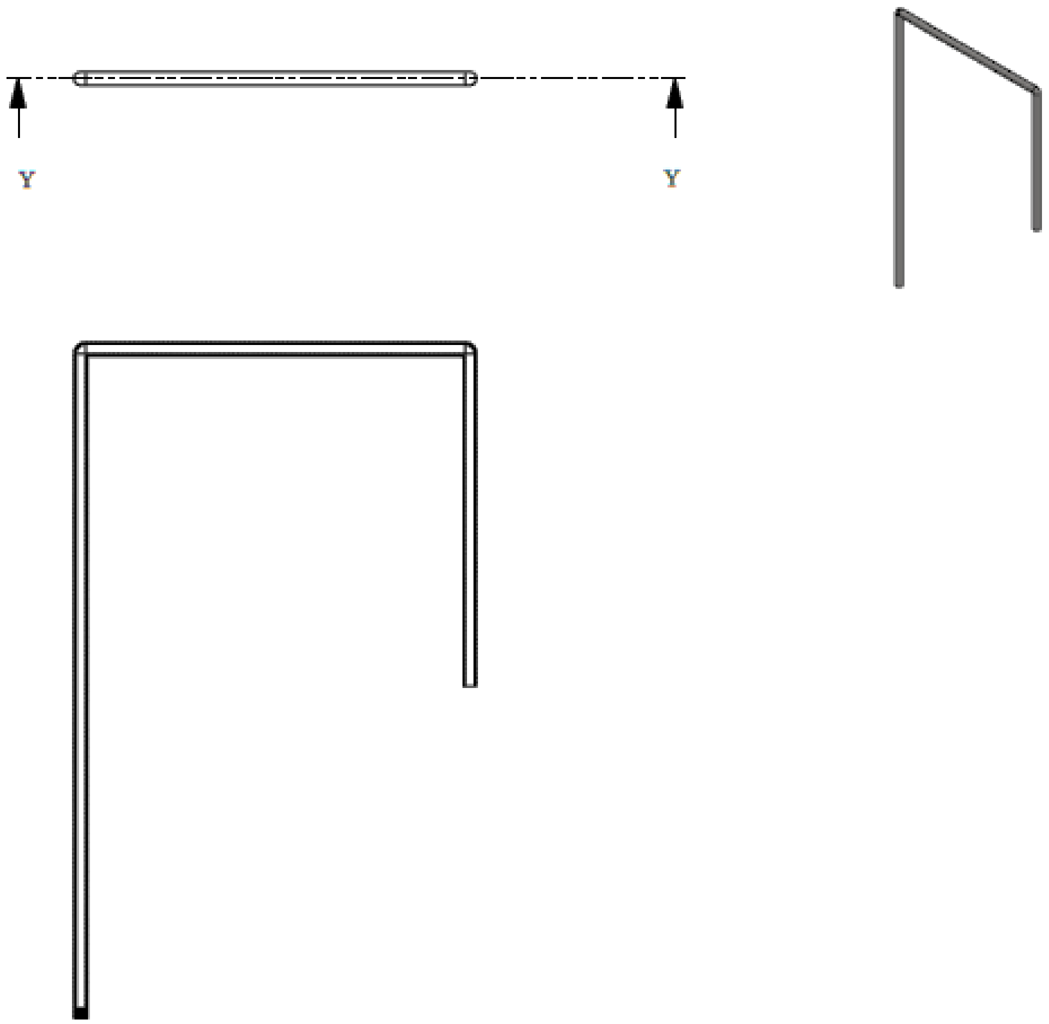
- Number of tube = 8
- Number of baffles = 36
- Baffle space = 37.5

All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Tube Bundle**	Drawing No 10
Checked by	Eyouel Abate		Scale 1:1
Approved by	Balewgize Amare		



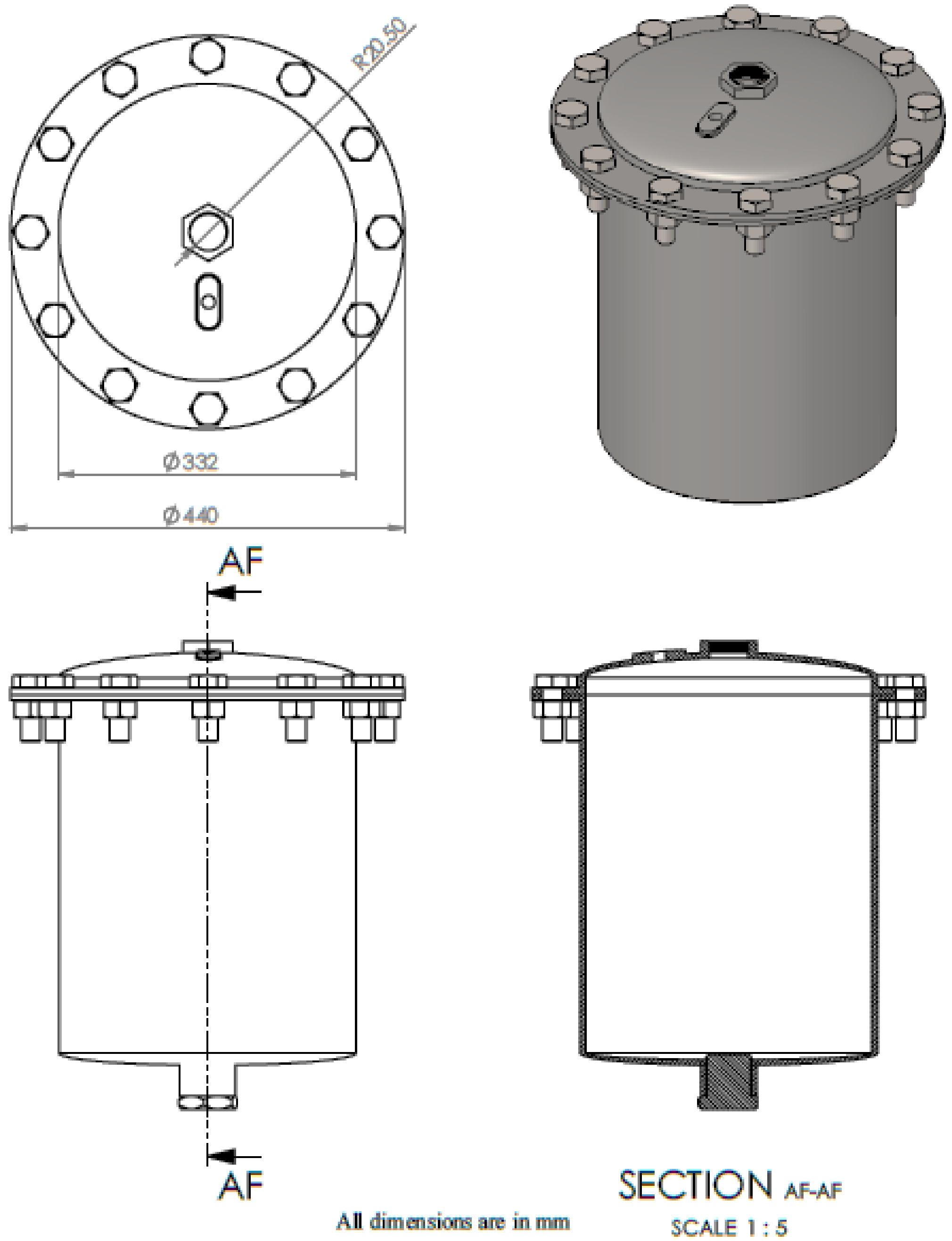
Drawn by	Tesfahun Meshesha	**Condenser cover**	Drawing No 12
Checked by	Eyouel Abate		Scale 1:5
Approved by	Balewgize Amare		



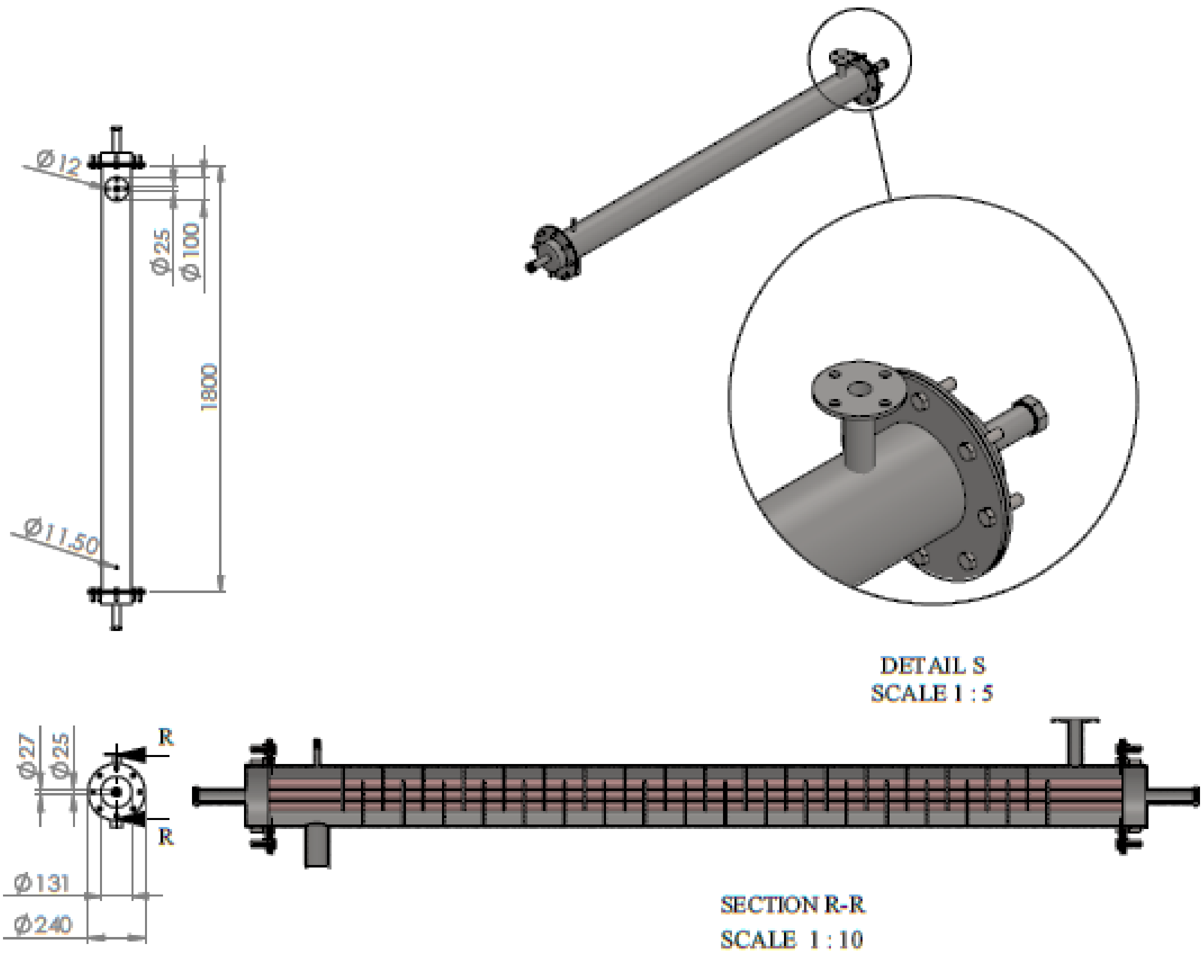
SECTION Y-Y
SCALE 1 : 5

All dimensions are in mm

Drawn by	Tesfahun Meshesha	Secondary condensation tube	Drawing No 13
Checked by	Eyouel Abate		Scale 1:1
Approved by	Balewgize Amare		

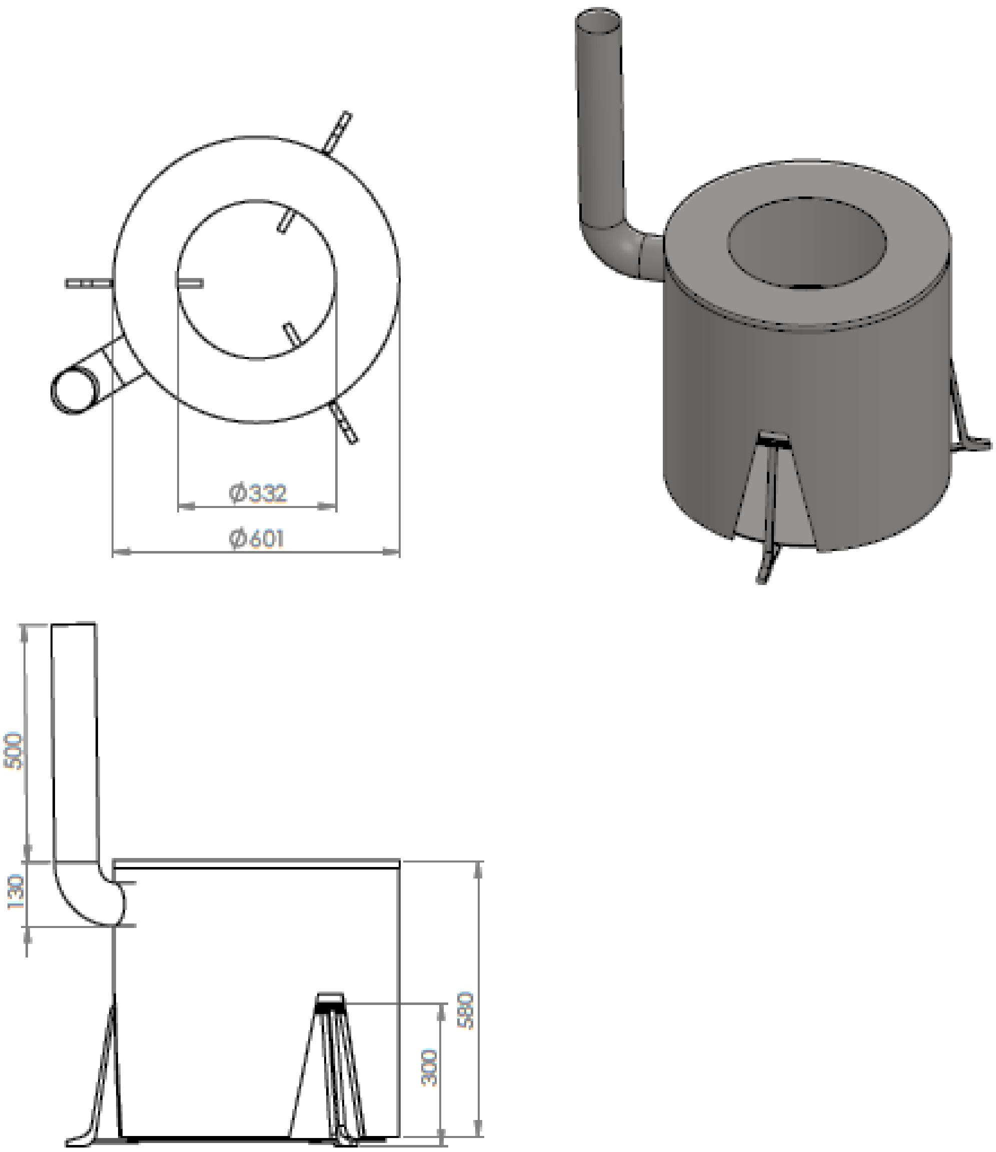


Drawn by	Tesfahun Meshesha	**Reactor Assembly**	Drawing No 14
Checked by	Eyouel Abate		Scale 1:5
Approved by	Balewgize Amare		



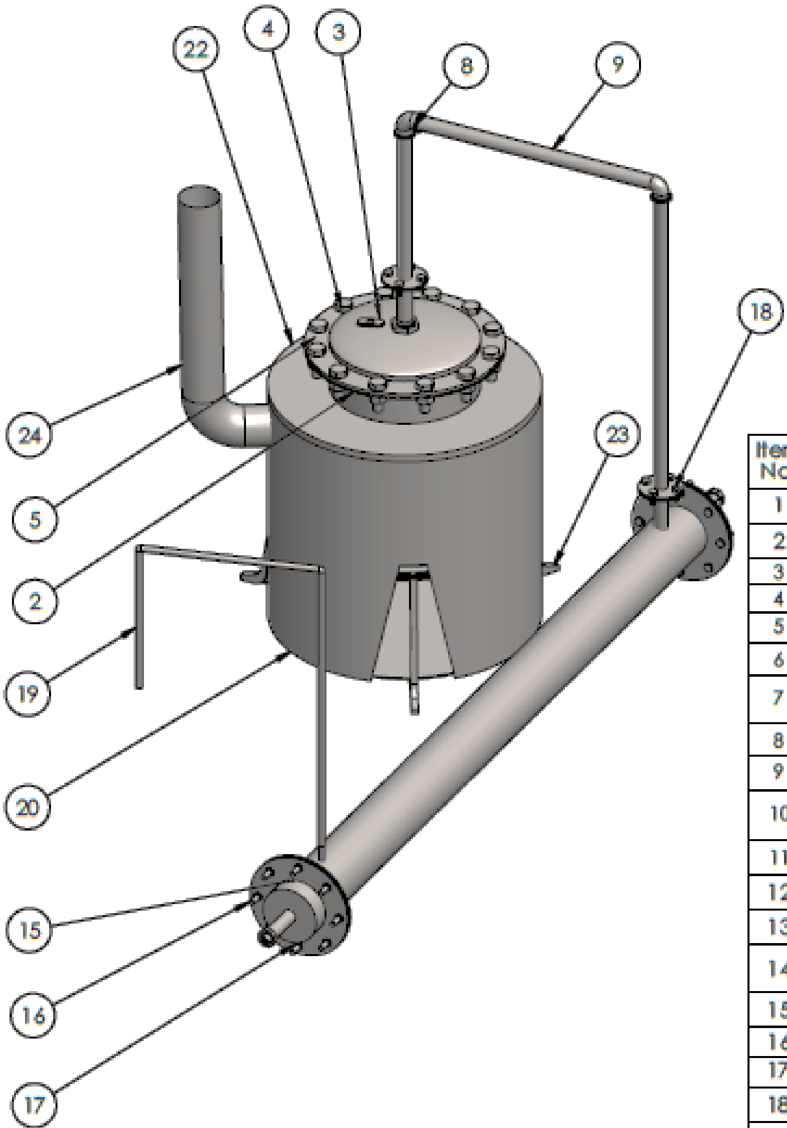
All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Condenser Assembly**	Drawing No 15
Checked by	Eyouel Abate		Scale 1:20
Approved by	Balewgize Amare		

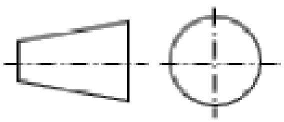


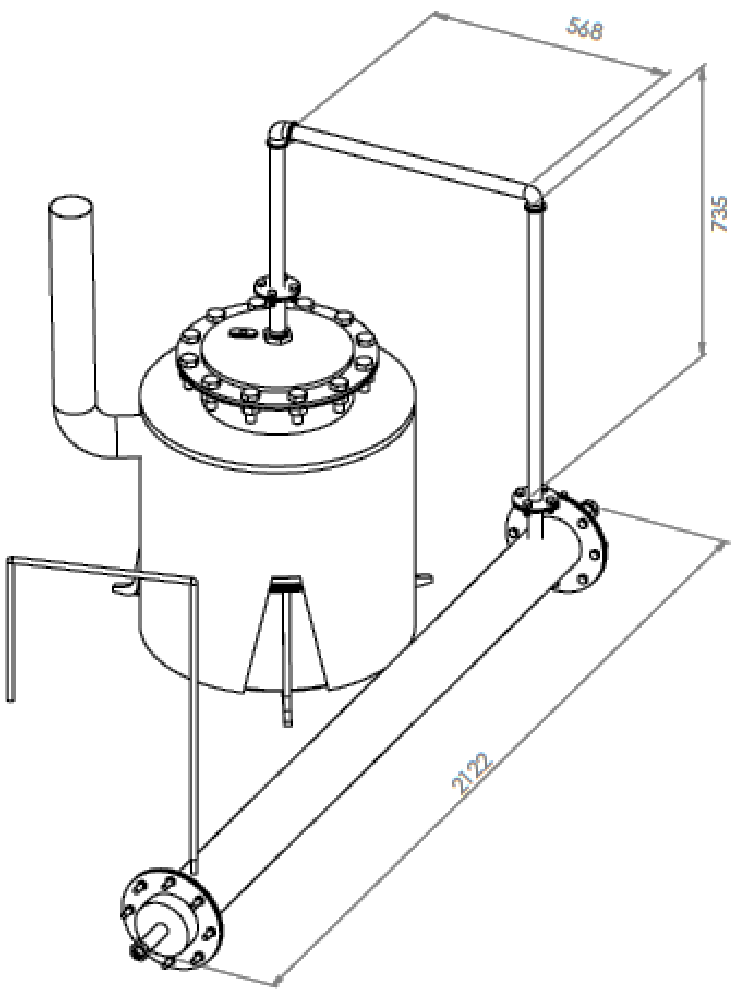
All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Furnace**	Drawing No 16
Checked by	Eyouel Abate		Scale 1:1
Approved by	Balewgize Amare		



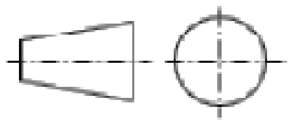
Item No.	Part Number	Qty.
1	Residus discharge pin	1
2	Reactor Shell	1
3	Reactor Cover	1
4	Bolt - M22 x 60	12
5	Hexagon Nut - M22	14
6	Reactor socket	1
7	Pyrolysis gas tube reactor end	1
8	Elbow	1
9	Pyrolysis gas tube bend	1
10	Pyrolysis gas tube condender end	1
11	Condenser shell	1
12	Baffles	36
13	Tube	8
14	Gasket for condenser	1
15	Condenser cover	2
16	Bolt - M12 x 45	16
17	Hexagonal nut - M12 x 1.5	24
18	Bolt - M12 x 25	8
19	Secondary condensation tube	1
20	Furnace outer wall	1
21	Furnace inner wall	1
22	Furnace cover	1
23	Furnace support	1
24	Chimney	1

Drawn by	Tesfahun Meshesha	**Overall assembly**	Drawing No 17
Checked by	Eyouel Abate		Scale 1:10
Approved by	Balewgize Amare		



Note:
Length = 2132mm
Width = 888mm
Height = 1120mm

All dimensions are in mm

Drawn by	Tesfahun Meshesha	**Overall Dimension**	Drawing No 18
Checked by	Eyouel Abate		Scale 1:10
Approved by	Balewgize Amare		