

Used Tires Recycling and Utilization in Saudi Arabia

Project of CHE 496 & 497 Final Year Design Project
(B.S Graduation Project I & II)

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PROJECT STATEMENT

Final Year Design Project (496 – 497)

Project Title

Used Tires Recycling and Utilization in Saudi Arabia.

Introduction

Used tires has become a true problem in the past few years especially in Saudi Arabia. It cause serious environmental issues. Therefore, by recycling used tires, it will be a good saving for the environmental and the country economics. Tires are mainly manufactured from both natural & synthetic rubber, so used tires will be taken back to their origin by shredding them into small chips and removing steel & fabrics to produce rubber powder or which known as crumb rubber. Also, another way to utilize tires is by pyrolysis process which produce hydrocarbon gases, biofuel and carbon black.

Objective

In this project a group of 3 students, will work as a team to study a tire recycling process using 39,000 metric tons/year of used tires as a starting raw material.

General Tasks & Requirements

The students are requested to:

- ☐ Perform extensive literature survey regarding: uses of recycled rubber; alternatives for recycling used tires; local demand for the end products of recycled tires; potential for applying this process in KSA.
- ☐ Select a suitable process flow sheet; perform detailed hand-calculation of material and energy balances.
- ☐ Perform detailed design of plant units where each student is required to design at least two main units in the developed flow sheet and perform HAZOP & control loops on the designed units. Other units will be designed by a group of maximum two students.
- ☐ Perform plant economic evaluations and related environmental and safety issues.

Executive Summary

In this project, 39,000 metric tons/year of scrap tires are used as raw material. The process flowsheet has been selected from pre-published proposal flowsheets. The report follows the guidelines given in the project statement.

The project report consists of ten chapters as follows:

Chapter one contains an introduction which includes, overview about the history of tire recycling. In addition, structure of tires. Also, a global production of tires and potentials of recycling tires in Saudi Arabia.

Chapter two contains an overview about recycling in general and scrap tires recycling in particular. It also contains the steps, methods and processes of recycling of scrap tires. In addition, it contains an environmental and economic impact.

Chapter three is about the different technologies for production of crumb rubber which are ambient grinding and cryogenic grinding. Also, a comparison between them which include the advantages and disadvantages of each method. In addition, it contains a flow sheet for the size reduction plant to produce crumb rubber and brief description about the equipment used. The process mainly consists of three steps. The final product size is around 1 mm crumb rubber. But the optimum size for pyrolysis process is 4 cm³ which is produced after the secondary crushing. Therefore, 70 % of the output of the secondary crushing is collected and used as feedstock to the pyrolysis process and the remaining 30 % is allowed to go for further reduction to produce crumb rubber. Finally, an overlook to the standards and different tests which are carried out to insure the quality and readiness for using the final product in several applications.

Chapter four is about the pyrolysis process. It consists of a process description, products (char, pyrolytic oil, gases), optimum operating conditions and a flowsheet for the process. The products of the process are 40.5% char, 51% pyrolytic oil and 8.5% gases. The produced gases have been recycled and used as fuel for the decomposition unit. Finally, a brief discussion of the effect of operating conditions on the products yields.

Chapter five contains an overall material and energy balances. It was found that using 39,000 metric ton/year (5 metric tons/hr) will produce 9697.32 metric tons/year (1230 Kg/hr) of crumb rubber and 23,868.8 metric tons/year (3027.5 Kg/hr) of feedstock to the pyrolysis process. The flow rates of the pyrolysis products are: 9666.8 metric tons/year (1226.137 Kg/hr) of char, 12168.5 metric tons/year (1543.44 Kg/hr) of pyrolytic oil and 2033.4 metric tons/year (257.9 Kg/hr) of hydrocarbon gases (incondensable gases). The total heat requirement of the pyrolysis plant is almost 1405 KJ/s and approximately 2500 KJ/s of the size reduction plant.

Chapter six contains the detailed design of the major equipment in the pyrolysis plant. It contains the design of two coolers to cool the decomposition unit effluent from 475 °C to 120 °C. Also, they are followed by two condensers and two flash drums to separate different components of the mixture where the temperature fallen down to around 50 °C. The two coolers have an area of 3.545 m² and 5.235 m² respectively. For the condensers, an area of 7.56 m² is required for the first one and 4.33 m² for the second one. Also, it is required to have two flash drums with volume of 1.66 m³ and 0.561 m³ respectively to separate the liquid-gas phases. The decomposition unit must have a volume of 13 m³ to accommodate the designing load of crumb rubber in each run. Finally, it contains a sizing for the remaining equipment.

Chapter seven is about the control loops and Piping and Instrumentation Diagram.

Chapter eight presents the details of economic evaluation of the project where it has been found that the Fixed Capital Investment (FCI) is \$ 15,000,000 and the working capital is \$ 3,000,000. Also, the annual revenue of the plant will be \$ 15,292,034 so the net profit will be around \$ 5,500,000. The payback period is around 3 years with a rate of return equal to 29 %.

Chapter nine contains the hazard analysis, which contains HAZOP Study of the pyrolysis plant and environmental considerations.

Chapter ten presents a discussion on site location and plant layout. A comparison was made between Riyadh, Jubail and Yanbu.

References and appendices are given at the end of the report.

Table of Contents

Title	Page
Project Statement	ii
Executive Summary	iii
Table of Contents	v
List of Tables	x
List of Figures	xiii
CHAPTER I	2
1. Introduction	3
1.1 History of Tires	3
1.2 Tire Structure	4
1.3 Tire Composition	5
1.4 Global Tires Production	6
1.5 Overview of Tires in Saudi Arabia	8
1.6 Used Tires	8
1.6.1 Disposal of Used Tires	9
1.6.2 Used Tires Disposal Related Problems	10
CHAPTER II	11
2. Literature Review	12
2.1 Recycling Definition	12
2.1.1 Benefits of Recycling	12
2.1.2 Steps of Recycling	12
2.2 Scrap Tires Recycling	13
2.2.1 Tire Components	13
2.2.1.1 Brief description of Some Main Components	15
2.2.2 Recycling of Scrap Tires	18
2.2.2.1 Steps of Recycling Tires	19
2.2.2.2 Methods of Recycling Scrap Tires	20

2.2.2.3 Processes of Recycling Scrap Tires	22
2.3 Used Tires in Cement Industry.....	24
2.4 Environmental Impact.....	25
2.5 Economic Potentials.....	25
CHAPTER III	27
3. Production of Crumb Rubber	28
3.1 Crumb Rubber Manufacturing Technology	28
3.1.1 Ambient Process	29
3.1.2 Cryogenic Process	32
3.1.3 Wet Grind Process	34
3.2 Comparison between Ambient and Cryogenic Technology	34
3.3 Flow Sheet of Scrap Tires Size Reduction Plant	36
3.4 Size Reduction	39
3.4.1 Equipment	39
3.5 Testing and Distribution	41
3.5.1 Quality Tests	41
3.5.2 Crumb Rubber Standards	42
3.6 Application and Uses of Crumb Rubber	43
3.7 Field Visit	44
CHAPTER IV.....	47
4. Pyrolysis Process	48
4.1 Pyrolysis Definition	48
4.2 Pyrolysis Products	49
4.3 Pyrolysis Process Description	51
4.3.1 Process Conditions	51
4.3.2 Process Products	52
4.3.3 Process Units	52
4.3.4 Process Description	52
4.3.5 Process Flow Sheet	54
4.4 The Effect of Operating Conditions on the Products Yields	56
4.4.1 Effect of Temperature	56

4.4.2 Effect of Particle Size	56
CHAPTER V	58
5. Material and Energy Balances	59
5.1 Material Balance	59
5.1.1 Material Balance for Size Reduction Plant	59
5.1.2 Material Balance for Pyrolysis Process	61
5.2 Energy Balance	66
5.2.1 Energy Balance for Size Reduction Process	66
5.2.2 Energy Balance for Pyrolysis Process	67
CHAPTER VI	71
6. Equipment Design and Sizing	72
6.1 Detailed Design of Major Equipment	72
6.1.1 Design of Cooler (E-201)	72
6.1.2 Design of Cooler (E-202)	73
6.1.3 Design of Condenser (E-203)	74
6.1.4 Design of Condenser (E-204)	75
6.1.5 Design of Flash Drum (V-201)	76
6.1.6 Design of Flash Drum (V-202)	77
6.2 Equipment Sizing	78
6.2.1 Compressors Sizing (C-201 --- 205)	78
6.2.2 Burner Sizing (H-201)	79
6.2.3 Decomposition Unit Sizing (DU-201 and 202)	80
6.2.4 Storage Tanks Sizing	81
6.2.4.1 Gas Storage Tank Sizing (TK-201)	81
6.2.4.2 Liquid Storage Tanks Sizing (TK-203 --- 206)	81
CHAPTER VII	83
7. Control System	84
7.1 Introduction	84
7.2 Control Terminology	85
7.3 Control Objectives	86
7.4 Control Loops of Major Equipment	87

7.4.1 Control Loop of Heat Exchanger (E-201)	87
7.4.2 Control Loop of Heat Exchanger (E-202)	88
7.4.3 Control Loop of Heat Exchanger (E-203)	89
7.4.4 Control Loop of Heat Exchanger (E-204)	90
7.4.5 Control Loop of Storage Tanks (TK-203 and 204)	91
7.4.6 Control Loop of Storage Tanks (TK-205 and 206)	92
7.4.7 Control Loop of Decomposition Unit (DU-201 and 202)	93
7.4.8 Control Loop of Flash Drums (V-201 and 202)	95
CHAPTER VIII	97
8. Economic Evaluation	98
8.1 Cost of Plant	98
8.1.1 Cost of Raw Materials C_{RM}	98
8.1.2 Cost of Equipment	98
8.1.3 Cost of Utility C_{UL}	100
8.1.4 Cost of Labor C_{OL}	100
8.1.5 Cost of Waste Treatment C_{WT}	100
8.1.6 Capital Cost	100
8.2 Cost of Manufacturing	100
8.3 Estimating Manufacturing Cost	101
8.4 Product prices	101
8.5 Profitability Analysis	102
8.6 Rate of Return (ROR%)	102
8.7 Payback Period (PBP)	102
8.8 Summary of Economic Evaluation	103
CHAPTER IX	104
9. Hazard Analysis	105
9.1 HAZOP Study	105
9.1.1 HAZOP Definition	105
9.1.2 HAZOP Process	106
9.1.3 HAZOP Analysis	107
9.2 Environmental Considerations	108

9.2.1 Solid Products	118
9.2.2 Liquid Products	118
9.2.3 Gas Products	119
9.2.4 Summary of Environmental Considerations	121
CHAPTER X	122
10. Site Feasibility Study	123
10.1 Site Location	123
10.2 Site Selection	125
10.3 Site Layout	131
Conclusion and Recommendation	132
References	134
Appendices	137
Appendix A (Detailed Calculations of Material & Energy Balances)	137
Appendix B (Detailed Calculation of Design and Sizing of Equipment)	146
Appendix C (Heat Capacities)	196
Appendix D (Figures used in Calculations)	198
Appendix E (Crumb Rubber Samples)	204
Appendix F (Thermal Gravimetric Analysis (TGA))	207
Appendix G (Material Safety Data Sheet (MSDS))	209

List of Tables

1.1 Passenger Car Tire Components	5
1.2 Truck Tire Components	5
1.3 Share of World Tire Production by Geographic Region	6
2.1 Basic Composition of Tire	13
2.2 Material Composition of Tire	14
2.3 Distribution of SR and NR on Different Types of Tires	14
2.4 Energy Content of Fuel	23
3.1 Comparison between Ambient and Cryogenic Processing	35
3.2 Comparison between Ambient and Cryogenic Crumb Rubber	35
3.3 Comparison of Environmental Effect of Ambient and Cryogenic Processes	36
3.4 Compositions of Feed Stream Components	37
4.1 Elemental Analysis of Scrap Tire Rubber	47
4.2 Influence of Some Process Conditions on Product Yields Presented by Different Authors .	48
4.3 Optimum Pyrolysis Conditions	49
4.4 Percentages of Pyrolysis Products	50
4.5 The Major Components and Their boiling Points	54
5.1 Symbols of All Components	60
5.2 Mass Flow Rates of Overall Streams Components for 5 tonne/hr feed	60
5.3 Mass Fractions of Overall Streams Components for 5 tonne/hr feed	61
5.4 Inlet Gases to the Burner	62
5.5 Outlet Gases from the Burner	63
5.6 Summary of Materials in all streams (Kg / hr)	64
5.7 Summary of Enthalpies in all Streams	69
5.8 Summary of Heat loads in all Units	70
6.1 Summary of Detailed Design for Cooler (E-201)	72
6.2 Summary of Detailed Design for Cooler (E-202)	73
6.3 Summary of Detailed Design for Condenser (E-203)	74
6.4 Summary of Detailed Design for Condenser (E-204)	75

6.5 Summary of Detailed Design for Flash Drum (V-201)	76
6.6 Summary of Detailed Design for Flash Drum (V-202)	77
6.7 Summary of Sizing Specifications for Compressors (C-201 --- 205)	78
6.8 Summary of Sizing Specifications for Burner (H-201)	79
6.9 Summary of Sizing Specifications for Decomposition Unit (DU-201 and 202)	80
6.10 Summary of Sizing Specifications for the Gas Storage Tank (TK-201)	81
6.11 Summary of Sizing Specifications for the Liquid Storage Tanks (TK-203 --- 206)	82
7.1 Control Symbols	86
7.2 Control Specifications of Heat Exchanger (E-201)	88
7.3 Control Specifications of Heat Exchanger (E-202)	89
7.4 Control Specifications of Heat Exchanger (E-203)	90
7.5 Control Specifications of Heat Exchanger (E-204)	91
7.6 Control Specification of Storage Tank (TK-203) and (TK-204)	92
7.7 Control Specification of Storage Tank (TK-205) and (TK-206)	93
7.8 Control Specification of Decomposition Unit (DU-201) and (DU-202)	94
7.9 Control Specification of Flash Drums (V-201) and (V-202)	95
8.1 Raw Material Cost	98
8.2 Summary of Equipment Costs	99
8.3 Products Prices	101
8.4 Summary of Economics Evaluation	103
9.1 Guide Words	107
9.2 HAZOP analysis for Node 1 Flow	109
9.3 HAZOP analysis for Node 1 Temperature	110
9.4 HAZOP analysis for Node 1 Pressure	111
9.5 HAZOP analysis for Node 1 Composition	111
9.6 HAZOP analysis for Node 2 Flow	112
9.7 HAZOP analysis for Node 2 Temperature	113
9.8 HAZOP analysis for Node 2 Pressure	114
9.9 HAZOP analysis for Node 2 Composition	114
9.10 HAZOP analysis for Node 3 Flow	115
9.11 HAZOP analysis for Node 3 Temperature	116

9.12 HAZOP analysis for Node 3 Pressure	117
9.13 HAZOP analysis for Node 3 Composition	117
9.14 Weight Fractions of Pyrolysis Liquid Products	119
9.15 Summary of Environmental Considerations	121
10.1 Comparison between Industrial Cities	128
10.2 Prices at Riyadh 2 nd Industrial City	128

List of Figures

1.1 Structure of Tires	4
1.2 Global Tire Production	7
2.1 Composition of Tires	14
2.2 Chemical Formula of Natural Rubber	15
2.3 Chain Structure of NR	15
2.4 Synthetic Rubber Structures	17
2.5 Use of Scrap Tires as TDF	24
3.1 Typical Ambient Grinding System	31
3.2 Schematic Diagram of an Ambient Scrap Tire Processing Plant	31
3.3 Typical Cryogenic Grinding System	33
3.4 Schematic Diagram of a Cryogenic Scrap Tire Processing Plant	33
3.5 Flow Sheet Diagram of Scrap Tires Size Reduction Plant	38
3.6 Crumb Rubber Factory	45
3.7 Crumb Rubber Factory	46
3.8 Crumb Rubber Factory	46
4.1 Pyrolysis Process	48
4.2 Schematic Diagram for Continuous Process	53
4.3 Pyrolysis Flow Sheet	55
4.4 Effect of Temperature on the Pyrolysis Products	56
4.5 Effect of Particle Size on the Pyrolysis Products	57
6.1 Flow Diagram for Cooler (E-201)	72
6.2 Flow Diagram for Cooler (E-202)	73
6.3 Flow Diagram for Condenser (E-203)	74
6.4 Flow Diagram for Condenser (E-204)	75
6.5 Flow Diagram for Flash Drum (V-201)	76
6.6 Flow Diagram for Flash Drum (V-202)	77
6.7 Flow Diagram for Compressors (C-201 --- 205)	78
6.8 Flow Diagram for Burner (H-201)	79

6.9 Flow Diagram for Decomposition Unit (DU-201 and 202)	80
6.10 Flow Diagram for Gas Storage Tank (TK-201)	81
6.11 Flow Diagram for Liquid Storage Tanks (TK-203 --- 206)	81
7.1 Process System	84
7.2 Input / Output of Process Control	85
7.3 Control Loop of Heat Exchanger (E-201)	87
7.4 Control Loop of Heat Exchanger (E-202)	88
7.5 Control Loop of Heat Exchanger (E-203)	89
7.6 Control Loop of Heat Exchanger (E-204)	90
7.7 Control Loop of Storage Tanks (TK-203) and (TK-204)	91
7.8 Control Loop of Storage Tanks (TK-205) and (TK-206)	92
7.9 Control Loop of Decomposition Unit (DU-201) and (DU-202)	94
7.10 Control Loop of Flash Drums (V-201) and (V-202)	95
7.11 Piping and Instrumentation Diagram (P&ID)	96
8.1 Cash Flow Diagram	103
9.1 HAZOP Flow Sheet	108
10.1 Location of Riyadh 2 nd Industrial City	129
10.2 Location of Riyadh 2 nd Industrial City	129
10.3 Land Chosen and Dimensions	130
10.4 Site layout for Plant	131

CHAPTER I

Introduction

CHAPTER 1

INTRODUCTION

Rubber recycling is not a new subject. In fact its history goes back more than a hundred years to a time when rubber was a scarce commodity. In 1910, an ounce of rubber cost the same as an ounce of silver. Over time rubber recycling declined. One reason for this was the increased use of synthetic rubber made from cheap imported oil. This reduced the value of recycled natural rubber and made it less cost-effective. Another reason relates to the development and spread of steel belted radials. These tires eventually became scrap tires that were extremely resilient and therefore extremely difficult and expensive to recycle. With the decline in rubber recycling, the growth of stockpiles of scrap tires increases [1].

1.1 History of Tires

The first rubber tires appeared in the mid-1800s. They were solid or cushion tires in which the rubber itself carried the load, absorbed shocks, and resisted cutting and abrasions. The pneumatic or air-filled tire, which carried the load and absorbed shocks by the compressed air in the tire casing, was patented as early as 1845. Solid rubber tires were preferred over pneumatic tires because of their durability, so pneumatic tires fell into disuse. The popularity of bicycles in the late 1800s revived the idea of the pneumatic tire, and in 1888 a Belfast veterinary surgeon named John Boyd Dunlop obtained a patent for a pneumatic bicycle tire [1].

Goodyear finally produced a radial tire in 1977 by investing billions of dollars in radial technology. Other American tire companies either merged or were bought out. All American new cars came with radial tires by 1983 [2].

In 1898 Goodyear Tire and Rubber Company - named after George Goodyear, the discoverer of vulcanized rubber - was formed in America by Frank Seiberling. Then Firestone Tire & Rubber Company was started by Harvey Firestone in 1900. Other tire makers followed [3].

In 1992 by Michelin introduces the first durable silica-filled tire, also known as "green tires". Then at 1998 Michelin develops tire that's vertically anchored and unseatable, allowing it to run flat after a loss of pressure [1].

In 2000 by Firestone recalls tires after Congressional hearings into rollover accidents of Ford Explorers in Firestone and Ford tire controversy [2].

1.2 Tire Structure

Most steel belted radial passenger and light truck tires are composed of an inner liner, two polyester reinforced body plies, two steel beads, two bead reinforcing strips, two anti-chafing strips, two steel belts, with belt edge wedges or wrap around gum strips, the sidewalls, and the tread. Many tires also include one or two layers of nylon or polyester constricting belts or strips over the steel belts (safety belts or cap plies) [4].

The structure of tires is shown in Figure 1.1.

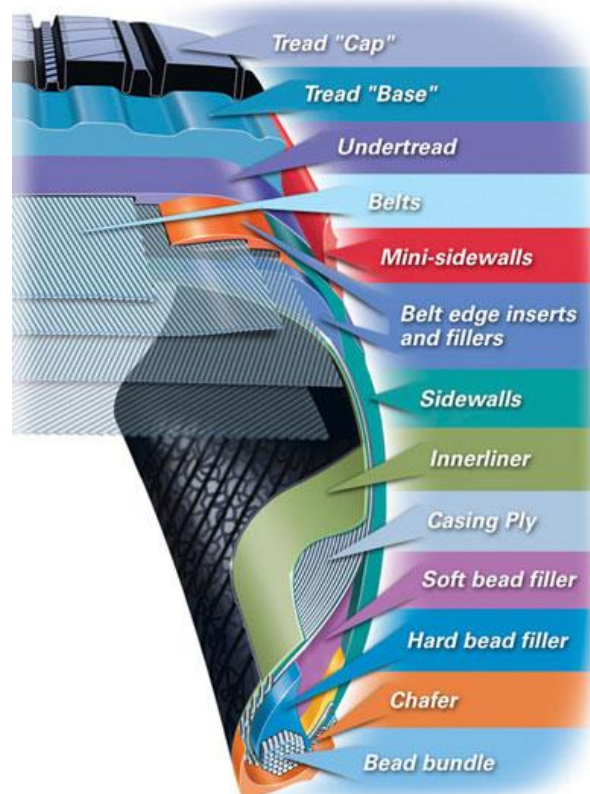


Figure 1.1 Structure of Tires [5].

1.3 Tire Composition

Table 1.1 and Table 1.2 list the major classes of materials used to manufacture tires by the percentage of the total weight of the finished tire that each material class represents. Table 1.1 shows the components of a passenger car tires and Table 1.2 shows the components of a truck tires.

Table 1.1 Passenger Car Tire Components [6]

Component	Percentage of weight
Natural rubber	14 %
Synthetic rubber	27%
Carbon black	28%
Steel	14 - 15%
Fabric, fillers, accelerators ,antiozonants, etc.	16 - 17%
Average weight	New 25 lbs, Scrap 20 lbs.

Table 1.2 Truck Tire Components [6]

Component	Percentage of weight
Natural rubber	27 %
Synthetic rubber	14%
Carbon black	28%
Steel	14 - 15%
Fabric, fillers, accelerators, antiozonants, etc.	16 - 17%
Average weight	New 120 lbs., Scrap 100 lbs.

1.4 Global Tires Production

Pneumatic tires are manufactured according to relatively standardized processes and machinery, in around 450 tire factories in the world. With over 1 billion tires manufactured worldwide annually [7].

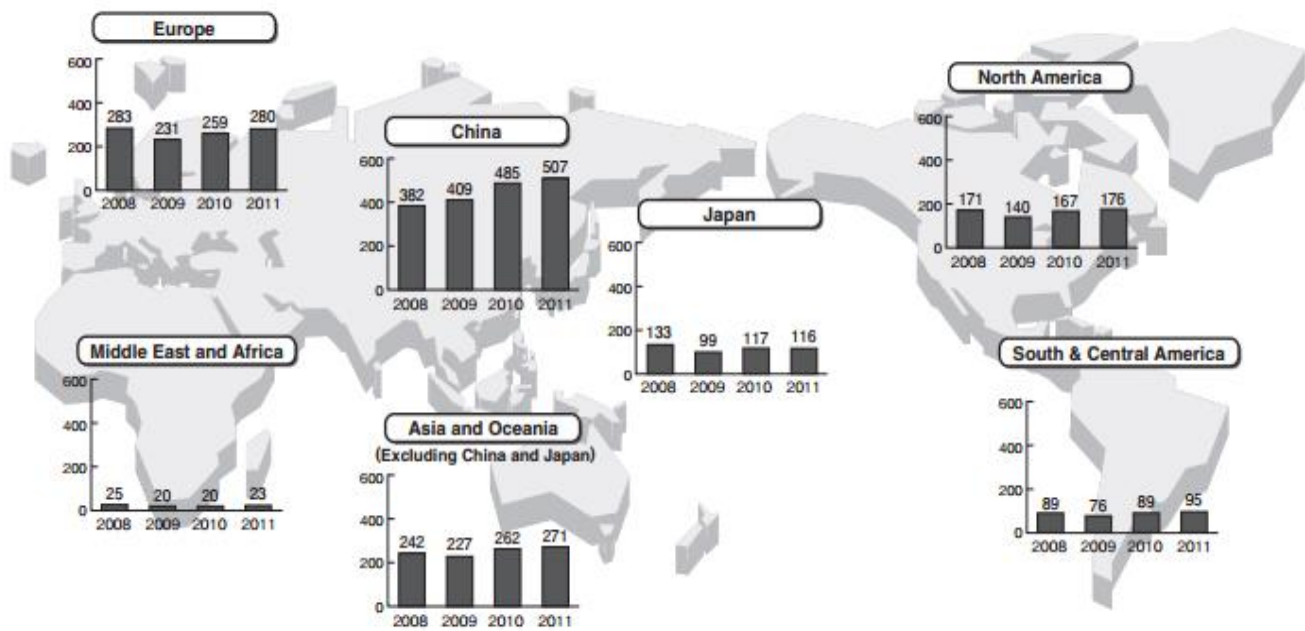
"In 2012 the total production of tires of the world was 14.71 million tons decreased by 1% from the previous year. Out of this volume, the production of Asia and Oceania is estimated to be 63%. Of this, China accounts for 36% and Japan accounts for 8%" [8].

Table 1.3 shows the share of world tire production by geographic region and Figure 1.2 shows the global production of tires, and it is clear that Middle East has the lowest production rate around the world.

Table1.3 Share of World Tire Production by Geographic Region [7]

	2009	2009/2008(%)	2010	2010/2009(%)	2011	2011/2010(%)	2012	2012/2011(%)	composition ratio(%)
Asia and Oceania	7,365	97	8,673	118	8,899	103	9,269	104	63
(China)	(4,090)	(107)	(4,849)	(119)	(4,961)	(102)	(5,261)	(106)	(36)
(Japan)	(998)	(73)	(1,208)	(121)	(1,225)	(101)	(1,160)	(95)	(8)
(Korea)	(457)	(88)	(588)	(129)	(614)	(104)	(633)	(103)	(4)
Europe	2,310	82	2,586	112	2,794	108	2,653	95	18
North America	1,398	82	1,671	120	1,732	104	1,653	95	11
South & Central America	761	86	890	117	905	102	905	100	6
Middle East and Africa	202	82	201	100	224	111	231	103	2
Total	12,036	91	14,021	117	14,554	104	14,711	101	100

Source: IRSG (International Rubber Study Group)



N.B.: 1. Unit: x10,000 tons (produced rubber)
 2. Including tyres other than vehicle tyres.

Source: IRSG (International Rubber Study Group)

Figure 1.2 Global Tire Production [8].

1.5 Overview of Tires in Saudi Arabia

"Demand for tires and tubes is set to grow by 12% annually in Saudi Arabia [8]. Being the largest market for automotive tires in the Middle East, Saudi Arabia still imports them to satiate its needs. It runs up almost \$800 million in imported tire bills alone on a yearly basis. The country imports 13 million tires every year and volumes are expected to keep on rising as consumer demand increases over the next few years. The major products include Tires (passenger, truck, bus, trailers), Tires (OTR, Agricultural, Industrial/ TBR), Rims, Tubes and Casings, Tire Repair Material, Patches, Retreading Material and Equipment" [9].

"A largely import-driven market, as there is little to no local manufacturing, the Saudi market is a magnet for leading international brands, with Japanese and American tire majors leading the way, followed by a strong representation from European and Asian brands. All tires imported into Saudi Arabia have to pass the stringent safety specifications laid down by the Saudi Arabian Standards Organization, before they can be marketed in the country" [8].

"Major companies reigning the market currently are Yokohama, Bridgestone, Hankook, and Michelin. In 2010, Japanese manufacturers topped the list of suppliers with a 41% share of the Saudi import market, while US companies came in fourth place after South Korea and China. Saudi tire industry practitioners believe that prices increases over the last two years has led to some traders buying low-quality low-priced tires instead. On the other hand, although the tire prices are rising, domestic demand in the country has not gone down." [9].

"There are approximately 60 tire brands sold in Saudi Arabia, half of which are well-known brands sourced from companies in the U.S., Japan, South Korea, China, Indonesia, Turkey, India and Europe. Demand is expected to remain high for temperature and traction passenger car tires since they can withstand Saudi Arabia's hot and harsh climate." [9].

1.6 Used Tires

Solid waste management is one of the major environmental concerns worldwide. For the last 30 years many studies have been conducted in order to assess the feasibility of using industrial by-products and waste materials in civil engineering applications. The motive for such

studies has been and still is the high cost, the continuous reduction and negative environmental impact of supplying natural aggregates, the legislation, which bans the disposal of wastes in landfills and recycling in general, which is demanded, in terms of sustainable development [10].

1.6.1 Disposal of Used Tires

Tires that are not recycled or reused are usually shredded and disposed of in landfills, or stockpiled whole. Stockpiling whole tires creates two significant hazards: mosquitoes & fires. Due to their shape and impermeability, tires managed in stockpiles tend to hold water for long periods of time. This stagnant water provides an ideal breeding ground for mosquitoes and sites for mosquito larvae development. Tire stockpiling has contributed to the introduction of non-native mosquito species as used tires are imported from other countries. These new mosquito species are often more difficult to control and spread more disease. Stockpiling whole tires also poses a significant fire hazard. These fires, some of which may be started intentionally, generate large amounts of heat and smoke and are difficult to extinguish [11]. This is due to the fact that:

- Tires, in general, have more heat energy by weight than coal (37,600 kJ/kg vs. 27,200 kJ/kg) [11].
- There is a 75% void space present in a whole waste tire, which makes it difficult to either quench the fire with water or cut off the oxygen supply. Some tire fires have burned continuously for months, such as the 9-month Rhinehart tire fire in Winchester, In addition, tire fires cause damage to surrounding areas. For example, a tire blaze beneath an elevated highway melted the asphalt" [11].

The landfilling of whole tires consume a large volume of landfill space because the tires are relatively incompressible and 75% of the space a tire occupies is void. This void space provides potential sites for gas collection and harboring of rodents. In landfills, waste tires capture explosive methane gas and "float" upward sometimes shooting to the surface with tremendous force and piercing the landfill cover. The primary advantage to landfilling whole tires is that processing costs are avoided. However, landfills' bad experience with whole scrap tires has led to extremely high tipping fees or total bans on whole tires. Shredding or splitting of tires is becoming increasingly common as part of the disposal process. Shredded tires stored above ground pose less of a hazard than do whole tires. Shredding eliminates the buoyancy

problem and makes tires into a material that can easily be landfilled. Shredding can reduce a tire's volume up to 75%. This volume reduction can also reduce transportation costs because fewer trips are required and maximum hauling weights may be achieved more easily. The main disadvantage of shredding waste tires before landfilling is that an extra processing step is required [11].

1.6.2 Used Tires Disposal Related Problems

Massive disposal sites of scrap tires is common in many cities of modern times as about one scrap tire is produced per person every year. The stored used tires slowly degrade under the effects of solar radiation as well as rusting of steel takes place. Degraded material would slowly contaminate soil and underground water over years. The disposal sites waiting under the sun for extended periods of time might catch on fire either by accident or because of bottles or broken glass focusing sunlight. Tires burn with thick black smoke and heat, quickly spreads over the whole disposal area, and leaves oily residue contaminating the soil. Such fires are difficult to put off and generates significant amount of air pollution. One of the overseen problems of scrap tire disposal yards is that these areas become breeding places for rodents and mosquitoes. Stagnant water that collects inside tires is a suitable breeding place for mosquitoes. Elimination of scrap tire disposal sites by proper recycling would also have secondary advantages of eliminating disposal related problems [12].

In Saudi Arabia, there are approximately twenty million (20×10^6) scrap tires are generated annually. Scrap tires that are illegally dumped or improperly stored can pose a serious threat to public health and safety, as well as to the environment. The result can be urban blight and significant costs to residents. Scrap tires can serve as a nesting area for pests and a breeding ground for mosquitos which can spread encephalitis and other illnesses. Waste tires can also catch fire and release toxic smoke.

To eliminate these problems, to have a clean environment and to generate an economic opportunities, scrap tires need to be recycled.

CHAPTER II

Literature Review

CHAPTER 2

LITERATURE REVIEW

2.1 Recycling Definition

Recycling is the process of collecting and processing materials that would otherwise be thrown away as trash and turning them into new products.

It is challenging to find ways to produce more energy, reduce the waste production while minimizing use of limited natural resources [13].

2.1.1 Benefits of Recycling

- Reduces the amount of waste sent to landfills and incinerators.
- Conserves natural resources such as timber, water, and minerals.
- Prevents pollution by reducing the need to collect new raw materials.
- Saves energy.
- Reduces greenhouse gas emissions that contribute to global climate change.
- Helps sustain the environment for future generations.
- Helps create new well-paying jobs in the recycling and manufacturing industries.

2.1.2 Steps of Recycling

- Collection and sorting of the waste material.
- Recycling the waste material.
- Marketing the product of waste material.

2.2 Scrap Tires Recycling

2.2.1 Tires Components

More than 100 raw materials are used in the production of automobile tires, including raw rubber, tire cord, carbon black, bead wire and compounding ingredients. Approximately half of these materials are chemical products based on petroleum, principally naphtha. As a result, the tire industry is dependent on petroleum [6].

The percent distribution of raw materials used in tires in 2012 (Figure 2.1) was approximately the same as the previous year, rubber constituting about half of a tire (natural rubber 29% and synthetic rubber 22%), next comes reinforcing agent 25%, and then tire cord 13% [8].

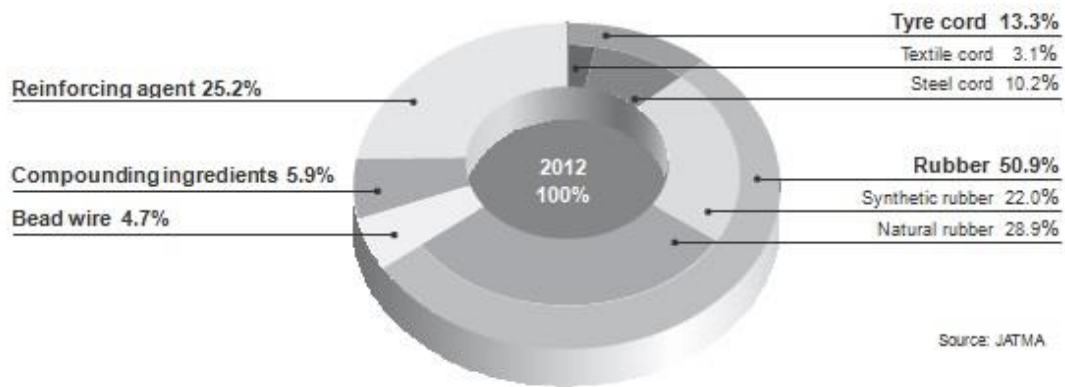
Table 2.1, Table 2.2 and Figure 2.1 show the material composition of tires.

Table 2.1 Basic composition of Tire [8]

Composition	Examples
Rubber	Natural rubber, Synthetic rubber
Compounding ingredients	Vulcanizing agent, Vulcanizing accelerator, Vulcanizing accelerator aid, Antioxidant, Filler, Softener
Reinforcing agent	Carbon black, Silica
Tire cord	Steel cord, Textile cord

Table 2.2 Material Composition of Tire [10]

Material	Avg. %
Rubber	46 %
Carbon black	22%
Metal	20.75%
Textile	5.5 %
Zinc oxide	1.5 %
Sulfur	1 %
Additives	6.25 %

**Figure 2.1** Composition of Tire [10].

Typical percentages of the rubber mix in various types of tires are shown below in table 2.3

Table 2.3 Distribution of SR and NR on different types of tires [13]

Tire Type	Synthetic Rubber	Natural Rubber
Passenger tire	55%	45%
Light Truck Tire	50%	50%
Race Tire	65%	35%
Off Road Tire	20%	80%

2.2.1.1 Brief Description of Some Main Components

- **Natural Rubber**

Natural rubber is a natural polymeric material that obtained from latex sap of trees.

Poly (2-methyl-1,3-butadiene), cis-1,4-Polyisoprene, gum elastic, Indian rubber. These are Synonyms and Trade names for natural rubber [14].

Natural rubber is obtained by cutting the bar of tree called *Hevea brasiliensis*. This tree is located in many countries such as South America, Singapore and Malaysia. There are other trees the natural rubber is extracted from them but *Hevea brasiliensis* is the one that produce a commercial amounts [15].

The chemical formula of natural rubber is:

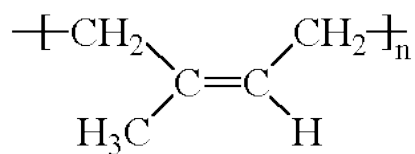


Figure 2.2 Chemical Formula of Natural Rubber [15].

The chain structure of natural rubber:

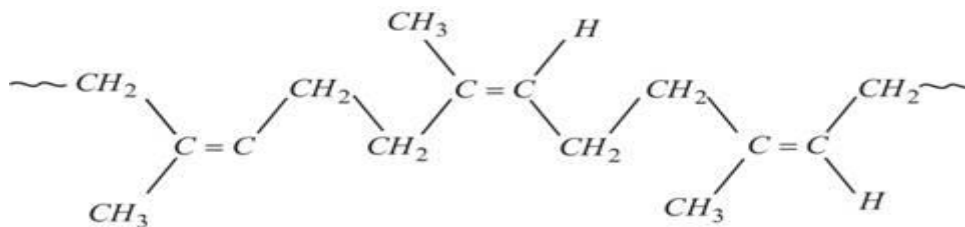


Figure 2.3 Chain Structure of NR [16].

The molecular weight ranges from 100000 to 4×10^6 . The average values of molecular weight of natural rubber between 680000 – 840000.

Natural rubber as raw is a translucent, light yellow to dark brown, soft and elastic material. When keeps below 0 C⁰ rubber getting hardness. On the other hand, with rise of temperature it is getting soft and weak [15].

- **Synthetic Rubber**

Synthetic rubber is a rubber made by copolymerization of isobutylene (2-methylpropene) $(\text{CH}_3)_2\text{C}=\text{CH}_2$ with a small amount of isoprene.

Most of synthetic rubbers are produced by two main stages; First, the production of monomer or monomers, then the polymerization to form rubber. The synthetic rubber is produced from petroleum-based hydrocarbons such as isoprene, butadiene, chloroprene, isobutylene and styrene. To prepare synthetic rubber (Thiokol) there are two steps. First, is the preparation of sodium polysulfide by the reaction of sulfur with a strong base, sodium hydroxide, NaOH. Then, is the reaction of sodium polysulfide with ethylene dichloride [17, 18, 19].

Raw synthetic rubber is colorless, translucent and somewhat elastic substance comparing with natural rubber. Stiffness is lower than natural rubber, but the breaking elongation is higher. Oxidation and cracking-resistance are better than natural rubber, but more corrosive and poorer in tear resistance [18].

It can be seen that many chemical structures (microstructures) are possible and that different catalyst systems result in specific microstructures with different physical properties. The polymerization of isoprene monomer can proceed in a 1,2-, 3,4-, or 1,4- mode to give the structures shown in Figure 2.4 [19].

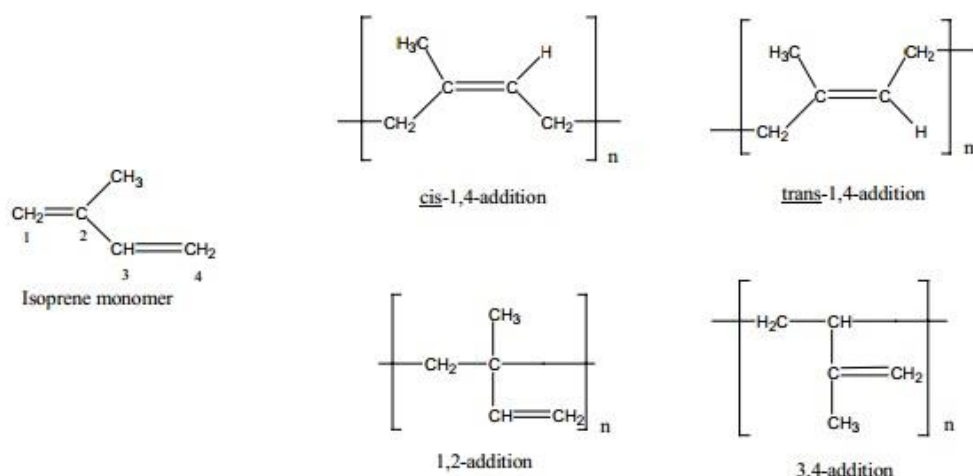


Figure 2.4 Synthetic Rubber Structures [18].

The molecular weight ranges from 5×10^4 to 5.8×10^6 . The average values of molecular weight of synthetic rubber 2×10^6 [21,22]

- **Carbon Black**

Carbon black is virtually pure elemental carbon in the form of colloidal particles that are produced by incomplete combustion or thermal decomposition of gaseous or liquid hydrocarbons under controlled conditions. Its physical appearance is that of a black, finely divided pellet or powder. Acetylene Black, Channel Black, Furnace Black, Gas Black, Lampblack, Thermal Black are synonyms of carbon black. With the exception of sulfur, no other material increased the usefulness of rubber as much as carbon black. It is used in tires, rubber and plastic products, printing inks and coatings. Approximately 90% of carbon black is used in rubber applications, 9% as a pigment, and the remaining 1% as an essential ingredient in hundreds of diverse applications. Carbon black is an additive used with rubber. Most of carbon black produces is used in rubber products with size 1-500 nanometers (nm), and large number of rubber grade carbon black fall in 20-26 nm. The primary purpose for using carbon black is to reinforce the rubber. The reinforcement is meant the enhancement the tensile strength, modulus, abrasion and tear resistance [16, 23].

- **Steel**

Steel is one of the most important and widely used products in the world. Steel refers to an iron-carbon alloy at which the presence of carbon in the alloy in the form of carbides, although steels usually contain other elements as well. The steel belts that used in tires is are made up of thin steel wires that are woven together into thicker cords, then woven again to form large sheets of braided steel. The steel that used in cars is called steel cord. Steel cord is a construction of several thin wires reinforcing the casing and at the same time keeping the tire flexible enough to resist shocks and to improve comfort [21].

The steel used by tire industry is ASTM 1070 and above tire-cord quality wire rod to manufacture new tires. The steel used in tires has two distinct functions. It is used as steel belting (such as that underlying the tread near the outer diameter of tire) in some tires, and for the circular metal component (bead) that is encased in rubber at the inner diameter of tire. The circular metal component assists in sealing the inner diameter against the rim of the vehicle wheel. According to the rubber manufactures association, typical passenger-car tire contains about 1.13 Kg of steel [21].

- **Fabrics**

Fabrics are used as reinforcing materials and designed to keep the tires on shape. They consist more than one component. The main fabrics' components are: Nylon, Polyester and Rayon.

And the percentages are different from tires to tires depending on uses [24].

2.2.2 Recycling of Scrap Tires

Scrap tires recycle is a process where tires are collected then recycled and finally marketed.

Recycling of scrap tires until the 1960's in the US can be taken as an example; about half of the manufactured automobile tires used to be recycled since only synthetic or natural rubber was

used in the tire manufacturing process and tires could have been directly used without major processing.

2.2.2.1 Steps of Recycling Tires

❖ Collection and Sorting

Scrap tire collecting and hauling are critical components in effective use of the tire resource. Collection can be local for small, nearby markets, or regional, for large markets and centralized processing facilities. The impact of efficient collection on the economic viability of scrap tire management alternatives is often underestimated. Hauling, on the other hand, will evolve with the management program.

If no regulations or enforcement exist to govern tire disposal, transportation costs will encourage discarding them at the closest site, especially for small collection vehicles such as pickup trucks. However, once regulations are in place and enforced, competitive pressure will force the use of efficient collection methods and vehicles [25].

- **Methods of Collection**

Scrap tires are normally generated where replacement tires are installed, such as at tire stores, car dealerships, and repair shops. Tires are a naturally segregated waste stream unless they are mixed with other wastes intentionally. They are generally collected separately, without contamination from other materials.

Tires can be collected on scheduled intervals or an as-needed basis. Route collection generally involves trucks travelling scheduled routes at designated frequency, with tires loaded by the driver, an assistant, or store personnel. Tires are counted during loading for invoicing. Charges for this type of pickup are generally based on the number of tires, distance, and other factors.

Trailers are often parked at stores with high volumes and adequate space. The trailers are loaded by store employees and locked to prevent vandalism, dumping, and arson. When the trailer is full, the store notifies the collector and an empty trailer is delivered at the same time that the full trailer is removed. The store is generally charged a fixed fee per trailer based on distance, turnover frequency, gradable casings, and other cost-sensitive factors.

And for sorting there are almost two main categories, either by size or weight [25].

❖ **Recycling**

The recycling of scrap tires may be defined under two different categories: i) using the scrap tires as whole or mechanically modified shapes (in crumps or shredded), and ii) chemical process for separation of scrap tire contents into different materials.

2.2.2.2 Methods of Recycling Scrap Tires

The possible ways of recycling waste tires are as follows:

- **Retreading and reusing of tires**

In this process, the remaining tread is ground away from a tire to be remolded and a new tread rubber strip is fused to the old carcass by vulcanization. The economic potential of the process is major advantage and the quality of the products is a disadvantage of retreading [26].

- **Recycling by production of crumb rubber**

By Ambient or cryogenic processes (cooling of rubber to a temperature ranging between -60 to -100°C) milling of tires the ground rubber of various sizes can be produced. These materials are used in other applications. For example: as component in asphalts, carpets, sport surfaces and children's playgrounds. By the cryogenic process the absence of direct air emissions are the major advantages. However, the high consumption of energy, liquid nitrogen in the cryogenic process and the limited market for the products are the main disadvantages of the process [26].

- **Combustion**

Waste tires can be used directly as fuels in the incinerators. Due to their high heating value (36 MJ/Kg) scrap tires are excellent materials for energy recovery. The use of tires directly as fuel in incinerators has the following advantages: Reduced power-production costs, maximum heat recovery, and environmentally acceptable process. The disadvantages are: no material

recovery, large capital investment, need for flue gas cleaning, CO₂ emission, high operating costs. Scrap tires are used also as fuel in cement kilns and paper mills [26].

- **Pyrolysis**

Tire pyrolysis (thermal decomposition in an oxygen-free environment) is currently receiving renewed attention. Recycling of tires by pyrolysis offers an environmentally attractive method. The products of the tire pyrolysis process are: Solid char (30-40 wt %), liquid residue (40-60 wt %), and gases (5-20 wt %). The solid residue contains carbon black and the mineral matter initially present in the tire. This solid char may be used as reinforcement in the rubber industry. Also, the derived oils may be used directly as fuels, petroleum refinery feedstock or a source of chemicals. The gaseous fraction is composed of non-condensable organics as, H₂, H₂S, CO, CO₂, CH₄, C₂H₄, C₃H₆ etc. The gas fraction can be used as fuel in the pyrolysis. There are several methods are used in pyrolysis to generate the heat: [26].

- Combustion.
- Ultrasonic.
- Microwave.
- Plasma.

- **Devulcanization**

Devulcanization means returning rubber from its thermoset, elastic state back into plastic, moldable state.

Devulcanization on the other hand is, literal, the reverse process of vulcanization, meaning that sulphidic crosslinks are cleaved, since only carbon-sulfur and sulfur-sulfur bonds are formed during vulcanization [27,31].

- **Liquefaction**

When the tire and coal were co-liquefied at 400°C it was observed that the conversion of coal increased in the same way as with the addition of hydrogen to coal.

That depends on several factors such as Temperature, hydrogen pressure and ratio of coal/tire [28,33].

2.2.2.3 Processes of Recycling Scrap Tires

The main parts of recycling tires are:

- **Reduce The Size of Tires**

Actually, most of process are required a small particles of tires. So, to reduce the particles to a certain size there are two main methods of size reduction:

- Ambient Size Reduction (Ambient Grinding)

Ambient size reduction is a grinding process to reduce the feedstock to a needed size where referred to as “Ambient” because all size reduction steps take place at or near ambient temperature (room temperature), no cooling is applied to reduce the size.

Ambient grinding is a multi-step processing technology that uses a series of machines (usually three) to reduce the size of tires and to separate the rubber, metal and fabric composition from the tire.

Whether using granulation equipment or cracker mills, the first processing step is typically reduce the original feedstock to small chips. The second machine in the series will grind the chips to separate the rubber from the metal and fabric. Then a finishing mill will grind the material to the required product specification. After each processing step, the material is classified by sifting screens that return oversize pieces to the granulator or mill for further processing. Magnets are used throughout the processing stages to remove wire and other metal contaminants. In the final stage, fabric is removed by air separators [10].

- Cryogenic Size Reduction

Cryogenic processing refers to the use of liquid nitrogen or other materials/methods to freeze tire chips or rubber particles prior to size reduction. Most rubber becomes embrittled or "glass-like" at temperatures below -80°C. The use of cryogenic temperatures can be applied at

any stage of size reduction of scrap tires. Typically, the size of the feed material is a nominal 2 inch chip or smaller. The material can be cooled in a tunnel style chamber, immersed in a "bath" of liquid nitrogen, or sprayed with liquid nitrogen to reduce the temperature of the rubber or tire chip. The cooled rubber is ground in an impact type reduction unit, usually a hammer mill.

Cryogenic grinding avoids heat degradation of the rubber and produces a high yield of product that is free of almost all fiber or steel, which is liberated during the process [10].

- Tire derived fuel (TDF)

While uncontrolled tire fires cause substantial air and ground pollution, the incineration of whole tires or tire chips in industrial furnaces is environmentally safe.

Tires can be used to generate energy by combustion tires. The calorific value of tire derived fuel (TDF) exceeds that of coal Table 2.6, while the sulfur content is in the same order of magnitude or even lower. Tire size depends on type of furnace. That means it can be used either as whole or as crumb [21, 26].

Table 2.4 Energy Content of Fuel

Fuel	Heating Value
Heating oil	42 MJ/Kg
Natural gas	38 MJ/m ³
Coal	25 MJ/Kg
Wood biomass	20 MJ/Kg
Tires	36 MJ/Kg
Mixed Plastic waste	43 MJ/Kg

As an alternative energy source to coal, oil and natural gas, TDF is consumed by cement kilns, pulp and paper mills, and power plants across the continent.

In Addition, a million tires used as fuel in place of coal reduces carbon dioxide emissions by 19.5 percent [29].

❖ Application and uses:

Of the 130 million scrap tires used as fuel per year:

- Cement industry - 41 percent
- Pulp and paper mills - 20 percent
- Electric utilities - 18 percent
- Industrial/ institutional boilers - 13 percent
- Dedicated tire-to-energy facilities - 8 percent [29]

2.3 Used Tires in Cement Industry

Cement is produced in high temperature kilns as the raw materials are placed in cement kiln and heated to a temperature range of 1455 to 1510 °C (2650 to 2750 °F). At this temperature the formation of tricalcium silicate (ALITE), the principal compound of portland cement clinker, occurs. A flame temperature of 1925°C (3500°F) is necessary to be obtain at this temperature. Scrap tires (TDF) can be completely destroyed in cement kilns(Figure 2.5) since the temperatures are extremely high along with a positive oxygen atmosphere and relatively long periods of 4 to 12 seconds at the elevated temperatures ensures the complete combustion of the scrap tire; therefore, incomplete combustion or black smoke or odors release is prevented [30].



Figure 2.5 Uses of Scrap Tires as TDF [30].

Whole tires contain approximately 30 GJ/ton of energy, and this value increasing to 36 GJ/ton if most of steel is removed. Compared with the average coal (25 GJ/ton), a kiln operator can reduce coal consumption by 1.25 Kg for every 1 Kg of TDF used [30].

Another point of interest is that tires tend to contain less sulfur than most coals. Sulfur in tires ranges from 1.24 to 1,30 wt %. Sulfur in coal ranges from 1.1 to 2.3 wt % or higher, depending on the coal quality. The average coal used in the cement industry contains about 1,5 wt % sulfur.

On the other hand, in Saudi Arabia the fuel is used in the cement industry is different than coal. In addition, the energy in Saudi Arabia is cheaper than other countries. So, due to the high calorific value of scrap tires and their cost it would be more useful to be used as alternative fuel.

Finally, using whole tires as TDF reducing the operating cost relative to 100% coal. The use of scrap tires reduces the amount of coal used and consequently lowers the cost of coal consumption [12].

2.4 Environmental Impacts

Worldwide, the amounts of tires are often uncontrollably deposited, even because of the noticeable rapid depletion of available sites for waste disposal, causing great environmental problems. Water accumulation inside tires provides ideal temperature and moisture conditions for the spreading of mosquitoes, mice, rats and vermin. Tire crowd has contributed to the introduction of non-native mosquito species as used tires are imported from other countries. The new species of mosquitos are usually more difficult to control and spread more disease. At the same time the quantity of oxygen that exists in the interior of the tires is enough to cause fire in appropriate conditions because of its inflammable components with the resulting negative impact on the atmosphere and on human's health [34].

2.5 Economic Potentials

The benefit from tire recycling represents in different views. Starting from getting rid of scrap tires are occupied high number of square meters of white lands until getting valuable products. From economical point of view, the most problem with tire recycling is transportation. There are different methods to recycle tires.

In general, the tire could be used as whole or after reduced its size. It can be used in cement industrial as whole as an alternative fuel due to the high calorific value 30 GJ/ton of energy which is greater than coal. But in Saudi Arabia the oil fuel is used in cement industry. After the size reduction, three products will be produced crumb rubber, steel and fabric. Each one of these product is sold in the market [35].

There are further processes such as devulcanization and liquefaction. There is a petrochemical process which is pyrolysis. The products of pyrolysis as mentioned before Solid, Liquid and Gas. There are further process can be done on solid to get valuable product such as activated carbon or carbon black. In addition, the liquid oil can be sold directly as it or separate it by distillation column to have different products such as Benzene, Toluene and Xylene. Finally, the gas is used as heating media for the reactor, there for the process will be a closed loop [35].

CHAPTER III

Production of Crumb Rubber

CHAPTER 3

PRODUCTION OF CRUMB RUBBER

Crumb rubber is the name given to any material produced by reducing scrap tires or other rubber into uniform granules with removal of reinforcing materials such as steel and fiber along with any other type of inert contaminants such as dust, glass, or rock [36].

Crumb rubber is manufactured from two primary feed stocks: tire buffings, a byproduct of tire retreading and scrap tire rubber. Scrap tire rubber comes from three types of tires: passenger car tires, truck tires and off-the-road tires. End product yields for each of these tire types are affected by the tire's construction, strength and weight. On average, minimum of 5 kg of crumb rubber can be derived from one passenger tire [36].

Two methods are typically used. Ambient (dry grinding) and Cryogenic (freezing and cracking). The final product is sieved and separated into different size categories according to the feed specification of the next process or to the required application. If it is going to be used as is without further processing. The resulting product can then be used by numerous different industries to add desired properties as well as reduce the amount of other more costly materials or it can be used as feed stock the another chemical process in order to get a full benefits of recycling process [37].

3.1 Crumb Rubber Manufacturing Technology

Generally, crumb rubber is produced by reducing scrap tires down to sizes ranging from 4 mm (5 mesh) to 0.6 mm (30 mesh) particles and removing 99 percent or more of the steel and fabric from the scrap tires. There are several processes for manufacturing crumb rubber. Two main methods are used to grind tires to a required size: the first method is related to ambient size reduction using mechanical processes at or above room temperature and the second one is related to cryogenic size reduction by the use of liquid nitrogen or commercial agents to reduce it to a desired size. A third technology-the wet grind process-is also in use in the U.S. to produce finer mesh crumb rubber ranging from 40 mesh to 200 mesh [10, 37].

3.1.1 Ambient Process

Ambient grinding can be accomplished in two ways: granulation or cracker mills. In an ambient system, the rubber, tires or other feedstock remain at room temperature as they enter the cracker mill or granulator, i.e. no cooling is applied to embrittle the rubber particles.

Ambient grinding is conducive to any size particle, including whole tires. It can be accomplished in two ways: granulation or cracker mills. In an ambient system, the rubber, tires or other feedstock remain at room temperature as they enter the cracker mill or granulator.

Ambient grinding is a multi-step processing technology that uses a series of machines (usually three) to separate the rubber, metal, and fabric components of the tire. Whether using granulation equipment or cracker mills, the first processing step typically reduces the original feedstock to small chips. The second machine in the series will grind the chips to separate the rubber from the metal and fabric. Then a finishing mill will grind the material to the required product specification. After each processing step, the material is classified by sifting screens that return oversize pieces to the granulator or mill for further processing. Magnets are used throughout the processing stages to remove wire and other metal contaminants. In the final stage, fabric is removed by air separators.

In a typical plant layout, the tires are first processed using a preliminary double shaft shredder which produce rubber chips from 70 to 100 mm. The tire chips then enter a granulator, where the chips are reduced to a size of less than 10 mm in diameter, while liberating most of the steel and fiber from the rubber granules. After exiting the granulator, steel is removed magnetically. In order to move the material from one step to the other conveyer belts are present, and magnetic belts are used for iron scrap separation. The last step is the fine grinding of the tire material to a size lower than 1 mm. The machines most commonly used for fine grinding in ambient plants are: Secondary granulators, High speed rotary mills, Extruders or screw presses and Cracker mills.

Ambient grinding can be operated safely and economically if the bulk of the rubber output needs to be relatively coarse material, i.e., down to approximately 20 mesh material.

Rubber particles produced in the granulation process generally have a cut surface shape and rough texture, with similar dimensions on the cut edges, and tend to be partly devulcanized.

Cracker mills - primary, secondary or finishing mills - are all very similar and operate on basically the same principle: they use two large rotating rollers with serrations cut in one or both of them. The roll configurations are what make them different. These rollers operate face-to-face in close tolerance at different speeds. Product size is controlled by the clearance between the rollers. Cracker mills are low speed machines operating at about 20-50 RPM. The rubber usually passes through two to three mills to achieve various particle size reductions and further liberate the steel and fiber components.

These mills do not have screens built into the mill and as such the mill itself does not control the final particle. A stand-alone screening system will separate “sized” particles from oversize granules following the mill and re-circulate the oversize products. The crumb rubber particles produced by the cracker mill are typically long and narrow in shape and have a high surface area [10, 21, 36, 38].

Figures 3.1 and 3.2 show two examples of typical ambient grinding systems:

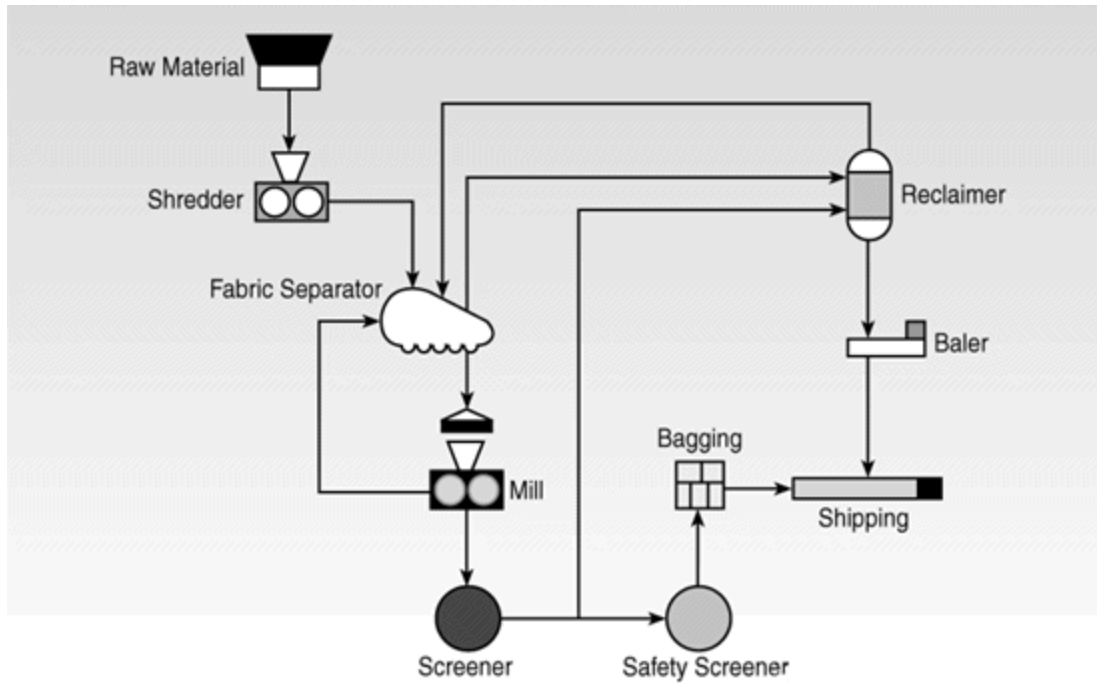


Figure 3.1 Typical Ambient Grinding System [36].

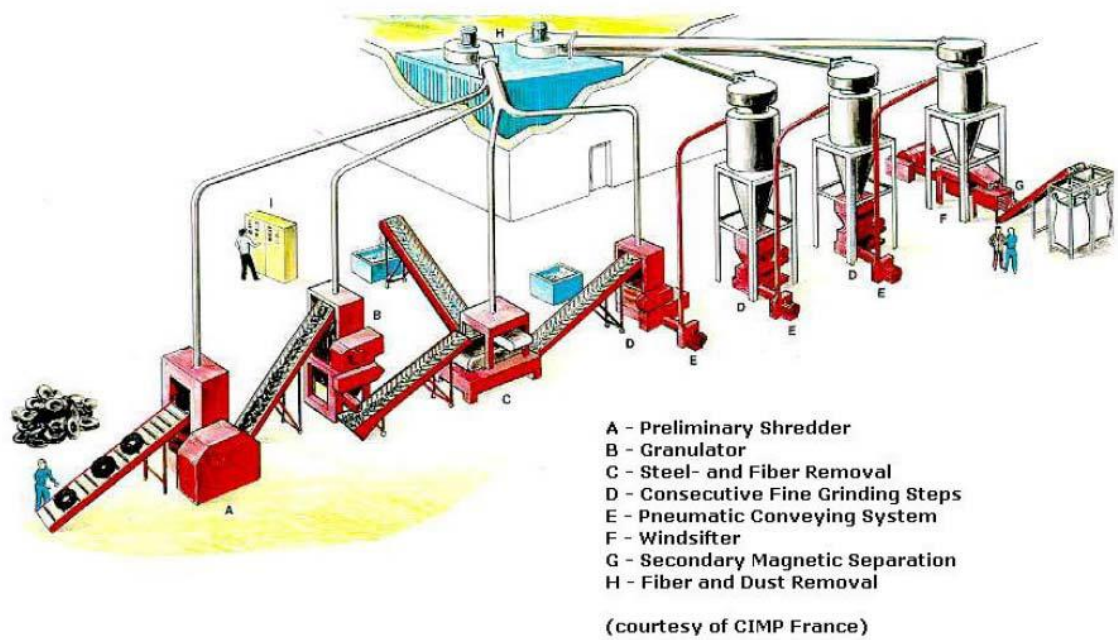


Figure 3.2 Schematic Diagram of an Ambient Scrap Tire Processing Plant [10].

3.1.2 Cryogenic Process

This process is called “cryogenic” because whole tires or tire chips are cooled down to a temperature of below -80°C (-112°F). Below this “glass transition temperature”, rubber becomes embrittle or “glass-like” and size reduction can be accomplished by crushing and breaking. Using of liquid nitrogen or other materials/methods to freeze tire chips or rubber particles prior to size reduction.

Typically, the size of the feed material is a nominal 2 inch chip or smaller. The material can be cooled in a tunnel style chamber, immersed in a "bath" of liquid nitrogen, or sprayed with liquid nitrogen to reduce the temperature of the rubber or tire chip. The cooled rubber is ground in an impact type reduction unit, usually a hammer mill. This process reduces the rubber to particles ranging from 1/4 inch minus to 30 mesh, with the majority of the particle distribution between 1/4 inch minus and 20 mesh.

Preliminary treatment of scrap tires (debeading, pre-shredding) is pretty much the same as in ambient plants. In the cryogenic process, the 2” (50 mm) tire chips are cooled in a continuously operating freezing tunnel to below -120°C and then dropped into a high RPM hammer mill. A typical throughput is 4,000 to 6,000 pounds per hour.

In the hammer mill, chips are shattered into a wide range of particle sizes, while, at the same time, liberating fiber and steel. Because the rubber granules may still be very cold upon exiting the hammer mill, the material is dried before classification into different particle sizes. Cryogenic grinding avoids heat degradation of the rubber and produces a high yield of product that is free of almost all fiber or steel, which is liberated during the process.

For scrap tire derived rubber, the steel is separated out of the product by the use of magnets. The fiber is removed by aspiration and screening. The resulting material appears shiny, has clean, fractured surfaces and low steel and fiber content and has very sharp edges of the particles and less surface area. The final product has a range of particle sizes, which can be used as is or further size-reduced. Production of finer (40 to 60 mesh) and very fine crumb rubber (60 minus and smaller mesh) requires a secondary high intensity grinding stage [10, 21, 36].

Figures 3.3 and 3.4 show two examples of typical cryogenic grinding systems:

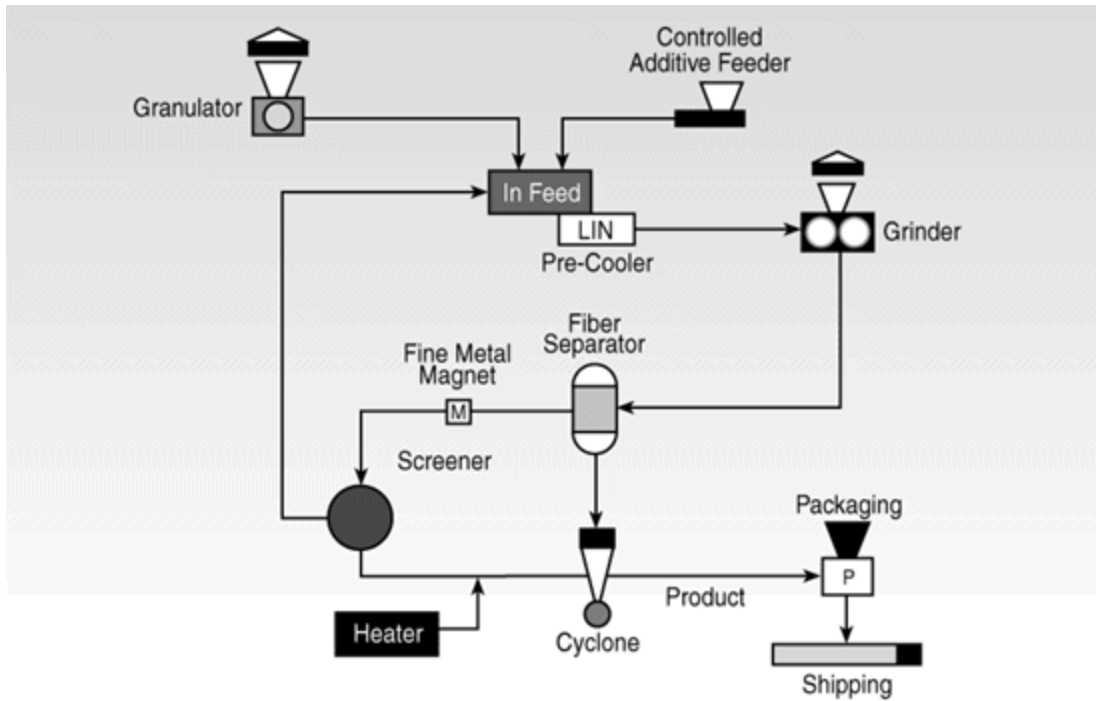


Figure 3.3 Typical Cryogenic Grinding System [36].

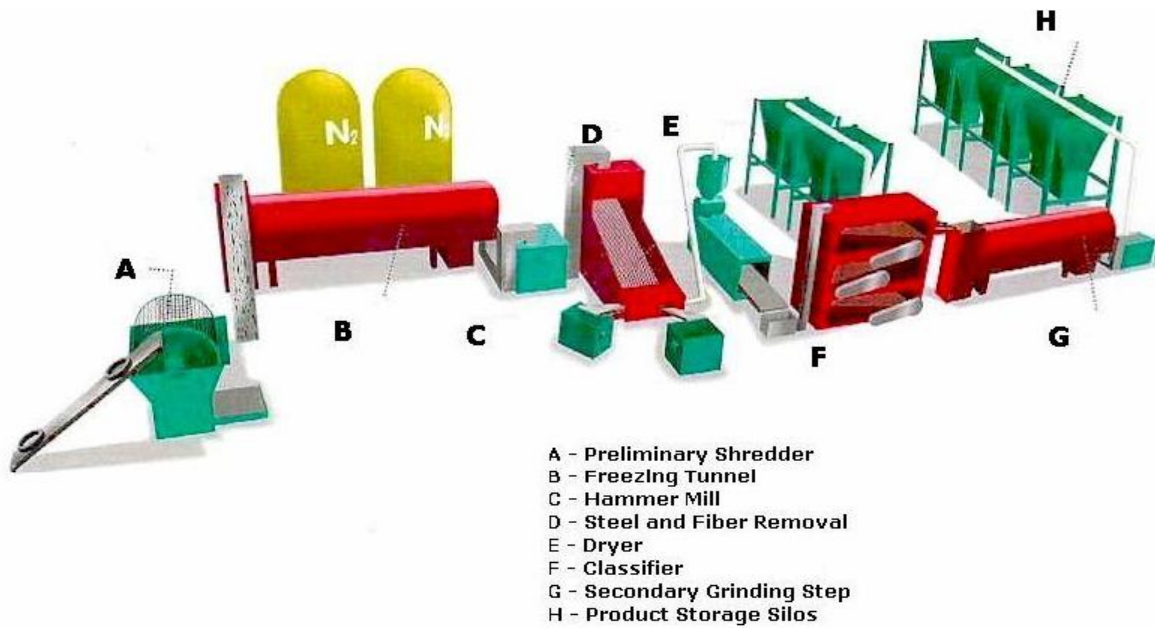


Figure 3.4 Schematic Diagram of a Cryogenic Scrap Tire Processing Plant [10].

3.1.3 Wet Grind Process (Ambient Method)

Micro milling, also called wet grinding, is a processing technology used to manufacture crumb rubber that is 40 mesh and finer.

The wet grind process mixes partially refined crumb rubber particles with water creating a slurry. This slurry is then conveyed through size reduction and classification equipment. When the desired size is achieved, the slurry is conveyed to equipment for removing the majority of the water and then drying. Aside from the use of water, the same basic principles that are used in an ambient process are utilized in a wet grinding process.

The major advantage for a wet grind process is the ability to create fine mesh crumb rubber. While products as coarse as 40 mesh are produced, the majority of the particles are 60 mesh and finer. A percentage of the overall throughput is finer than 200 mesh. Another advantage for a wet grind process is the cleanliness and consistency of the crumb rubber produced. The process literally “washes” the crumb rubber particles. The wet process removes the fine particles of fiber from the crumb rubber making a very clean product.

The wet process also produces a unique morphology in the particles. This has proven effective in the manufacturing of several goods used in automotive applications and in certain molded goods [36].

3.2 Comparison between Ambient and Cryogenic Technology

The question, which is “the best” processing technology for scrap tires, is often discussed in the industry. The answer to this question depends on a multitude of factors. It must be emphasized that, crumb rubber is not a standard commodity and is rarely sold solely based on specifications submitted in writing. In most cases, buyers of crumb rubber require samples for field tests before purchasing larger batches. Some buyers are very specific about what type of material (ambient or cryogenic) they require, whereas others do not have such preferences.

Thorough knowledge of the local and regional market requirement is a must before making the decision. Table 3.1 compares some of the most important parameters in cryogenic and ambient grinding processes [36].

Table 3.1 Comparison between Ambient and Cryogenic Processing [39]

Parameter	Ambient	Cryogenic
Operating Temperature	Max. 120 °C	Below – 80 °C
Size Reduction Principle	cutting, tearing, shearing	Braking cryogenically embrittled rubber pieces
Particle Morphology	spongy and rough, high specific surface	even and smooth, low specific surface
Particle Size Distribution	relatively narrow particle size distribution, only limited size reduction per grinding step	wide particle size distribution (ranging 10 mm to 0.2 mm) in just one processing step
Maintenance cost	Higher	Lower
Electricity Consumption	Higher	Lower
Liquid N ₂ Consumption	N/A	0.5 – 1.0 kg liquid N ₂ per kg tire input

Table 3.2 compares some of the most important parameters of crumb rubber produced by cryogenic and ambient processes. And the environmental effects of ambient and cryogenic processes are shown in Table 3.3.

Table 3.2 Comparison between Ambient and Cryogenic Crumb Rubber [10]

Physical property	Ambient Ground	Cryogenic Ground
Specific gravity	Same	Same
Particle shape	Irregular	Regular
Fibre content	0.5%	Nil
Steel content	0.1%	Nil
Cost	Comparable	Comparable

Table 3.3 Comparison of Environmental Effect of Ambient and Cryogenic Processes [39]

Parameter	Ambient	Cryogenic
Greenhouse Effect	122 kg Co2 / t tire	455 kg Co2 / t tire
Solid Waste Indicator'95	-1196 kg solid waste / t tire	-724 kg solid waste / t tire
ECO-Point	0.278 ECO-point / t PFU	42.543 ECO-point / t PFU

Generally speaking, cryogenic scrap tire processing is more economical if clean, fine mesh rubber powder is required.

Both ambient and cryogenic processing can be repeated to produce finer particles. Increasingly, the two methods with their attendant technologies, are combined into one continuous system in order to benefit from the advantages and characteristics of each and to reduce overall costs.

The ambient system is generally used for the initial size reduction phases. The cryogenic system is used to further reduce the material size and then to remove the metals and textiles. The outputs from either or both systems can be used directly or as feedstock for further processing [39].

3.3 Flow Sheet Diagram of Scrap Tires Size Reduction Plant

The following flow sheet has been selected (Figure 3.5). An ambient process has been selected because the cryogenic process requires liquid nitrogen, therefore to provide liquid nitrogen must establish a full side process. On the other hand, it is possible to buy it from the market but this will increase the cost and affect the economics of the whole recycling process. In addition, cryogenic process is used to produce a very fine particle which is not much required for further processes. The process have a series of three different size reduction equipment. The feed size is around 1000 to 1200 mm with a capacity of 5 metric tons per hour. The final product size is around 1 mm crumb rubber. Bur the optimum size for pyrolysis process is 4 cm³ which is produced after the secondary crushing. Therefore, 70 % of the output of the secondary crushing is collected and used as feedstock to the pyrolysis process and the remaining 30 % is allowed to

go for further reduction to produce crumb rubber. 90 % of steel is removed in the primary stage and the remaining 9.9 % is removed in the final stage. 85 % of fabric is removed in the primary stage and the remaining 14.9 % is removed in the final stage. The system produces black granules with almost no visual impurities such as textiles, steel, etc. Table 3.4 shows the compositions of feed stream components.

Table 3.4 Compositions of Feed Stream Components

Component	Symbol	Mass Fraction (x)
Rubber	R	0.51
Steel	S	0.15
Fabric	F	0.03
Reinforcing Agent	A	0.25
Compounding ingredients	I	0.06

Sh-101: Shredder, Cr-101: Granulator, Cr-102: Cracker Mills, Sc-101: Disk Screen Classifier, Sc-102: Screen, Sc-103: Zigzag Classifier, MB-101: Magnet Belt, Cy-101: Cyclone, DM-101: Drum Magnet, B-101: High Pressure Central Blower.

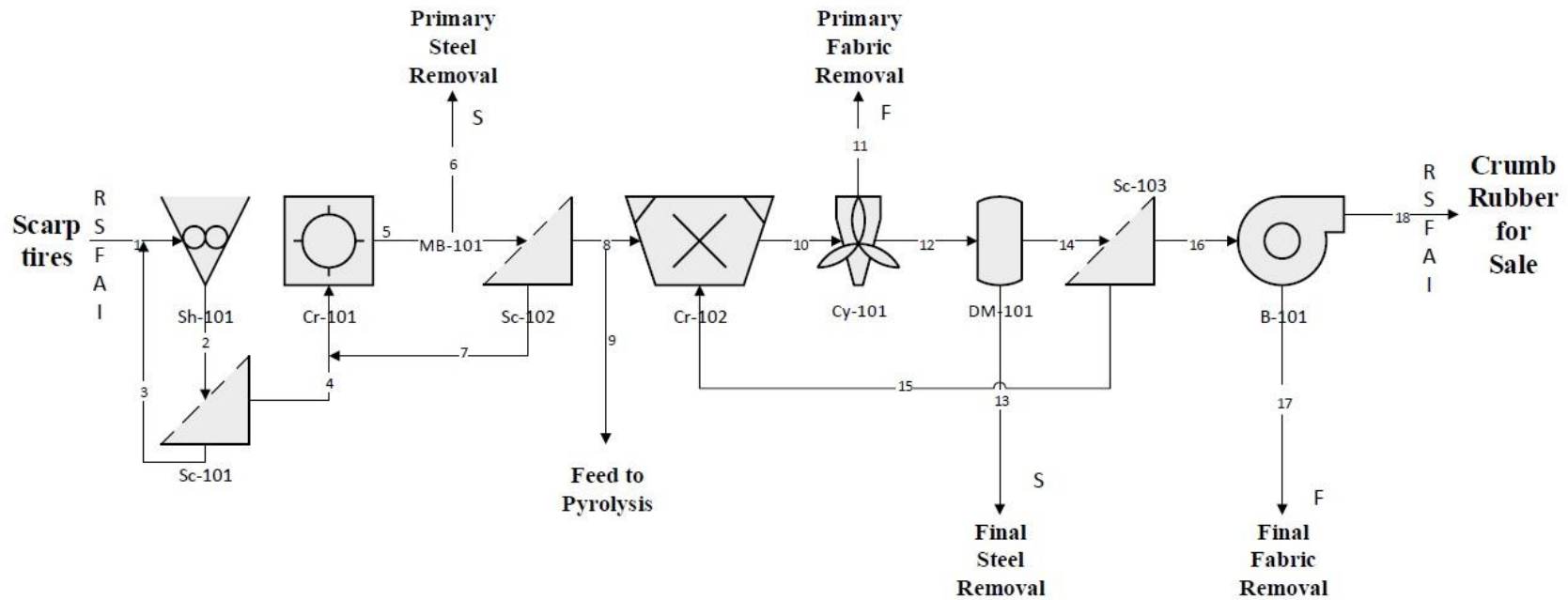


Figure 3.5 Flow Sheet Diagram of Scrap Tires Size Reduction Plant

3.4. Size Reduction

The term size reduction is applied to all the ways in which particles of solid are cut or broken into smaller pieces. Throughout the process industries, solids are reduced by different methods for different purposes. Commercial products must often meet stringent specifications regarding the size. Scrap tires reduced into powder (crumb rubber) of approximately 1 mm in diameter. Also, it reduced into 4 cm^3 as a feed to the pyrolysis process [40].

3.4.1 Equipment

To achieve the required size product, a series of size reduction equipment are needed. A brief description of the equipment used in the previous flow sheet is given below.

3.4.1.A Shredder

The scrap tire reduced into mostly 2" chips. The most common machines used for shredding scrap tires are rotary shear shredders with two counter rotating shafts which is the one used in our flow sheet. The machines are designed to work at low RPMs (20 to 40 RPM) and high torque and can easily handle all sorts of tires in the range of 1000 to 1200 mm in diameter. Most shredders are powered by electric motors (approx. 100 KW) for a system with 1 metric ton/hr as a feed, depending on the input material and the size of the chips produced [39, 41].

3.4.1.B Granulator

A machine that shears apart scrap tire rubber, cutting the rubber with revolving steel plates that pass at close tolerance, reducing the rubber to a size around 4 cm^3 . Most granulators are powered by electric motors (approx. 150 KW) for a system with 1 metric ton/hr as a feed [36, 41].

3.4.1.C Cracker Mill

A machine that tears apart scrap tire rubber by passing the material between rotating serrated steel drums, reducing the rubber to approximately 1 mm in size. The rolls of these

crackers are engineered using superior grade of Chilled Cast Iron to guarantee wear-resistant hard surface. All these mills are equipped with Anti friction roller bearings and give high output at lower operating cost. Most cracker mills are powered by electric motors (approx. 200 KW) for a system with 1 metric ton/hr as a feed [41, 42].

3.4.1.D Disk Classifier

The screens or sieves that are mounted in a production piece of equipment to separate the desired size of crumb from the other sizes, and recycle the other for the purpose of further size reduction [36].

3.4.1.E Zig-zag Classifier

The Zigzag classifiers permit precise separations in the range from approx. 0.1 - 10 mm with throughputs up to 5000 kg/h depending on the models. The cut point is easily and steplessly adjustable by means of a throttle flap [42].

3.4.1.F Conveyors

Conveyors transfer scrap tires from one location to another - vertical and horizontal. Vertical conveyors typically inclined by 40 degree angle to avoid accumulation of heavies. On a picking line, wastes dropped onto conveyors by front end loaders tends. They require maintenance due to dusty environment [44].

3.4.1.G Pneumatic Conveyors

Used to convey materials large distances across the plant [44].

3.4.1.H Drum Magnet

Rotating Drum Magnets are designed for continuous self-cleaning of metal contaminants from product flow streams. As scrap tires enters the housing inlet, an adjustable feed gate meters the flow of product to the drum face. The drum has a stationary, 180 degree arc, internal magnet, with an outer drum that rotates. When scrap tires passes over the powerful magnetic field, metal contaminants are attracted to the drum surface where they are safely held on to until the ferrous

material passes through the magnetic field where it is discharged to the rear of the drum housing. Cleaned free steel crumb rubber is discharged to the front of the drum housing [45].

3.5 Testing and Distribution

All crumb rubber products undergo routine quality testing including particle distribution, moisture content and metal contamination.

Different categories of source materials are used to produce size reduced rubber with differing properties and characteristics. As an example, the same size and consistency of material can be produced from truck tires, from passenger car tires, from buffings and from solid tires, using the same processing technology. However, the resulting materials may have different physical and chemical characteristics depending on the material source category, and will consequently be more suited to different end use applications. Source materials are generally separated at the point of collection and separation is maintained throughout the transportation, initial storage, and size reduction processes. Furthermore, a number of properties are generic and cannot be controlled or changed during the size reduction process.

3.5.1 Quality Tests

There is no standard for processing crumb rubber. Nearly every crumb rubber manufacturer has their own unique processing system that they have tweaked and modified to meet customers' specifications or end-product requirements. As a result, crumb rubber quality varies from operation to operation.

Despite this variability several key requirements for crumb rubber have emerged and are becoming the industry-recognized product characteristics that determine quality. In general, high quality crumb means low fiber content (less than 0.5 percent of total weight), low metal content (less than 0.1 percent) and high consistency. The accepted level of maximum moisture content is about 1 percent by weight. Excess moisture content limits crumb rubber use in many applications, especially molded and extruded products. Excess heat during processing can also degrade the rubber.

In addition, processors have adopted a “clean” standard for crumb rubber. At minimum producing higher quality, cleaner crumb rubber involves pre-qualifying feedstock and introducing and re-introducing crumb rubber to multiple types of equipment including magnets, density separators, and reciprocating screens to remove contaminants and sort the crumb rubber to the required sizes for different markets [36].

3.5.2 Crumb Rubber Standards

ASTM International, formerly the American Society for Testing and Materials (ASTM) produces the largest voluntary standards development systems in the world. This not-for-profit organization publishes thousands of standards per year used around the world to improve product quality, enhance safety, facilitate market access and trade, and build consumer confidence. Working in an open and transparent process, ASTM producer, user and consumer members participate in developing industry standards, test methods, specifications, guides and practices that support industries and governments worldwide [36].

There are several ASTM standards that apply to crumb rubber:

ASTM D5603 Standard Classification for Rubber Compounding Materials-Recycled Vulcanizate Particulate, classifies vulcanized particulate rubber according to maximum particle size, size distribution and parent materials including whole tires, tire peels, buffings generated from the tire tread and shoulder, buffings generated from tire tread, shoulder and sidewall and non-tire rubber [36].

ASTM D5644 Test Methods for Rubber Compounding Materials-Determination of Particle Size Distribution of Recycled Vulcanizate Particulate Rubber, discusses methods of determining particle size and particle size distribution for crumb rubber. The standard refers to the use of a mechanical sieve shaker for determining particle size and particle size distribution for crumb rubber and gives experimental details of running the test. Particle size and particle size distribution of recycled rubber depends on the end use of the material and may affect its handling, processing, and properties. Therefore, methods for analyzing particle size and particle size distribution are important tools for the rubber recycling industry [36].

3.6 Applications and Uses of Crumb Rubber

Rubber crumb is sold as feedstock for chemical devulcanization or pyrolysis processes, added to asphalt for highway paving and pavement sealers, or used for the production of a large number of recycled rubber-containing products. Some of the major applications of crumb rubber are as follows [48]:

Sport Surfaces

- Kindergarten Playgrounds and Recreation Areas.
- School Sports Areas.
- Athletic Tracks.
- Tennis and Basketball Courts.

Automotive Industry

- Bumpers.
- Splash Guards and Fenders.
- Floor Mats for Cars and Trucks.
- Floor Liners for Trucks and Vans.

Construction

- Hospital, Industrial, and Bathroom Flooring.
- Floor Tile.
- Foundation Waterproofing.
- Dam, Silo, and Roof Liners.

Adhesives and Sealants

- Adhesives and Sealing Compounds.
- Textured and Non-Slip Paints.
- Roof Coating and Waterproofing.

Geotechnical/Asphalt Applications

- Rubberized Asphalt for Roads and Driveways.
- Drainage Pipes.
- Soil Conditioner.
- Porous Irrigation Pipes.
- Road Building and Repair.

Shock Absorption and Safety Products

- Shock Absorbing Pads for Rails and Machinery.
- Sound Barriers for Highways.
- Abrasion Lining in Mining Equipment.

Rubber and Plastic Products

- Pipe Insulation and Lining.
- Garbage Cans.
- Shoe Soles and Heels.
- Wire and Cable Insulation [48].

3.7 Field Visit

In the 26th of March 2014, the group has arranged a visit to a manufacture that produces a crumb rubber. The manufacture is located in Riyadh industrial city. Fifteen tones of tires are the daily average production of crumb rubber.

There are different sizes of crumb rubber. First is mish 8, which is the largest size. Then is mish 16, which is finer than the first one. Third size is mish 30 which is the finest size called powder.

In general, there are mainly two fields that concerned with crumb rubber. First, is the Asphalt preparation for roads, they used crumb rubber to enhance the properties of asphalt. Second, is at football playgrounds to protect the industrial grass. There is also iron extracted from tires which is being sold too.

About the price of crumb rubber, it is different from size to another. In general, the price is increase while the size decreases. The mish 8 crumb rubber is about SR 750 – SR 850. The 16 mish is approximately SR 850 – SR 1000. Finally, the mish 30 is vary between SR 1000 – SR 1200.

Maintenance of equipment is the critical cost. The machines need maintenance regularly as the owner said. This manufacture has its own maintenance technicians.

The visit was very useful and adds a value to the group members. The manufacture crew was very helpful and corporative staff. Figure 3.6, Figure 3.7 and Figure 3.8 show photos have been taken in the field visit.



Figure 3.6 Crumb Rubber Factory.



Figure 3.7 Crumb Rubber Factory.



Figure 3.8 Crumb Rubber Factory.

CHAPTER IV

Pyrolysis Process

CHAPTER 4

PYROLYSIS PROCESS

4.1 Pyrolysis Definition

Pyrolysis has been used to produce charcoal from biomass for thousands of years. Pyrolysis of coal and biomass (mainly wood) was used commercially for the production of fuel gas and for smokeless solid fuel from the 1700s to early 1900s [49].

Pyrolysis basically involves the thermal decomposition of the tire rubber at high temperatures (300–900°C) in an inert atmosphere.

The products of the tire pyrolysis process are: Solid char (30-40 wt%), liquid residue (40-60 wt%), and gases (5-20 wt%). The influence of the process conditions on the amount and characteristics of individual fractions was studied by the authors only partially. The general trend is an increase in yields of liquid and gas fractions as the temperature increases [49].

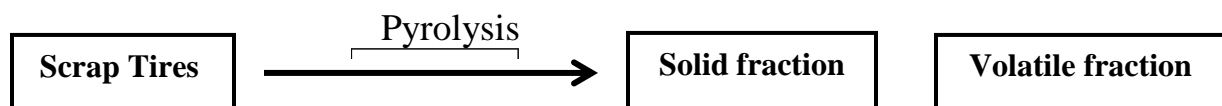


Figure 4.1 Pyrolysis Process.

The pyrolysis of solid tire wastes has received increasing attention since the process conditions may be optimized to produce high energy liquids, char and gases.

Tires consist of various types of rubber compounds with different compositions. Due analyzing different rubber compounds, various authors report different results of elemental analysis, as shown in Table 4.1

Table 4.1 Elemental Analysis of Scrap Tire Rubber [26]

Author	C (wt%)	H (wt%)	N (wt%)	S (wt%)	O (wt%)	Ashes (inorganic)
Berrueco et al	88.5	6.6	0.4	1.6	3.0	-
Loresgoiti et al	74.2	5.8	0.3	1.5	5.1	13.1
Roy et al	86.6	8.1	0.5	0.8	2.2	-
M. Rofiqul Islam, M.P, H.H, M.R	80.3	7.18	0.5	1.19		10.83

Due to high temperatures on the reactor (475 C°), the products will be two phases, one is solid phase which is char and the other is gas phase which contains Gas mixture and Vapor of liquid mixture. It is been reported that about 35% of pyrolytic liquids can be distilled at a temperature of 170 C°, 15% between 160-200 C° and 45% between 200-350C° [49].

4.2 Pyrolysis Products

Pyrolysis of waste tires leads to the production of a solid carbon residue (char), a condensable fraction (pyro-oil) and gases. The percentage of each phase is influenced by process conditions, such as temperature, pressure, heating rate, particle sizes, heat exchange system, catalysis etc.

The influence of some process conditions on char, liquid and gas yields presented by different authors is shown in Table 4.2 [49, 50].

Table 4.2 Influence of Some Process Conditions on Product Yields Presented by Different Authors [26]

Author	Temperature (oC)	Pressure kPa	Sample sizes	Solid (wt.%)	Liquid (wt %)	Gas (wt.%)
Berrueco et al	400-700	101	20 mm	47-63	30-43	2.4-4.4
Loresgoiti et al	400-700	101	20-30 mm	43-53	28-40	7-9
Roy et al	25-500	0.8-28	-	35-36	62	1-3
Barbooti et al	420-450	101	2-20 mm	31.5-51	36-62	7.3-16.8
M. Rofiqul Islam et al	375-575	101	2-8 cm ³	38-48.5	43-51	7.5-19

Pyrolytic char may be used as a solid fuel or as a precursorn for activated carbon manufacture. Also, as filler for waste water treatment or as binder for coke manufacturing, it is reported that another potentially important end-use of the pyrolytic carbon black which may be used as an additive for asphalt.

In the other hand, pyrolysis liquids (a mixture of paraffins, olefins and aromatic compounds) have been found to have a high gross calorific value (GCV) of around 41-44 MJ/kg, which may use as replacement for conventional liquid fuels. In addition to their use as fuels, the liquids have been shown to be a potential source of light aromatics components such as benzene, toluene and xylene.

In addition, has been reported that pyrolysis gas contains high concentrations of methane, ethane, butadiene and other hydrocarbon gases with a GCV of approximately 37 MJ/m³, sufficient to provide the energy required by the pyrolysis process.

The report of M. Rofiqul Islam, M. Parveen, H. HANIU and M. R. Islam Sarker “Innovation in Pyrolysis Technology for Management of Scrap Tire: a Solution of Energy and Environment” is taken as a reference in this project for two main reasons. First, the report is easy to handle. Second, the highest yield needed is oil, and this experiment is producing oil at highest yield comparing with solid and gas [49].

4.3 Pyrolysis Process Description

There are three main factors affected on the pyrolysis process:

- Temperature.
- Flow of Nitrogen.
- Size of scrap tire particles.

These factors depend on the final product needed.

The aim of this process, to be liquid mixture main product desired because of:

- The valuable products that can be sold.
- The high calorific value 41-44 MJ/kg
- Easy to handle comparing with gas.
- Presented of refinery manufactures in Saudi Arabia.

4.3.1 Process Conditions

The factors of the process are taken at the optimum conditions to gain high fraction of pyrolytic liquid [49].

The conditions are listed in Table 4.3.

Table 4.3 Optimum Pyrolysis Conditions

Temperature	475°C
Flow of Nitrogen	4.515 Kg/min
Size of scrap tire particles	4 cm ³
Feed	3027.5 Kg/h
Process time	1 h

These factors are taken from an experiment by M. Rofiquel Islam, M. Parveen, H. HANIU and M. R. Islam Sarker [49]

4.3.2 Process Products

As mentioned, the products from pyrolysis are Solid, Liquid and Gas. And it is been looking forward to get high percentage of liquid. Table 4.4 shows the percentages of the products.

Table 4.4 Percentages of Pyrolysis Products

Product	Percentage %
Solid char	40.5
Liquid	51
Gas	8.5

4.3.3 Process Units

The process units consist of two vertical fire-tube heating chamber of the decomposition unit with a volume of 13 m³ for each, a hopper used as feeder to the decomposition unit followed by two heat exchangers (coolers), then two condensers. After that the flow will enter a flash drum to separate the condensate from the gases. Also, a N₂ gas source is necessary to prevent oxygen from being inside the decomposition unit. Also, there is an air compressor, char collector, furnace.

At a distance of 0.8 m from the closed bottom of each decomposition unit, a gas distributor is fitted to distribute the N₂ gas and support the feedstock. Eight equally spaced stainless steel, 0.03 m diameter fire-tubes are insulated and fixed inside the decomposition unit.

The fire-tubes provided uniform heating across the cross-section of the decomposition chamber [49, 50].

4.3.4 Process Description

From the flow sheet (figure 4.3) at steady state operation, the crumb rubber is delivered from the Size reduction process with average size particles of 4 cm³ to the hopper at a rate of 3027.5 Kg/h. The decomposition unit is already filled with nitrogen to prevent the presence of

oxygen by rate of 22.575 Kg/min for 5 minutes. Otherwise, the crumb will burn. The decomposition unit is kept at a temperature of 475C^o, then, the crumb rubber is feeding to the first decomposition unit, after the first one is fed by 3027.5 Kg, the feed out from hopper will be stopped and the gas stream will open. After one hour, the process will be finished and the gas mixture (Gas and Vapor liquid) is continually out from decomposition unit to the next step. After half an hour from run, the hopper will feed the second chamber for half an hour. After the first decomposition unit finished, the second immediately run. Figure 4.2 is shown the process [49].

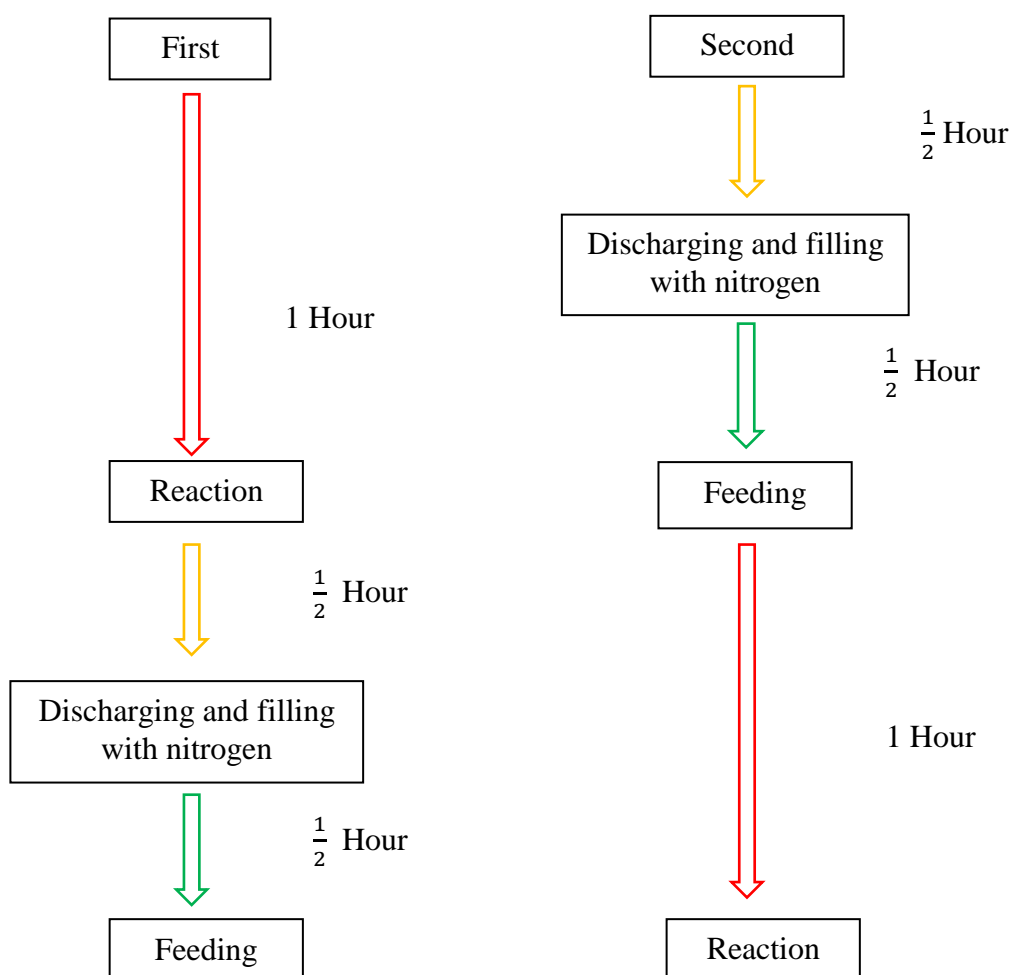


Figure 4.2 Schematic Diagram for Continuous Process.

Then, when gas mixture flow out from the decomposition unit it will feed to two coolers to decrease the temperature to 170 °C , then followed by condensers and flash drums to separate the pyrolytic oil from incondensable gases. The liquid mixture will be taken out to be sold. The gas mixture is feeding to gas storage to be used as fuel at the furnace to provide the required heat for the decomposition unit.

The separation has been done based on the difference in boiling points of the mixture components. Since the liquid fraction consist of verity of components, 7 major components has been chosen to represent the whole mixture. These seven components have been grouped into two groups based on their boiling points range. Table 4.5 shows the major components and their normal boiling point. Also, shows the chosen groups.

Table 4.5 The Major Components and their boiling points

Group	Component	Boiling Point (°C)
A	Styrene	145.16
	Ethyl Benzene	136.2
	Toluene	110.63
B	Benzene	80.09
	Hexene	63.48
	Hexane	68.73
	Cyclopentane	54.3

The solid char remains at the decomposition unit, after the process is finished will be pushed out by air compressor to be sold. It needs further processes to be commercially beneficial. The combustion gasses will move out to a scrubber to handle the concentration to meet regulation of Saudi Arabia [49, 50].

4.3.5 Process Flow Sheet

Figure 4.3 shows a flow sheet for the pyrolysis process.

Hopper	Thermal Decomposition Unit	Thermal Decomposition Unit	Compressor	Compressor	Furnace	Compressor	cooler	cooler	Flash drum	condenser	Flash drum	Storage tank
H-201	DU-201	DU-202	C-201	C-202	F-201	C-203	E-201	E-202	V-201	E-203	V-202	Tk-201
Storage tank	Condenser	Storage tank	Storage tank	Storage tank	Storage tank	Compressor	Compressor					
TK-202	E-204	TK-203	TK-204	TK-205	TK-206	C-204	C-205					

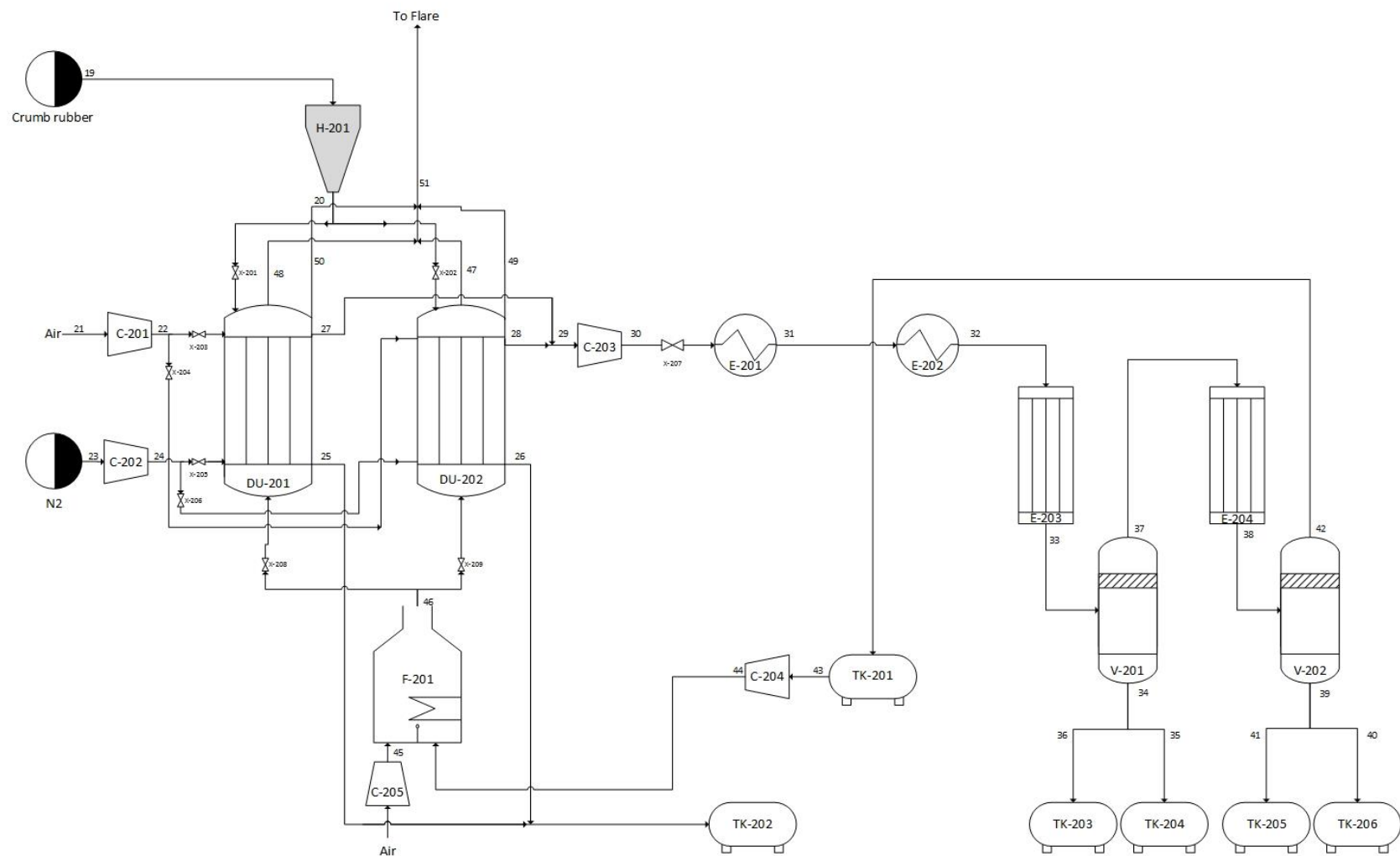


Figure 4.3 Flowsheet of the Pyrolysis Plant.

4.4 The Effect of Operating Conditions on the Products Yields

4.4.1 Effect of Temperature

Figure 4.4 shows the effect of set temperatures on the yields of pyrolytic products which are Solid, Liquid and gas under optimum nitrogen flow rate and for scrap tires of particle sizes 4 cm^3 . The optimum temperature for high yield of liquid is at $475\text{ }^\circ\text{C}$ [49].

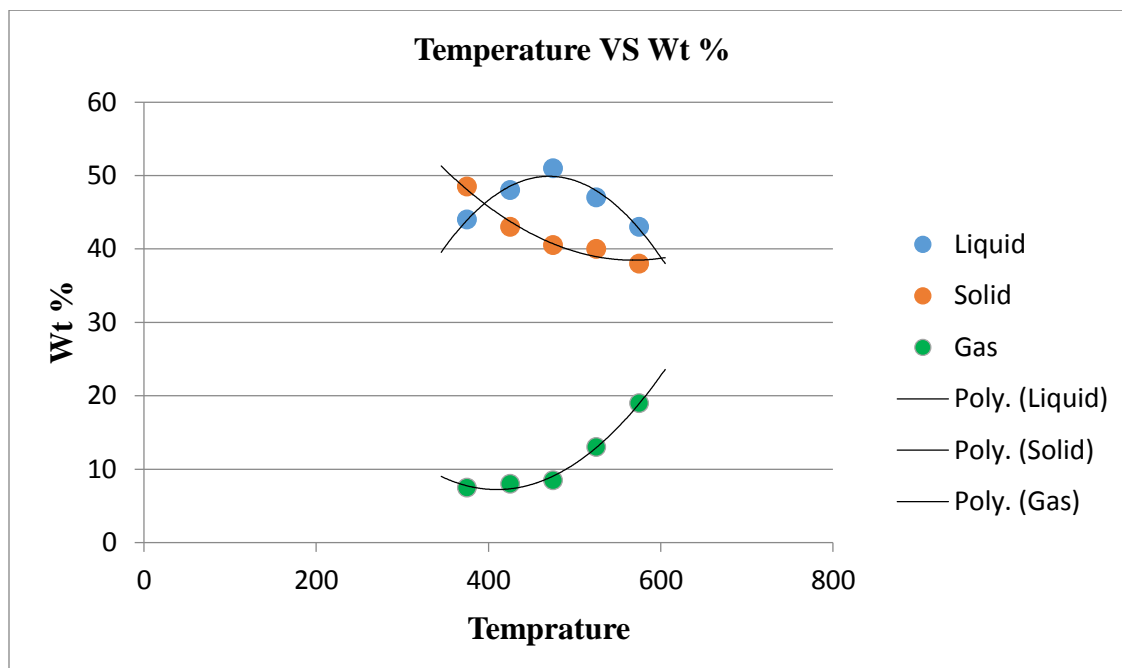


Figure 4.4 Effect of Temperature on the Pyrolysis Products [49].

4.4.2 Effect of Particle Size

The effect of particle size of scrap tires on the yields of pyrolytic products yields is shown in Figure 4.5 at the optimum temperature. The optimum size of particles to have high yield of liquid is at 4 cm^3 [49].

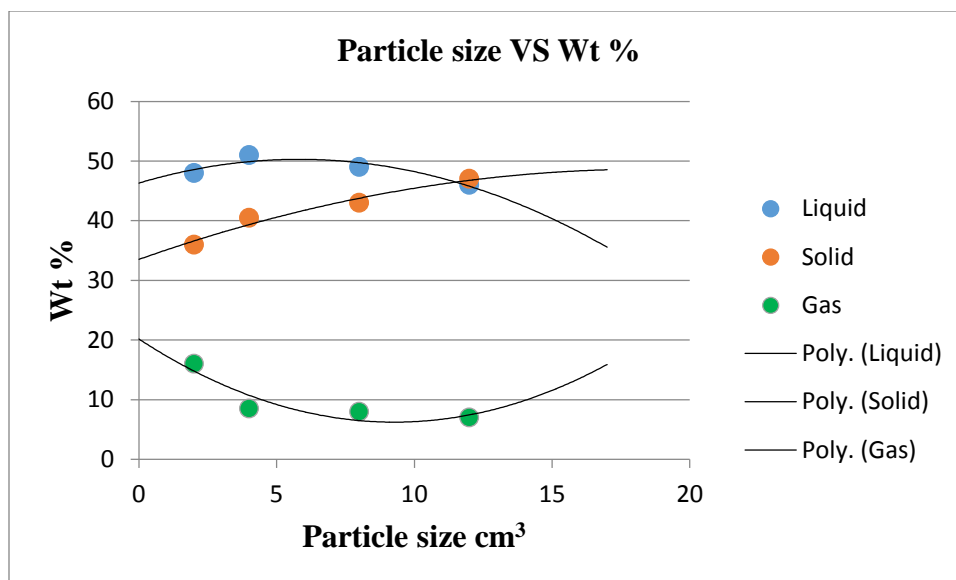


Figure 4.5 Effect of Particle Size on the Pyrolysis Products [49].

CHAPTER V

Material & Energy Balances

CHAPTER 5

MATERIAL AND ENERGY BALANCES

In this chapter a summary of calculations of overall material and energy balance are shown below. The detailed calculations are presented in appendix A.

5.1 Material Balance

5.1.1 Material Balance for Size Reduction Plant

Feed rate of scrap tires = 5 metric tons / hour = 5000 kg / hour

Calculations are based on stream factor = 0.9

→ Annual feed rate = $5 \times 24 \times 300 \times 0.9 = 39,000$ metric tons / year.

Input – Output + Generation – Consumption = Accumulation

Generation = Consumption = Accumulation = 0

→ The material balance equation: Input = Output

Degree of Freedom Analysis

Degree of freedom analysis was performed on the overall, as shown below.

Overall material balance: streams (1, 6, 9, 11, 13, 17, 18)

Unknowns:

- Process Variables = 19

Information:

- Material Balance Equations = 5
- Flow rate = 1

- Composition = 6
- Relations = 7

Since, Information = 19 = Unknowns \rightarrow there is a unique solution for this system.

Relations: $S^6 = 0.9 S^1$, $F^{11} = 0.85 (0.3 F^1)$, $R^9 = 0.7 R^1$, $S^9 = 0.7 (0.1 S^1)$, $F^9 = 0.7 F^1$,
 $A^9 = 0.7 A^1$, $I^9 = 0.7 I^1$

Tables 5.1, 5.2 and 5.3 show the mass flow rates and fractions of overall streams components.

Table 5.1 Symbols of all Components

Component	Symbol
Rubber	R
Steel	S
Fabric	F
Reinforcing Agent	A
Compounding ingredients	I

Table 5.2 Mass Flow Rates of Overall Streams Components for 5 tonne/hr feed

Stream No.	R	S	F	A	I
1	2.55	0.75	0.15	1.25	0.3
6	0	0.675	0	0	0
9	1.785	0.0525	0.105	0.875	0.21
11	0	0	0.03825	0	0
13	0	0.0224775	0	0	0
17	0	0	0.006705	0	0
18	0.765	0.0000225	0.000045	0.375	0.09

So, the total product rate = 1.23 metric tons/hr (9697.32 metric tons/year) of crumb rubber, and
a total feed to the pyrolysis = 3.0275 metric tons/hr (23,868.81 metric tons/year).

Table 5.3 Mass Fractions of Overall Streams Components

Stream No.	R	S	F	A	I
1	0.51	0.15	0.03	0.25	0.06
6	0	1	0	0	0
9	0.5896	0.0173	0.0347	0.2890	0.0694
11	0	0	1	0	0
13	0	1	0	0	0
17	0	0	1	0	0
18	0.6219	0.02×10^{-3}	0.04×10^{-3}	0.3049	0.0732

5.1.2 Material Balance for Pyrolysis Process

Assumptions:

- The conversion of the pyrolysis process is 100% [49] to produce gas, pyrolytic oil and char.
- The conversion of the furnace (F-201) is 100% (complete combustion).
- Excess air at stream No. 45 = 20% (to insure the complete combustion).
- The mixture consist of the major components only, and neglecting the effects of small ones becuses it is difficult to handle a huge number of components at once. Also, the effect of small components is extremely weak.

- Material Balance for the Furnace (F-201) (burner)

Since the mixture is a complex one and consist of variety of components, the average molecular weight formula will be used:

$$M_w(average) = \sum y_i \times M_{w_i} \quad (1)$$

In the burner, the flow of gases from the second flash (V-202) is burned in the burner with a 20% excess air. The combustion products then will enter the decomposition units (DU-201, DU-202) to heat the crumb rubber.

Data for calculation:

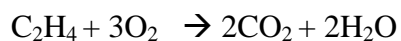
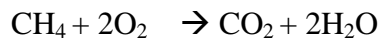
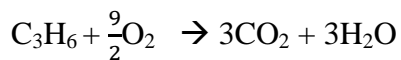
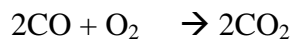
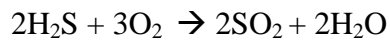
- Gas flow rate 257.337 Kg/h
- The Air flow rate 4044 Kg/h
- Inlet Temperature 30 C°
- Inlet Pressure 2 bar
- C_{p_i} (kJ/kg-K) 1.1006
- C_{p_o} (kJ/kg-K) 1.5180

Inlet flow gases described in Table 5.4

Table 5.4 Inlet Gases to the Burner

Component	Flow rate (Kg/h)	Mass fraction	LHV (KJ/Kg)
CO	16.78	0.065	10112
CO ₂	32.1	0.125	---
CH ₄	94.02	0.365	50000
C ₂ H ₄	31.33	0.122	47195
H ₂	15.43	0.06	120000
C ₃ H ₆	54.8	0.212	45800
H ₂ S	13.3	0.052	15191

The reactions are;



The total heating value = 4.23×10^4 KJ/Kg

The total heat generated by combustion = $(4.23 \times 10^4 \text{ KJ/Kg}) * (225.76 \text{ Kg/h})$
 $= 9.55 \times 10^6 \text{ KJ/h}$

Outlet flow gases described in Table 5.5.

Table 5.5 Outlet Gases from the Burner

Component	Flow rate (Kg/h)	Mass fraction
CO ₂	587	0.96
SO ₂	25	0.04

After doing a material balance for overall process, the following rates are obtained:

The production rate of char = 9666.8 metric tons/year (1226.137 Kg/hr),

The production rate of pyrolytic oil = 12168.5 metric tons/year (1543.44 Kg/hr)

and the production rate of gases = 2033.4 metric tons/year (257.9 Kg/hr) of gases.

Table 5.6 shows a summary of all components in each stream:

Table 5.6 Summary of Materials in all streams (Kg / hr)

Stream	Flow rate (Kg/hr)	Crumb rubber	Char	Pyrolytic oil	Gas	O ₂	N ₂	CO ₂	SO ₂	H ₂ O
19	3027.5	3027.5	0	0	0	0	0	0	0	0
20	3027.5	3027.5	0	0	0	0	0	0	0	0
21	2619000	0	0	0	0	549990	2069010	0	0	0
22	2619000	0	0	0	0	549990	2069010	0	0	0
23	22.575 Kg/5 min	0	0	0	0	0	22.575Kg/5 min	0	0	0
24	22.575 Kg/5 min	0	0	0	0	0	22.575Kg/5 min	0	0	0
25	1226.137	0	1226.137	0	0	549990	2069010	0	0	0
26	1226.137	0	1226.137	0	0	549990	2069010	0	0	0
27	1801.3625	0	0	1544.025	257.337	0	0	0	0	0
28	1801.3625	0	0	1544.025	257.337	0	0	0	0	0
29	1801.3625	0	0	1544.025	257.337	0	0	0	0	0
30	1801.3625	0	0	1544.025	257.337	0	0	0	0	0
31	1801.3625	0	0	1544.025	257.337	0	0	0	0	0
32	1801.3625	0	0	1544.025	257.337	0	0	0	0	0
33	1801.3625	0	0	1544.025	257.337	0	0	0	0	0
34	871.6462	0	0	871.6462	0	0	0	0	0	0
35	871.6462	0	0	871.6462	0	0	0	0	0	0
36	871.6462	0	0	871.6462	0	0	0	0	0	0

Stream	Flow rate (Kg/hr)	Crumb rubber	Char	Pyrolytic oil	Gas	O ₂	N ₂	CO ₂	SO ₂	H ₂ O
37	929.7158	0	0	672.3788	257.337	0	0	0	0	0
38	929.7158	0	0	672.3788	257.337	0	0	0	0	0
39	671.8	0	0	671.8	0	0	0	0	0	0
40	671.8	0	0	671.8	0	0	0	0	0	0
41	671.8	0	0	671.8	0	0	0	0	0	0
42	257.9158	0	0	0.5788	257.337	0	0	0	0	0
43	257.9158	0	0	0.5788	257.337	0	0	0	0	0
44	257.9158	0	0	0.5788	257.337	0	0	0	0	0
45	4044	0	0	0	0	943.97	3100.03	0	0	0
46	4301.9	0	0	0	0	123.02	3100.03	586.98	25	466.86
47	4301.9	0	0	0	0	123.02	3100.03	586.98	25	466.86
48	4301.9	0	0	0	0	123.02	3100.03	586.98	25	466.86
49	22.575Kg/5min	0	0	0	0	0	22.575Kg/5min	0	0	0
50	22.575Kg/5min	0	0	0	0	0	22.575Kg/5min	0	0	0
51	3122.605	0	0	0	0	123.02	3122.605	586.98	25	466.86

5.2 Energy Balance

5.2.1 Energy Balance for Size Reduction Plant

In size reduction equipment, the energy calculated using the Bond Work Index [46].

Work index (w_i) is an empirical factor that relates power consumption in crushing and grinding to the feed product size distribution. Also it is defined as, the gross energy requirement (kw-hr/tons of feed) to reduce a very large feed rate to a size that 80% of the product passes the screen [40].

$$W = 10 W_i \left[\frac{1}{\sqrt{D_p}} - \frac{1}{\sqrt{D_F}} \right] \quad [46] \quad (2)$$

Where,

W = actual work input (KWhr/ton)

W_i = Bond Work index (KWhr/ton)

D_p = Product diameter in (μm), 80 % passing.

D_F = Feed diameter in (μm), 80 % passing.

Now, the approximate work index calculations for the three major size reduction equipment (shredder, granulator, cracker mill) using information provided by ECO GREEN EQUIPMENT will be performed:

Shredder machine work index calculations:

$D_F = 1000 \text{ mm} = 1 \times 10^6 \mu\text{m}$, $D_p = 60 \text{ mm} = 6 \times 10^4 \mu\text{m}$, approximate work = 100 KW

$$\rightarrow W_i = 3244 \text{ KWhr/ton}$$

Granulator machine work index calculations:

$D_F = 60 \text{ mm} = 6 \times 10^4 \mu\text{m}$, $D_p = 15.9 \text{ mm} = 1.59 \times 10^4 \mu\text{m}$, approximate work = 150 KW

$$\rightarrow W_i = 3898 \text{ KWhr/ton}$$

Cracker mill work index calculations:

$$D_F = 15.9 \text{ mm} = 1.59 \times 10^4 \mu\text{m}, D_p = 1 \text{ mm} = 1 \times 10^3 \mu\text{m}, \text{ approximate work} = 200 \text{ KW}$$

$$\rightarrow W_i = 844 \text{ KWhr/ton}$$

Now, the work calculations for each machine will be performed:

Shredder machine work calculations:

$$W = 10 (3244 \times 5) \times \left(\frac{1}{\sqrt{6 \times 10^4}} - \frac{1}{\sqrt{1 \times 10^6}} \right) = 499.98 \text{ KW}$$

Granulator machine work calculations:

$$W = 10 (3898 \times 5) \times \left(\frac{1}{\sqrt{1.59 \times 10^4}} - \frac{1}{\sqrt{6 \times 10^4}} \right) = 749.98 \text{ KW}$$

Cracker mill work calculations:

$$W = 10 (844 \times 5) \times \left(\frac{1}{\sqrt{1 \times 10^3}} - \frac{1}{\sqrt{1.59 \times 10^4}} \right) = 999.81 \text{ KW}$$

So, approximately we need around 2500 KW for the whole plant.

5.2.2 Energy Balance for Pyrolysis Process

Assumption:

- The pressure effects are neglected in calculations.
- The furnace (F-201) is adiabatic.
- There is no lost in energy in the decomposition units (DU-201 & DU-202) .

Reference conditions are:

Crumb rubber: (solid, 25 °C, 1 atm)

Char: (solid, 25 °C, 1 atm)

Gas: (gas, 25 °C, 1 atm)

Vapor oil: (gas, 25 °C, 1 atm)

O₂: (gas, 25 °C, 1 atm)

N₂: (gas, 25 °C, 1 atm)

CO₂: (gas, 25 °C, 1 atm)

SO₂: (gas, 25 °C, 1 atm)

H₂O: (liquid, 25 °C, 1 atm)

Fuel: (liquid, 25 °C, 1 atm)

To calculate the enthalpy of any component in any stream, the following formulas have been used:

For no phase change:

$$H_i = \int_{T_{ref}}^T C p_i dt \quad (3)$$

For phase change:

$$H_i = \int_{T_{ref}}^{T_B} C p_{ig} dt + \Delta H_v + \int_{T_B}^T C p_{il} dt \quad (4)$$

Table 5.7 shows a summary of Streams results:

Table 5.7 Summary of Enthalpies in all Streams

Stream	T (C)	P (atm)	Phase
19	25	1	Solid
20	25	1	Solid
21	25	1	Gas
22	545.3	15	Gas
23	25	1	Gas
24	114.85	2	Gas
25	475	1	Solid
26	475	1	Solid
27	475	1	Gas
28	475	1	Gas
29	475	1	Gas
30	513.3	2	Gas
31	270	1.985	Gas
32	175	1.98	Gas
33	120	1.79	Gas+liquid
34	120	1.79	Liquid
35	120	1.79	Liquid
36	120	1.79	Liquid
37	120	1.79	Gas
38	50	1.789	Gas+liquid
39	50	1.789	Liquid
40	50	1.789	Liquid
41	50	1.789	Liquid
42	50	1.789	Gas
43	50	1	Gas
44	93	2	Gas
45	115.1	2	Gas
46	1956.13	2	Gas
47	534.87	1	Gas
48	534.87	2	Gas
49	-----	1	Gas
50	-----	1	Gas
51	-----	1	Gas

Table 5.8 Summary of Heat loads in all Units

Unit	Q (J/s)
Cooler (E-201)	307243.5
Cooler (E-202)	97981.14
Condenser (E-203)	132228.69
Condenser (E-204)	106072.13
Flash Drum (V-201 and V-202)	0
Compressor (C-201)	1320
Compressor (C-202)	633200
Compressor (C-203)	42500
Compressor (C-204)	9900
Compressor (C-205)	73900
Burner (H-201)	2652777.8
Decomposition Unit (DU-201 and DU-202)	- 2652777.8
Storage Tank (TK-201 and TK-202)	0

The total heat requirement of the plant is 583.184 KJ/s.

CHAPTER VI

Equipment Design and Sizing

CHAPTER 6

EQUIPMENT DESIGN AND SIZING

6.1 Detailed Design of Major Equipment

6.1.1 Design of Cooler (E-201)

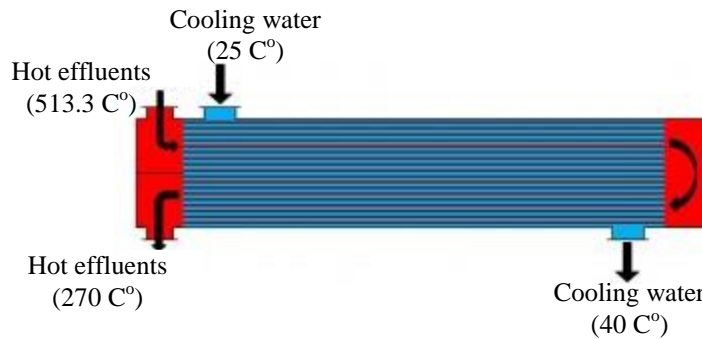


Figure 6.1 Flow Diagram for Cooler (E-201).

The objective is to design a cooler for the decomposition unit's effluents (Condensable and non-condensable gases) with a flow rate 1801.363 Kg/h to cool the mixture down from 513.1 °C to 270 °C using water coming at 25 °C and leaves at 40 °C. Table 6.1 shows the summary of detailed design for cooler (E-201).

Table 6.1 Summary of Detailed Design for Cooler (E-201)

Specification	Value
Heat Load (Q)	307243.5 J/s
Cooling water flow required	17612.54 kg/h
Overall heat transfer coefficient (U) assumed	250 W/m ² .°C
Required Area for Heat transfer	3.545 m ²
Heat transfer coefficients for tube side (h _i)	681.237 W/m ² .°C
Heat transfer coefficients for shell side (h _o)	728.55 W/m ² .°C
Overall heat transfer coefficient (U) calculated	279.85 W/m ² .°C
Pressure drop for tube side ΔP _t	15.078 KPa
Pressure drop for shell side ΔP _s	71.412 KPa

6.1.2 Design of Cooler (E-202)

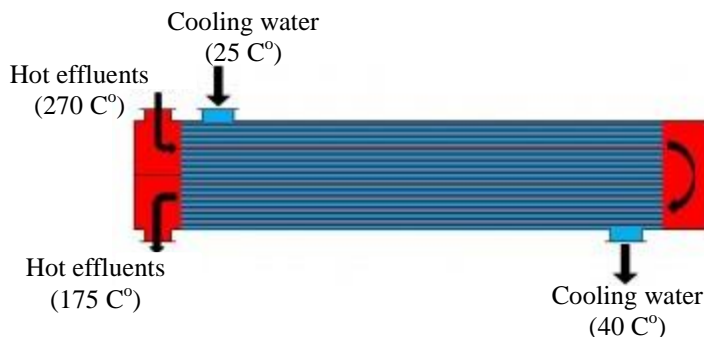


Figure 6.2 Flow Diagram for Cooler (E-202).

The objective is to design a cooler for the decomposition unit's effluents (Condensable and non-condensable gases) with a flow rate 1801.363 Kg/h to cool the mixture down from 270 °C to 175 °C using water coming at 25 °C and leaves at 40 °C. Table 6.2 shows the summary of detailed design for cooler (E-202).

Table 6.2 Summary of Detailed Design for Cooler (E-202)

Specification	Value
Heat Load (Q)	97981.14 J/s
Overall heat transfer coefficient (U) assumed	100 W/m ² .°C
Cooling water flow required	5616.708 kg/h
Required Area for Heat transfer	5.235 m ²
Heat transfer coefficients for tube side (h _i)	399.55 W/m ² .°C
Heat transfer coefficients for shell side (h _o)	224.411 W/m ² .°C
Overall heat transfer coefficient (U) calculated	126.76 W/m ² .°C
Pressure drop for tube side ΔP _t	5.16 KPa
Pressure drop for shell side ΔP _s	5.125 KPa

6.1.3 Design of Condenser (E-203)

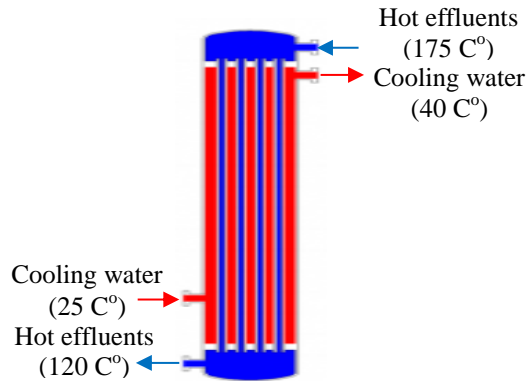


Figure 6.3 Flow Diagram for Condenser (E-203).

The objective is to design a condenser for the decomposition unit's effluents (Condensable and non-condensable gases) with a flow rate 1801.363 Kg/h to condensate the heavy liquid vaporized in the mixture at temperature from 175 °C to 120 °C using water coming at 25 °C and leaves at 40 °C. Table 6.3 shows the summary of detailed design for condenser (E-203).

Table 6.3 Summary of Detailed Design for Condenser (E-203)

Specification	Value
Heat Load (Q)	132228.6936 J/s
Overall heat transfer coefficient (U) assumed	150 W/m ² .°C
Cooling water flow required	7579.92 kg/h
Required Area for Heat transfer	7.56 m ²
Heat transfer coefficients for non-condensable mixture	92.69 W/m ² .°C
Heat transfer coefficients for condensable mixture	3743.9 W/m ² .°C
Heat transfer coefficients for tube side (hi)	9591.93 W/m ² .°C
Heat transfer coefficients for shell side (ho)	185.813 W/m ² .°C
Overall heat transfer coefficient (U) calculated	167.81 W/m ² .°C
Pressure drop for tube side ΔPt	1.185 KPa
Pressure drop for shell side ΔPs	4.3 KPa

6.1.4 Design of Condenser (E-204)

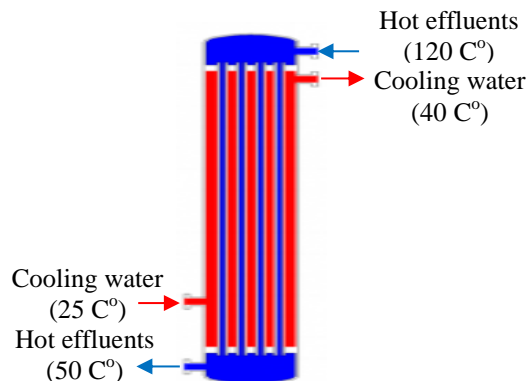


Figure 6.4 Flow Diagram for Condenser (E-204).

The objective is to design a condenser for the decomposition unit's effluents (Condensable and non-condensable gases) with a flow rate 929.72 Kg/h to condensate the light liquid vaporized in the mixture at temperature from 125 °C to 50 °C using water coming at 25 °C and leaves at 40 °C. Table 6.4 shows the summary of detailed design for condenser (E-204).

Table 6.4 Summary of Detailed Design for Condenser (E-204)

Specification	Value
Heat Load (Q)	106072.13 J/s
Overall heat transfer coefficient (U) assumed	500 W/m ² .°C
Cooling water flow required	6080.52 kg/h
Required Area for Heat transfer	4.33 m ²
Heat transfer coefficients for non-condensable mixture	194.74 W/m ² .°C
Heat transfer coefficients for condensable mixture	7591 W/m ² .°C
Heat transfer coefficients for tube side (hi)	7785.73 W/m ² .°C
Heat transfer coefficients for shell side (ho)	746.42 W/m ² .°C
Overall heat transfer coefficient (U) calculated	513.922W/m ² .°C
Pressure drop for tube side ΔPt	1.31 KPa
Pressure drop for shell side ΔPs	65.5 KPa

6.1.5 Design of Flash Drum (V-201)

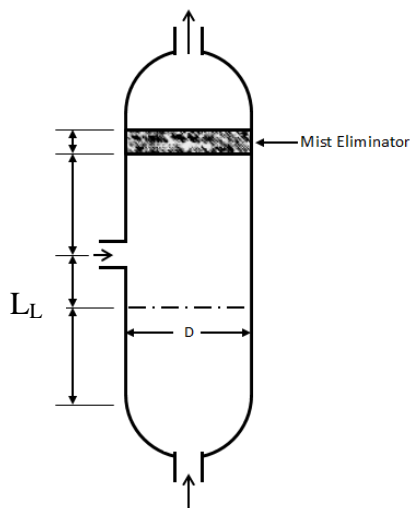


Figure 6.5 Flow Diagram for Flash Drum (V-201).

A liquid-gas phase separator (Flash Drum) will be used to separate the first condenser effluent which has a flow of 1801.363 kg/hr at 50 °C and 1.84 atm . The flash drum will be with mist eliminator to prevent the liquid droplets from rising with the vapor. Table 6.5 shows the summary of detailed design for flash drum (V-201).

Table 6.5 Summary of Detailed Design for Flash Drum (V-201)

Specification	Value
Cross sectional area (A)	0.6452 m ²
Diameter of the flash (D)	0.907 m
Liquid level height (L_L)	0.1497 m
The total height (L)	1.967 m
The shell thickness	4.77 mm
The head thickness	4.77 mm
Total Volume	1.66 m ³

6.1.6 Design of Flash Drum (V-202)

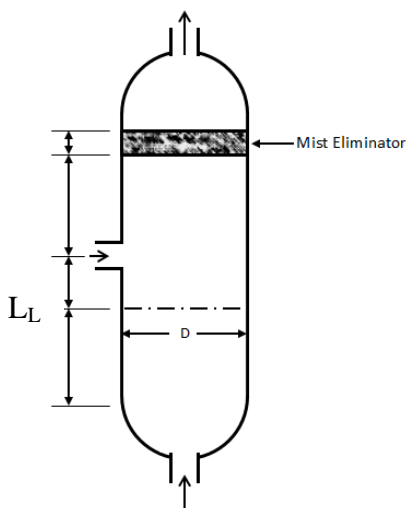


Figure 6.6 Flow Diagram for Flash Drum (V-202).

A liquid-gas phase separator (Flash Drum) will be used to separate the second condenser effluent which has a flow of 929.72 Kg/hr at 50 °C and 1.84 atm . The flash drum will be with mist eliminator to prevent the liquid droplets from rising with the vapor. Table 6.6 shows the summary of detailed design for flash drum (V-202).

Table 6.6 Summary of Detailed Design for Flash Drum (V-202)

Specification	Value
Cross sectional area (A)	0.275 m ²
Diameter of the flash (D)	0.5915 m
Liquid level height (L_L)	0.3011 m
The total height (L)	1.646 m
The shell thickness	4.77 mm
The head thickness	4.77 mm
Total Volume	0.561 m ³

6.2 Equipment Sizing

6.2.1 Compressors Sizing (C-201, 202, 203, 204 and 205)

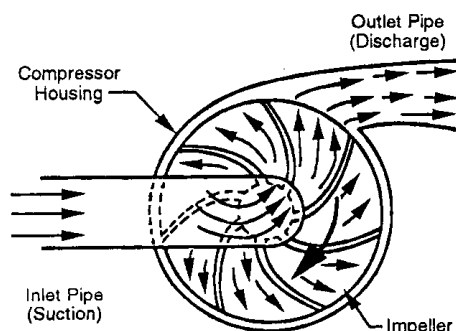


Figure 6.7 Flow Diagram for Compressors (C-201 --- 205).

A compressor is one of the most complicated and costly device which is used to raise the pressure for gas line. Each compressor is generally a function of the gas capacity, action and discharge head. Centrifugal compressor is used. For sizing a compressor only work need to be calculated. Table 6.7 shows the summary of sizing specifications for compressors.

Table 6.7 Summary of Sizing Specifications for Compressors (C-201 --- 205)

C-201		C-202	
Compressed Flow	0.7 mol/s	Compressed Flow	50 mol/s
$W_{\text{theoretical}}$	1.32 KW	$W_{\text{theoretical}}$	633.2 KW
Outlet Pressure	2 bar	Outlet Pressure	15 bar
C-203		C-204	
Compressed Flow	9.67 mol/s	Compressed Flow	4.91 mol/s
$W_{\text{theoretical}}$	42.5 KW	$W_{\text{theoretical}}$	9.9 KW
Outlet Pressure	2 bar	Outlet Pressure	2 bar
C-205			
Compressed Flow		4.91 mol/s	
$W_{\text{theoretical}}$		73.9 KW	
Outlet Pressure		2 bar	

6.2.2 Burner sizing (H-201)

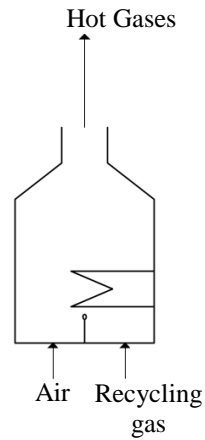


Figure 6.8 Flow Diagram for Burner (H-201).

In the burner, the flow of gases from the second flash (V-202) is burned in the burner with a 20% excess air. The combustion products then will enter the decomposition units (DU-201, DU-202) to heat the crumb rubber. Table 6.8 shows the summary of sizing specifications for the burner (H-201).

Table 6.8 Summary of Sizing Specifications for Burner (H-201)

Specification	Value
Gas flow rate	225.76 Kg/h
The Air flow rate	4044 Kg/h
Total heating value	4.23×10^4 KJ/Kg
Total heat generated by combustion	9.55×10^6 KJ/h
The temperature for the outlet gas	1940 °C

6.2.3 Decomposition Unit Sizing (DU-201 & 202)

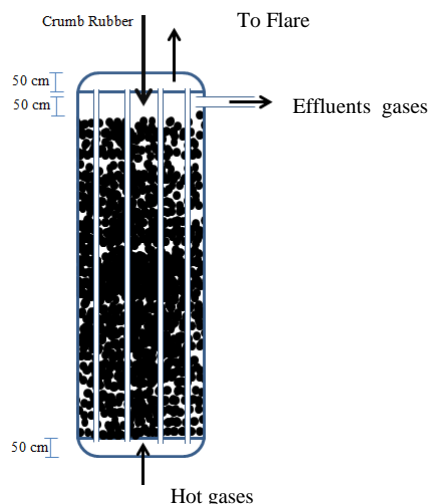


Figure 6.9 Flow Diagram for Decomposition Unit (DU-201 & 202).

The crumb rubber will be fed into the decomposition unit at a rate of 3027.5 Kg/hr, and then the crumb rubber will decompose at 475 °C and 1 atm in the absence of oxygen. A source of Nitrogen will be used to have an inert atmosphere. Also, a source of air will be used during the discharging period to remove the char from the decomposition unit. Table 6.9 shows the summary for sizing specification for the decomposition unit (DU-201 & 202).

Table 6.9 Summary of Sizing Specifications for the Decomposition Unit (DU-201 & 202)

Specification	Value
Flow of crumb rubber per batch	3027.5 Kg
Volume needed for the crumb rubber	7.8 m ³
Number of pipes	8 pipes
Volume of pipes	0.0175 m ³
Total volume of Decomposition unit	13 m ³

6.2.4 Storage Tanks Sizing

6.2.4.1 Gas Storage Tank Sizing (TK-201)

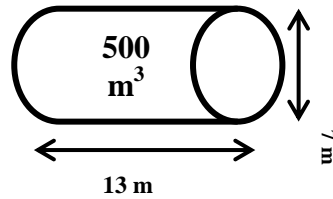


Figure 6.10 Flow Diagram for Gas Storage (TK-201).

A storage tank is used to keep the incondensable gases which comes from the top effluent of the second flash drum (V-202).

Table 6.10 shows the summary of sizing specifications for the gas storage tank (TK-201).

Table 6.10 Summary of Sizing Specifications for the gas storage Tank (TK-201)

Specification	Value
Flow	257.9 Kg/h
Maximum Storage Time	2 Hours
Volume required	500 m ³

6.2.4.2 Liquid Storage Tanks Sizing (TK-203, 204, 205 and 206)

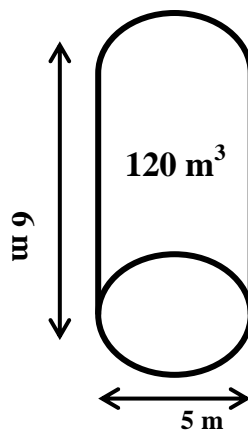


Figure 6.11 Flow Diagram for Liquid Storage (TK 203 --- 206).

The liquid storage is used to store the liquid effluent from flash drums V-201 & V-202 with temperature 50 C and pressure 1.6 atm. Table 6.11 shows the summary of sizing specifications for the liquid storages (TK-203, 204) & (TK-205, 206).

Table 6.11 Summary of Sizing Specifications for the Liquid Storage Tanks (TK-203 --- 206)

Storage Tanks (TK-203 and 204)	
Flow	874.75 Kg/h
Maximum Storage Time	4 days
Volume required	120 m ³
Storage Tanks (TK-205 and 206)	
Flow	671.8 Kg/h
Maximum Storage Time	4 days
Volume required	120 m ³

CHAPTER VII

Control System

CHAPTER 7

CONTROL SYSTEM

7.1 Introduction

Control is used to modify the behavior of a system so it behaves in a specific desirable way over time. In addition, control is an interconnection of components forming a system configuration that will provide a desired system response.

The controlled process has an input and output variables as shown in the figure 7.1. Its response is described in terms of dependence of the output variable on the input variable. Variables such as pressure, temperature or flow rate usually have to be set on significant conditions. So, this setting should not change while the process running.

The controlled variable is first measured and an electrical signal is created to allow an independent control loop to control the variable.

The measured value in the controller must then be compared with the set point value desired. The result from the comparison determines any action that needs to be taken.

At the end, a suitable location has to be determined in the system where the controlled variable can be influenced.



Figure 7.1 Process System.

7.2 Control Terminology

Controlled variables - these are the variables which quantify the performance or quality of the final product, which are also called output variables.

Manipulated variables - these input variables are adjusted dynamically to keep the controlled variables at their set-points.

Disturbance variables - these are also called "load" variables and represent input variables that can cause the controlled variables to deviate from their respective set points.

Set point variable - is the one that is set by the operator, master controller or computer as a desired value for a 'controlled variable'. It is also called sometimes as 'reference value'.

Set-point change - implementing a change in the operating conditions. The set-point signal is changed and the manipulated variable is adjusted appropriately to achieve the new operating conditions. Also called servomechanism (or "servo") control.

Disturbance change - the process transient behavior when a disturbance enters, also called regulatory control or load change. A control system should be able to return each controlled variable back to its set-point.

Figure 7.2 shows the different inputs and outputs to the system.

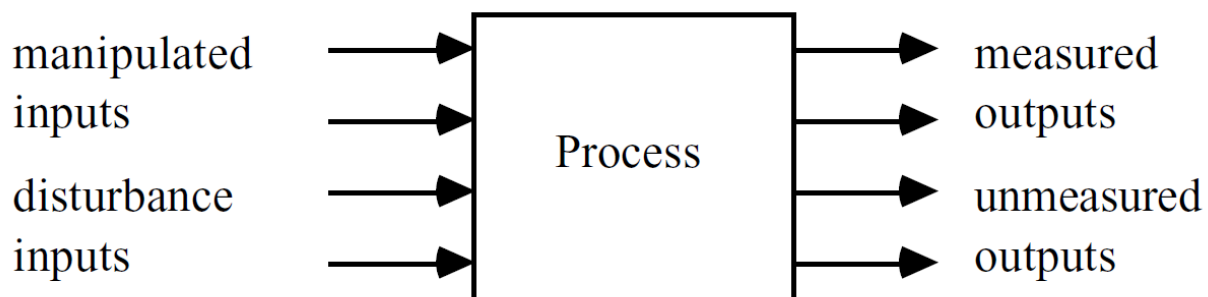


Figure 7.2 Input / Output of Process Control.

7.3 Control Objectives


The main objectives of control are to:

- Increase product throughput.
- Increase yield of higher valued products.
- Decrease energy consumption.
- Decrease pollution.
- Decrease off-spec product.
- Increase Safety.
- Extend life of equipment.
- Improve Operability.
- Decrease production labor.

Control Symbols used:

Table 7.1 shows the most common symbols used in control loops.

Table 7.1 Control Symbols

Symbol	Definition
	Control Valve
LC	Level Control
TC	Temperature Control
FC	Flow Control
TT	Temperature Transmitter
AC	Analyzer Control
PC	Pressure Control
PT	Pressure Transmitter

7.4 Control Loops of Major Equipment

7.4.1 Control Loop of Heat Exchanger (E-201)

Heat exchanger works as cooler after the decomposition takes place. The cooler is reducing the temperature of the decomposition unit's effluents (Condensable and non-condensable gases) from 513.1 °C to 270 °C. The coolant fluid is water at 25 °C and the output at 40 °C. The flow rate of hot gas is 1801.363 Kg/h. In the other hand, the flow of cooling water is 17612.54 kg/h.

To keep the temperatures within the designing range, a control loop system should be maintained. The controlled variable is the temperature of gas outlet and the manipulated variable is the flow of cooling water. Figure 7.3 and Table 7.2 show the control loop and control specifications of heat exchanger E-201.

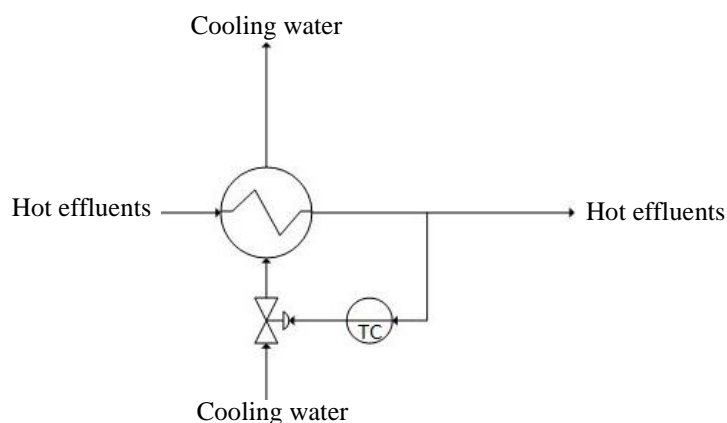


Figure7.3 Control Loop of Heat Exchanger (E-201).

Table 7.2 Control Specifications of Heat Exchanger (E-201)

Equipment	Heat exchanger (E-201)
Control Strategy Selected	Backward Control (Temperature)
Controlled Variables	Temperature of hot fluid
Measured variables	Temperature of hot fluid
Manipulated Variables	Flow of cooling water
Disturbances	Flow of cooling water
Set-Points	270 °C

7.4.2 Control Loop of Heat Exchanger (E-202)

Heat exchanger works as cooler after the first cooler (E-201). The cooler is reducing the temperature of the decomposition unit's effluents (Condensable and non-condensable gases) from 270 °C to 175 °C. The coolant fluid is water at 25 °C and the output at 40 °C. The flow rate of hot gas is 1801.363 Kg/h. In the other hand, the flow of cooling water is 5616.708 kg/h.

To keep the temperatures within the designing range, a control loop system should be maintained. The controlled variable is the temperature of gas outlet and the manipulated variable is the flow of cooling water. Figure 7.4 and Table 7.3 show the control loop and control specifications for the heat exchanger (E-202).

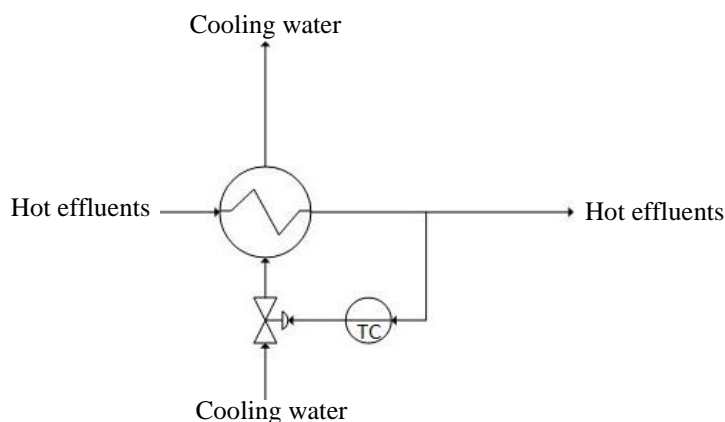
**Figure7.4** Control Loop of Heat Exchanger (E-202).

Table 7.3 Control Specification of Heat Exchanger (E-202)

Equipment	Heat exchanger (E-202)
Control Strategy Selected	Backward Control (Temperature)
Controlled Variables	Temperature of hot fluid
Measured variables	Temperature of hot fluid
Manipulated Variables	Flow of cooling water
Disturbances	Flow of cooling water
Set-Points	175 °C

7.4.3 Control Loop of Heat Exchanger (E-203)

Heat exchanger works as condenser after the second cooler (E-202). The condenser is condensing some of the vapor liquids in the gas product of the decomposition unit's effluents (Condensable and non-condensable gases) by reducing the temperature from 175 °C to 125 °C. The coolant fluid is water at 25 °C and the output at 40 °C. The flow rate of hot gas is 1801.363 Kg/h. In the other hand, the flow of cooling water is 7579.928 kg/h.

To keep the temperatures within the designing range, a control loop system should be maintained. The controlled variable is the temperature of gas outlet and the manipulated variable is the flow of cooling water. Figure 7.5 and Table 7.4 show the control loop and control specifications for the heat exchanger (E-203).

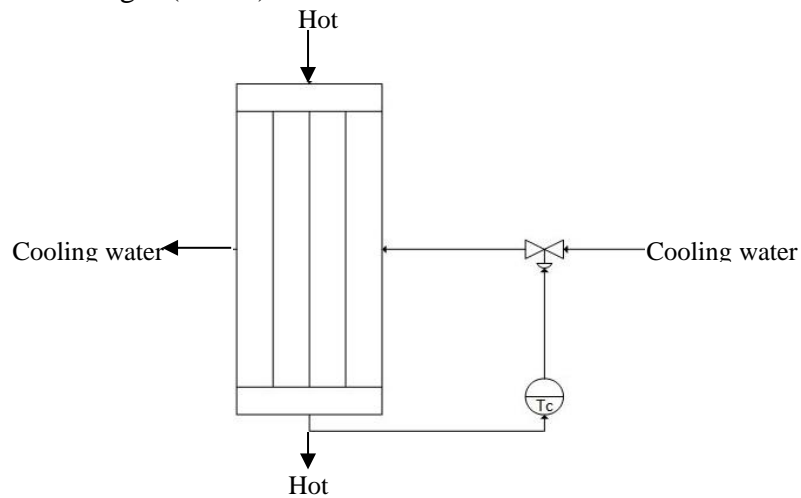
**Figure 7.5** Control Loop of Heat Exchanger (E-203).

Table 7.4 Control Specification of Heat Exchanger (E-203)

Equipment	Condenser (E-203)
Control Strategy Selected	Backward Control (Temperature)
Controlled Variables	Temperature of hot fluid
Measured variables	Temperature of hot fluid
Manipulated Variables	Flow of cooling water
Disturbances	Flow of cooling water
Set-Points	125 °C

7.4.4 Control Loop of Heat Exchanger (E-204)

Heat exchanger works as condenser after the first condenser (E-203). The condenser is condensing the rest of the vapor liquids in the gas product of the reactor's effluents (Condensable and non-condensable gases) by reducing the temperature from 125 °C to 50 °C. The coolant fluid is water at 25 °C and the output at 40 °C. The flow rate of hot gas is 929.72 Kg/h. In the other hand, the flow of cooling water is 6080.519 kg/h.

To keep the temperatures within the designing range, a control loop system should be maintained. The controlled variable is the temperature of gas outlet and the manipulated variable is the flow of cooling water. Figure 7.6 and Table 7.5 show the control loop and control specifications for the heat exchanger (E-204).

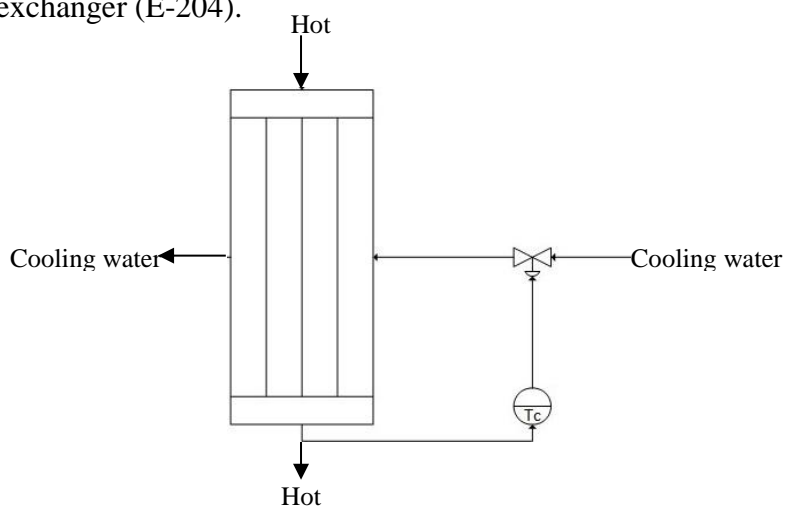
**Figure7.6** Control Loop of Heat Exchanger (E-204).

Table 7.5 Control Specification of Heat Exchanger (E-204)

Equipment	Condenser (E-204)
Control Strategy Selected	Backward Control (Temperature)
Controlled Variables	Temperature of hot fluid
Measured variables	Temperature of hot fluid
Manipulated Variables	Flow of cooling water
Disturbances	Flow of cooling water
Set-Points	50 °C

7.4.5 Control Loop of Storage Tanks (TK-203) and (TK-204)

The purpose of this unit is to store the liquid effluent from flash drum V-201 with a temperature of 125 °C and a pressure of 1.78 atm.

To keep the level within the designing range which is 3 m. Figure 7.7 and Table 7.6 show the control loop and control specifications for the storage tanks (TK-203) and (Tk-204).

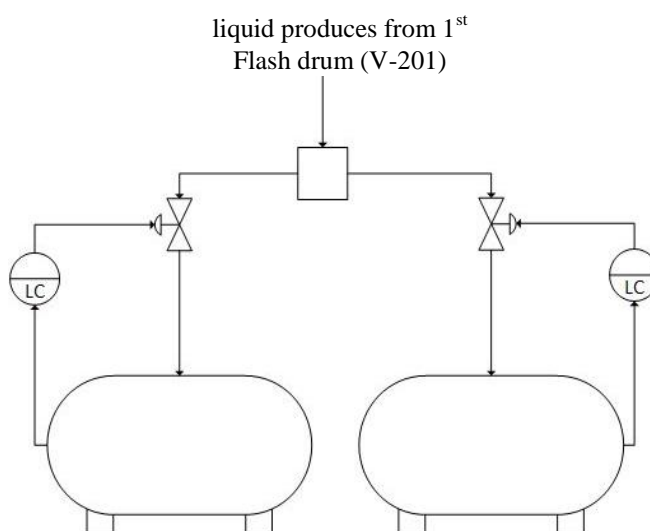
**Figure7.7** Control Loop of Storage Tanks (TK-203) and (TK-204).

Table 7.6 Control Specification of Storage Tank (TK-203) and (TK-204)

Equipment	Tank TK-203 and TK-204
Control Strategy Selected	Backward Control (Level)
Controlled Variables	Level
Measured variables	Level
Manipulated Variables	Input flow rate
Disturbances	Input flow rate
Set-Points	3 m

7.4.6 Control Loop of Storage Tanks (TK-205) and (TK-206)

The purpose of this unit is to store the liquid effluent from flash drum V-202 with a temperature of 50 °C and a pressure of 1.6 atm.

To keep the level within the designing range, which is 3 m. Figure 7.8 and Table 7.7 show the control loop and control specifications for the storage tanks (TK-205) and (TK-206).

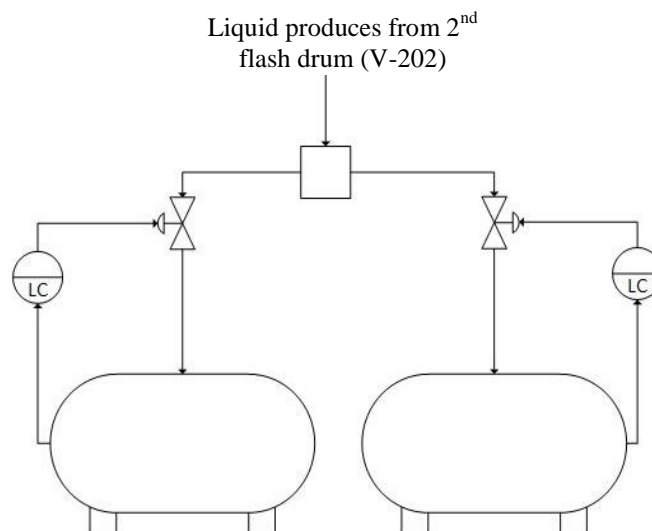


Figure 7.8 Control Loop of Storage Tanks (TK-205) and (TK-206).

Table 7.7 Control Specification of Storage Tanks (TK-205) and (TK-206)

Equipment	Tank TK-205 and TK-206
Control Strategy Selected	Backward Control (Level)
Controlled Variables	Level
Measured variables	Level
Manipulated Variables	Input flow rate
Disturbances	Input flow rate
Set-Points	3 m

7.4.7 Control Loop of Decomposition Unit (DU-201) and (DU-202)

The crumb rubber will be fed into the decomposition unit at a rate of 3027.5 Kg/hr, then the crumb rubber will decompose at 475 °C and 1 atm in the absence of oxygen. A source of Nitrogen will be used to have an inert atmosphere. Also, a source of air will be used during the discharging period to remove the char from the decomposition unit.

It is aimed to keep the operation conditions at its optimum. First, the temperature inside the decomposition unit must be within the designing range ($T = 475\text{ }^{\circ}\text{C}$). Second, the pressure inside the decomposition unit must be atmospheric pressure. Finally, the decomposition unit must be completely empty of oxygen during the running time. Figure 7.9 and Table 7.8 show the control loop and control specifications for the decompositions units (DU-201) and (DU-202).

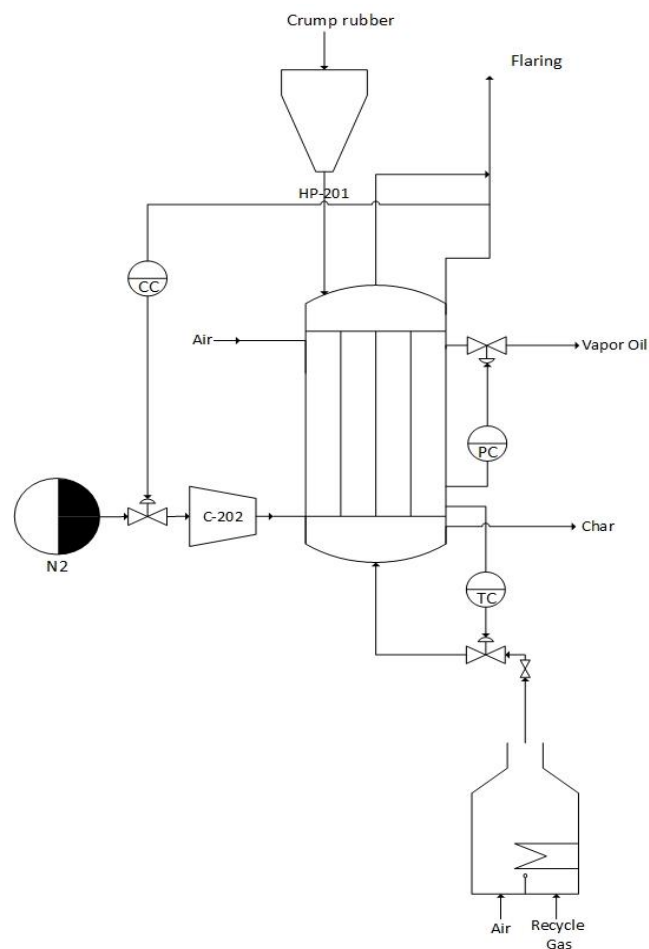


Figure7.9 Control Loop of Decomposition Units (DU-201) and (DU-202).

Table 7.8 Control Specification of Decomposition Units (DU-201) and (DU-202)

Equipment	Decomposition Unit DU-201 and DU-202
Control Strategy Selected	Backward Control (Pressure) Backward Control (Temperature) Backward Control (Concentration)
Controlled Variables	Pressure, Temperature and Concentration
Measured variables	Pressure, Temperature and Oxygen concentration at purge stream
Manipulated Variables	Pressure valve Nitrogen flow rate
Disturbances	Compressing Pressure Burner Temperature
Set-Points	Temperature = 475 °C Pressure = 1 atm Concentration of O ₂ = 0 % at purge stream.

7.4.8 Control Loop of Flash Drum (V-201) and (V-202)

The second condenser effluent will be fed into a flash drum to separate the liquid-gas phases. The liquid phase is separated at the top of the vessel and the vapor phase at the bottom. The feed has a flow rate of 1801.363 kg/hr at 50 °C and 1.84 atm. Figure 7.10 and Table 7.9 show the control loop and control specifications for the flash drums (V-201) and (V-202).

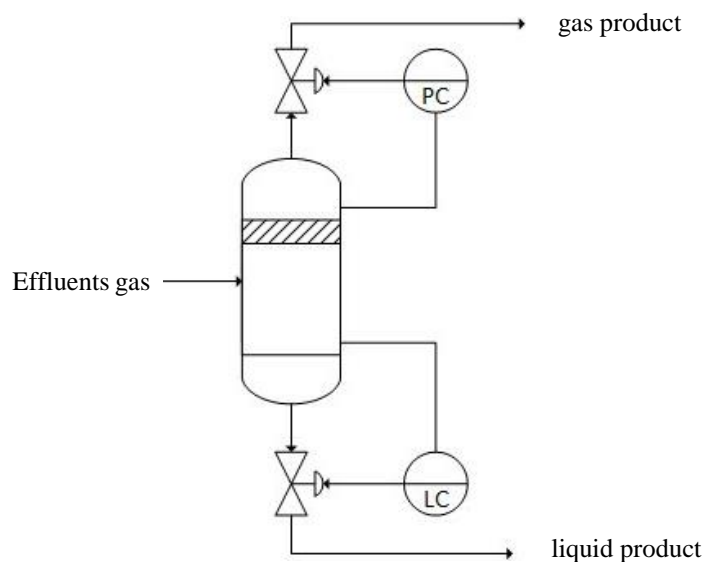


Figure7.10 Control Loop of Flash Drum (V-201) and (V-202).

Table 7.9 Control Specification of Flash Drum (V-201) and (V-202)

Equipment	Flash drum (V-201 & V-202)
Control Strategy Selected	Backward Control (Pressure) Backward Control (Level)
Controlled Variables	Pressure of the vessel Level of liquid
Measured variables	Pressure of the vessel Level of liquid
Manipulated Variables	Pressure valve on the top of the vessel Liquid flow rate at the bottom of the vessel
Disturbances	Pressure and flow of the feed
Set-Points	1.84 atm 0.16 m for V-201 0.301 m for V-202

Figure 7.11 shows the flow sheet with all control loops.

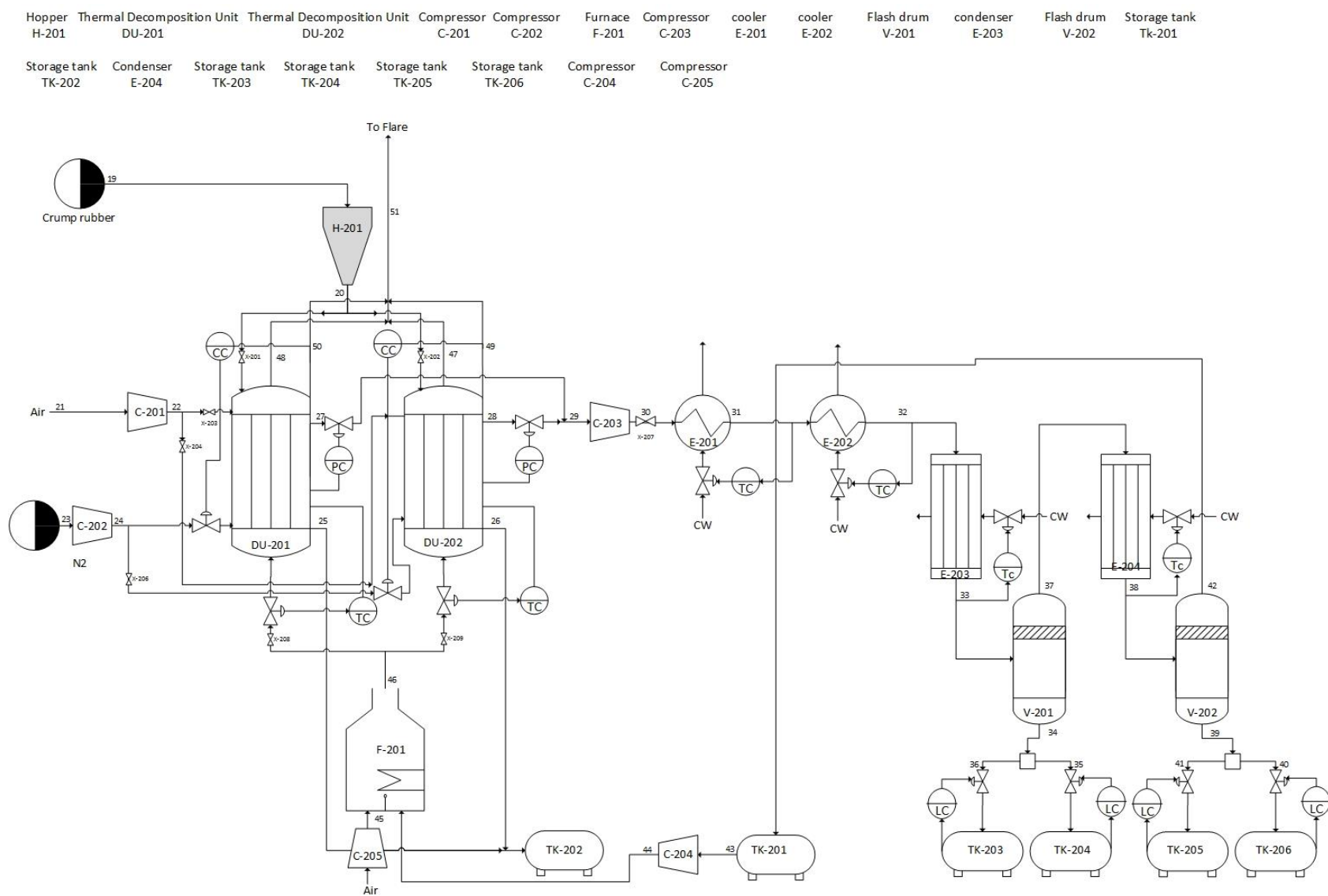


Figure 7.11 Piping & Instrumentation Diagram (P&ID).

CHAPTER VIII

Economic Evaluation

CHAPTER 8

ECONOMIC EVALUATION

The economic evaluations have been done by CAPCOST spreadsheet. The CEPCI has been used is 575 for February 2014 and Taxes 2.5%. In addition, the land cost is \$ 130000 / Year and 10% for annual interest rate.

8.1 Cost of Plant

The cost of raw material, equipment, utility and labor will be calculated to estimate the fixed capital investment (FCI) and cost of manufacturing (COM).

8.1.1 Cost of Raw Material C_{RM}

Table 8.1 shows the cost of raw material.

Table 8.1 Raw Material Cost

Material Name	Price (\$/kg)	Flow rate (kg/h)	Annual Cost
Scrap Tire	\$ 0.04	5000.00	\$ 1,664,400
Nitrogen	\$ 4.00	10.00	\$ 332,880
Total C_{RM}		\$ 1,997,280	

8.1.2 Cost of Equipment

The cost of equipment is summarized in Table 8.2.

Table 8.2 Summary of Equipment Costs

Symbol	Type	Equipment Attribute	MOC	Cost
C-201	Compressor	1.32 KW	Carbon Steel	\$ 595,000
C-202	Compressor	633 KW	Carbon Steel	\$ 781,000
C-203	Compressor	42.5 KW	Stainless Steel	\$ 1,250,000
C-204	Compressor	9.9 KW	Stainless Steel	\$ 1,250,000
C-205	Compressor	73.9 KW	Carbon Steel	\$ 595,000
E-201	Heat Exchanger	3.55 m ²	Cupro- Nickel	\$ 40,600
E-202	Heat Exchanger	5.24 m ²	Cupro- Nickel	\$ 40,600
E-203	Heat Exchanger	7.56 m ²	Cupro- Nickel	\$ 40,600
E-204	Heat Exchanger	4.33 m ²	Cupro- Nickel	\$ 40,600
F-201	Burner	10900 MJ/h	Stainless Steel	\$ 2,260,000
R-201	Decomposition unit	13 m ³	Stainless Steel	\$ 108,000
R-202	Decomposition unit	13 m ³	Stainless Steel	\$ 108,000
Tk-201	Storage Tank	500 m ³	Carbon Steel	\$ 108,000
Tk-203	Storage Tank	120 m ³	Carbon Steel	\$ 71,100
Tk-205	Storage Tank	120 m ³	Carbon Steel	\$ 71,100
HP-201	Hopper	H= 3 m D= 1.4 m	Carbon Steel	\$ 43,900
V-201	Flash Drum	H= 1.97 m D= 0.907 m	Stainless Steel	\$ 40,200
V-202	Flash Drum	H= 1.65 m D= 0.272 m	Stainless Steel	\$ 22,500
Z-100	Size Reduction Plant	-	-	\$ 1,162,432
Total Equipment Cost			\$ 8,628,632	

8.1.3 Cost of Utility C_{UL}

The cost of utility when the cost of electricity \$ 14.8/GJ and the cost of cooling water \$ 2.9/GJ is mainly for cooling water and electricity for size reduction plant.

Total Cost of Utility $C_{UL} = \$ 278,000$ / year

8.1.4 Cost of Labor C_{OL}

The plant required 15 operators to run it.

Total Cost of Labor $C_{OL} = \$ 953,280$ / year

8.1.5 Cost of Waste Treatment C_{WT}

By assuming that there are no wastes need to be treated.

8.1.6 Capital Cost

Fixed Capital Investment FCI = \$ 15,000,000

Working Capital = \$ 3,000,000

8.2 Cost of Manufacturing

The cost of manufacturing can be calculated by two methods with depreciation or without.

- **Without Depreciation**

$$COM_d = 0.18 \text{ FCI} + 2.73 \text{ } C_{OL} + 1.23 (C_{UL} + C_{WT} + C_{RM})$$

$$COM_d = \$ 8,129,647 \text{ / year}$$

- **With depreciation**

$$COM = 0.28 \text{ FCI} + 2.73 \text{ } C_{OL} + 1.23 (C_{UL} + C_{WT} + C_{RM})$$

$$COM = \$ 9,629,647 \text{ / year}$$

8.3 Estimating Manufacturing cost

There are three manufacturing costs, direct manufacturing cost, fixed manufacturing cost and general manufacturing cost.

- Direct Manufacturing Cost

$$\text{Total Direct Manufacturing cost} = C_{UL} + C_{WT} + C_{RM} + 1.33 C_{OL} + 0.03 \text{ COM} + 0.069 \text{ FCI}$$

$$\text{Total Direct Manufacturing cost} = \$ 4,867,031.81 / \text{year}$$

- Fixed Manufacturing Cost

$$\text{Total Fixed Manufacturing Cost} = 0.708 C_{OL} + 0.168 \text{ FCI}$$

$$\text{Total Fixed Manufacturing cost} = \$ 3,194,922.24 / \text{year}$$

- General Manufacturing Cost

$$\text{Total General Manufacturing Cost} = 0.177 C_{OL} + 0.009 \text{ FCI} + 0.16 \text{ COM}$$

$$\text{Total General Manufacturing Cost} = \$ 1,844,474.08 / \text{year}$$

8.4 Products Prices

The summary of products and their estimated prices are shown in Table 8.3.

Table 8.3 Products Prices

Material Name	Price (\$/kg)	Flow rate (kg/h)	Annual Cost
Crumb Ruber	\$ 0.27	1230.00	\$ 2,733,028
First Condenser Liquid	\$ 0.82	870.00	\$ 5,900,714
Second Condenser Liquid	\$ 0.88	672.00	\$ 4,910,672
Iron	\$ 0.30	700.00	\$ 1,747,620
Total Revenue			\$ 15,292,034

8.5 Profitability Analysis

The Net profit = Revenue – Expenses – Income Tax

Revenue = The products' prices = \$ 15,292,034 / year

Expenses = COM = \$ 9,629,647 / year

Income Tax = (Revenue – Expenses) (Tax Rate)

$$= (\$ 15,292,034 - \$ 9,629,647) \times (2.5\%) = \$ 141,559.675 / \text{year}$$

The Net profit = Revenue – Expenses – Income Tax

$$= \$ 15,292,034 - \$ 9,629,647 - \$ 141,559.675 = \$ 5,520,827.325 / \text{year}$$

The Net profit = \$ 5,520,827.325 / year

After-Tax Cash Flow (ACF) = Net profit + Depreciation

$$\text{ACF} = \$ 5,520,827.325 + \$ 1,500,000 = \$ 7,020,827.325$$

ACF = \$ 7,020,827.325

8.6 Rate of Return (ROR %)

$$\text{ROR} = (\text{After-Tax Cash Flow} / \text{TCI}) * 100$$

Where,

TCI: Total Capital Investment = FCI + Working Capital

$$\text{TCI} = \$ 15,000,000 + 3,000,000 = \$ 18,000,000$$

$$\text{ROR} = (\$ 7,020,827.3 / \$ 18,000,000) * 100 = 29 \%$$

ROR = 29 %

8.7 Payback Period (PBP)

$$\text{PBP} = \text{TCI} / \text{ACF}$$

$$\text{PBP} = \$ 18,000,000 / \$ 7,020,827.3 = 2.56 \text{ years}$$

PBP = 2.56 years

Figure 8.1 shows the cash flow diagram of the project.

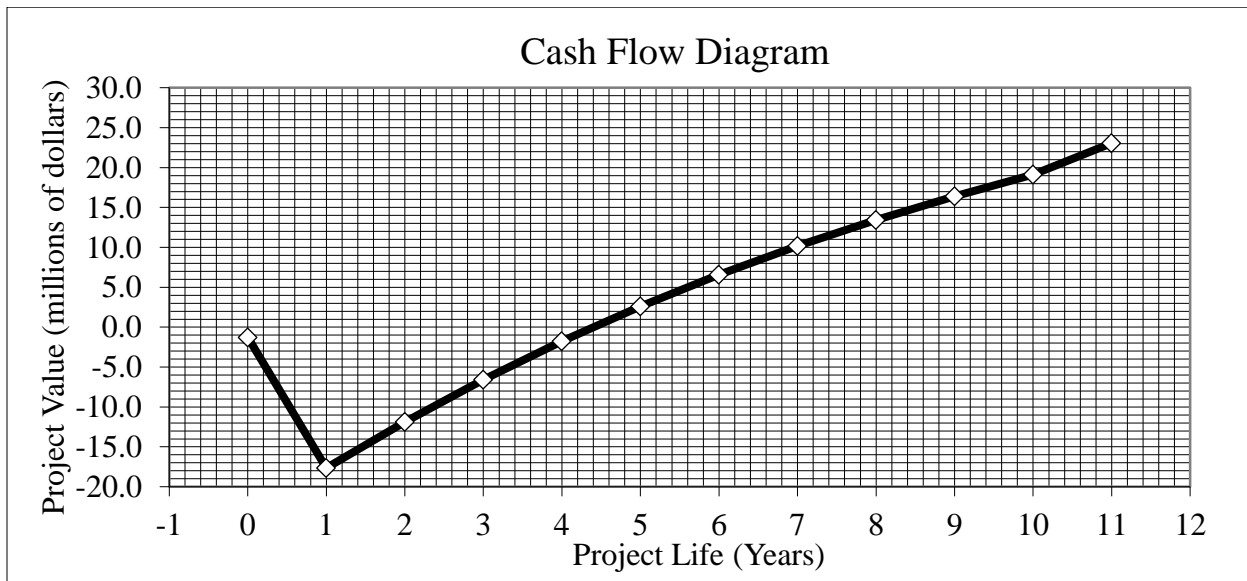


Figure 8.1 Cash Flow Diagram.

8.8 Summary of Economics Evaluation

Table 8.4 shows the summary of all economics evaluation.

Table 8.4 Summary of Economics Evaluation

C_{RM}	\$ 1,997,280
Total Equipment Cost	\$ 8,628,632
C_{UL}	\$ 278,000
C_{OL}	\$ 953,280
FCI	\$ 15,000,000
Working Capital	\$ 3,000,000
COM_d	\$ 8,129,647
COM	\$ 9,629,647
Revenue	\$ 15,292,034
The Net profit	\$ 5,520,827.325
ACF	\$ 7,020,827.325
ROR	29%
PBP	2.56 years

CHAPTER IX

Hazard Analysis

CHAPTER 9

HAZARD ANALYSIS

9.1 HAZOP Study

9.1.1 HAZOP Definition

Hazard and Operability consideration (HAZOP) is a structured and systematic technique for system examination and risk management. In particular, HAZOP is often used as a technique for identifying potential hazards in a system and identifying operability problems likely to lead to nonconforming products.

HAZOP is based on a theory that assumes risk events are caused by deviations from design or operating intentions. Identification of such deviations is facilitated by using sets of “guide words” as a systematic list of deviation perspectives. This approach is a unique feature of the HAZOP methodology that helps stimulate the imagination of team members when exploring potential deviations [53].

The definitions of the process terms that are used:

Nodes: The Node is some specific sections of the system intent are evaluated. A node can be a subsystem, a function group, a function or a sub-function.

Guide Words: The guide words used to identify possible deviations in this HAZOP should be listed. An explanation of any specialized words used for the facility should also be given.

Deviations: A deviation is a way in which the process conditions may depart from the design intent as suggested by each guide word, eg high pressure.

Causes: Potential causes that would result in the deviation occurring. These causes can be hardware failures, human errors, an unanticipated process state (e.g., change of composition), external disruptions (e.g., loss of power), etc.

Consequences: Results of deviations (e.g. release of toxic materials). Normally, the team assumes active protection systems fail to work.

Action: Action is the suggestions for design changes, procedural changes, or areas for further study to avoid the problems.

9.1.2 HAZOP Process

The HAZOP process creates deviations from the process design intent by combining guide words (No, more, less, etc.) with process parameters resulting in a possible deviation from design intent. For example, when the guide word "No" is combined with the parameter "flow" the deviation "no flow" results. A list of guide words used is given below. It should be pointed out that not all guideword/parameter combinations will be meaningful. A table of meaningful guideword/parameter combinations and their application is given below.

Guidewords:

- No
- More
- Less
- Reverse

The application of parameters will depend on the type of process being considered, the equipment in the process and the process intent. The most common specific parameters that have been used are flow, temperature, pressure, and Composition. In almost all instances, these parameters should be evaluated for every node. Additionally, the nodes should be mentioned on the flow sheet.

A set of parameters are shown in Table 9.1.

Table 9.1 Guide Words

Guide Words	Comments
NO, NOT, NONE	No part of the intentions is achieved but nothing else happens
MORE OF and LESS OF	These refer to quantities and properties such as flow rates and temperatures
REVERSE	This is mostly applicable to activities, for example reverse flow or chemical reaction

9.1.3 HAZOP Analysis

For the pyrolysis flow sheet, three nodes are chosen. They are shown in the flow sheet figure 9.1.

Node 1: The stream starts from Nitrogen source to the (DU-201, DU-202).

Node 2: The stream starts from the (DU-201, DU-202) to cooler (E-201)

Node 3: The stream starts from first cooler (E-201) to Second cooler (E-202).

Figure 9.1 shows all three nodes on the pyrolysis plant flowsheet.

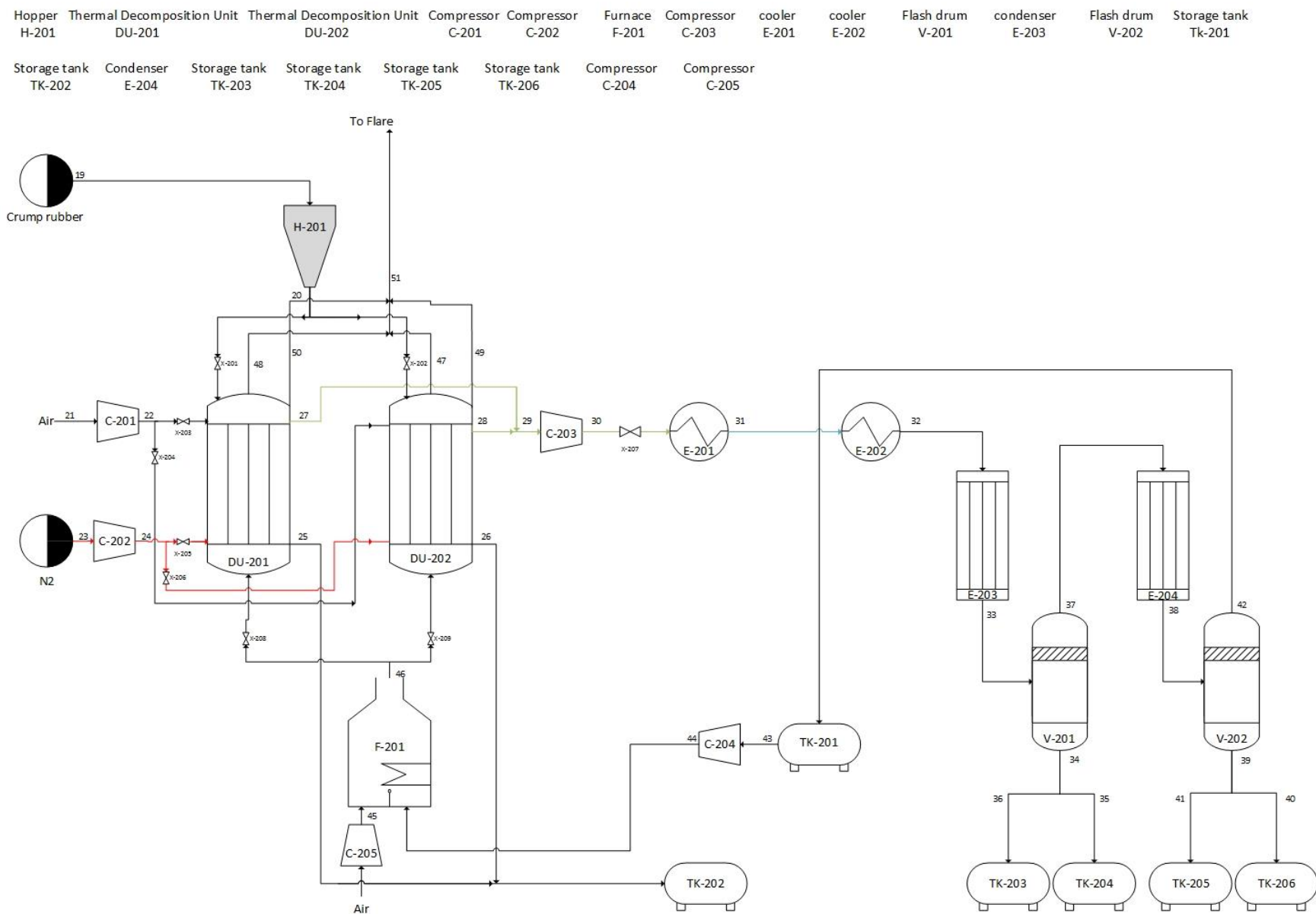


Figure 9.1 HAZOP Flowsheet.

9.2 Environmental Consideration

The environmental consideration or environmental aspects and impacts identification process is one of the most important parts of any Environmental Management System (EMS), as it lays the foundation for how the management system will run in the future and the environmental improvements it should address. In basic terms, it will assess environmental risk. It also has the ability to give information on the level and amount of environmental impact, and to give valuable information how to reduce the pollution.

In the environmental consideration, the impact of the materials affecting the environment directly is mentioned. In addition, the regulation of emissions must be written. Also, the methods are used to reduce the concentration of the hazardous of materials.

9.2.1 Solid Product

The solid or char will produced after the pyrolysis process finished. The char contains carbon black and the mineral matter initially present in the tire. After the char remains in the reactor, it will be pushed out by air compressor to be collected in bags and then sold.

In general, there are no harmful components. The problem with the small particles of char (Particulate matters) that 10 micrometers in diameter, it may attack the respiratory system of human. It can be solved by using of respirator mask.

9.2.2 Liquid Products

The Liquid product is produced after condensing the gas phase comes out from the decomposition unit. The liquid product contains mostly Hydrocarbons as shown in Table 9.14. These hydrocarbons will be collected and sold to other manufactories to be used in further processes. In general, there are no emissions and harmful from these hydrocarbons if there is no problems in transportation.

Table 9.14 Weight Fraction of Pyrolysis Liquid Products

Component	Wt%
Toluene	0.231653
Benzene	0.156943
Hexene	0.111975
Hexane	0.079759
Styrene	0.071806
Ethyl Benzene	0.181398
Cyclopentane	0.023607
Total	1

Most of liquid components are hydrocarbons. So, the problem with the mixture is about the explosion. Therefore, safety precautions are needed when handle the liquid product by taking in consideration the pressure and heat. Also, keeping it away from ignition or heating source.

9.2.3 Gas Product

The gas product is mainly contains: H_2 , H_2S , CO , CO_2 , CH_4 , C_2H_4 , C_3H_6 and other light hydrocarbons. These hydrocarbons will be burn at the furnace to provide the heat for the decomposition unit.

The emissions from the complete combustion of these components are:

- H_2O
- CO_2
- SO_2

CO_2

Carbon dioxide (CO_2) is a colorless, odorless, non-flammable gas that is a product of cellular respiration and burning of fossil fuels. CO_2 is present in the atmosphere at 0.035%. In terms of worker safety, Occupational Safety and Health Administration (OSHA) has set a permissible exposure limit (PEL) for CO_2 of 5,000 parts per million (ppm) over an 8-hour work

day, which is equivalent to 0.5% by volume of air. High levels of CO₂ can displace oxygen (O₂) and nitrogen (N₂), potentially causing health problems.

To reduce the CO₂ concentration in the emission mixture, an absorber will be used with an aqueous solution of monoethanolamine (MEA) in a packed absorption column. In addition, by using polymeric based membranes designed for carbon dioxide separation from mixed-gas systems [51].

SO₂

Sulfur Dioxide is a colorless, corrosive gas with an irritating pungent odor.

Some people perceive its odor as burnt matches. Its odor allows it to be detected at low concentrations. Sulfur dioxide is made by combustion of hydrogen sulfide. Sulfur dioxide affects human health when it is breathed in. It irritates the nose, throat, and airways to cause coughing, wheezing, shortness of breath, or a tight feeling around the chest.

The Occupational Safety and Health Administration (OSHA) has set a limit of 2 ppm over an 8-hour workday.

To reduce the SO₂ concentration in the emission mixture, an absorber will be used with an aqueous fulvic acid solution [52].

9.2.4 Summary of Environmental Consideration

Table 9.15 shows a summary of environmental consideration

Table 9.15 Summary of Environmental Consideration

Component		Problem	Cause	Consequences	Limit of emission	Prevent
Solid		Particulate matters. 10 micrometers in diameter.	Reduction in the particles after size reduction and pyrolysis.	Attack the respiratory system of human.	-	Be sure to collect in safe bags.
Liquid		Explosion	High pressure or temperature.	May explosion.	-	Be aware about the dangers of liquids while collect and transport.
Gas		Emissions	Leakage or purge	Air pollution	-	Reduce the emission by flaring or separation processes.
	CO ₂	Emission	A product of combustion.	High levels of CO ₂ causing health problems.	5,000 ppm over an 8-hour workday.	By using aqueous solution of monoethanolamine (MEA) in an absorber or polymeric based membranes
	SO ₂	Emission	A product of combustion H ₂ S	Affects human health by breathing. Irritates the nose, throat, and airways to cause coughing and breathing problems.	2 ppm over an 8-hour workday.	By using an aqueous Fulvic acid solution or ionic liquids in an absorber.

CHAPTER X

Site Feasibility Study

CHAPTER 10

SITE FEASIBILITY STUDY

10.1 Site Location

To build a manufacture or plan, the location is an essential that must to be taken in considerations due to maximize the income to the client as well as suitability for future expansion. In general, the location of the plant depends on many criteria available of raw materials, products distribution, available of land and infrastructures. In addition, site location also plays an important role in the profitability and success of the manufacture for the estimated lifetime of operation. The location is considered on a local basis, where each state is evaluated in order to find the most suitable place. It is necessary to consider available industrial region within the country. The following factors should be considered in selecting a plant site:

- Available of Raw Materials
- Available of market
- Land Available and Cost
- Utilities
- Transportation Facilities
- Labor Supply
- Waste Disposal
- Weather

Available of Raw Materials

The plant that will be constructed should be built near to the raw material. Selecting the closest location to the supplier will reduce the transportation cost of raw material to the plant.

For operational point of view, it will reduce the operational cost since the plant will require a daily input of raw material throughout a year.

Available of Market

The proposed plant site should ideally be located close to the primary market in order to minimize transportation costs. The local demand of the product should also be taken into consideration in selecting a suitable plant site.

Land availability and cost

The cost of the land depends on the location. The land price should be reasonable to reduce the total investment cost. It is important to choose the lowest land price when establishing a new plant to gain the highest economic value.

Utilities

Utilities supply is an important thing for every plant. Utilities provide the electricity, industrial gases and other utilities such as steam and water. These utilities are used to run the process in the plant. The utilities supply must be sufficient and reliable in order to have the plant running smoothly.

Transportation Facilities

The sea, railroads, and highways are the common means of transportation used by major industrial concerns. The kind and amount of products and raw materials determine the most suitable type of transportation facilities. In any case, careful attention should be given to local freight rates and existing railroad lines.

Labor Supply

Plant should be located where labor is available. Available, inexpensive manpower from the surrounding area will contribute in reducing the cost of operation.

Waste Disposal

A good industrial site is when it is provided with a good waste and disposal facility. If there are none, then the best way is to choose the area which is the nearest to this facility.

Weather

The weather or climate of where the plant is going to be established is also important. This is because if the plant is going to be built in a colder climate, more energy requirement is needed for heating purposes as more insulation needed for the equipment. Extreme hot or cold weather may affect the plant's operation and economic operation. Furthermore, the humidity may affect the product or the raw material quality. Also, humidity may become an environmental issue.

10.2 Site Selection

The plant of tire recycling is categorized as mechanical and petrochemical project. The plant must be located in an industrial area provided by the government.

In Saudi Arabia, there are many industrial areas in different locations. The main industrial areas are Riyadh, Jubail and Yanbu.

Riyadh Industrial City

The Riyadh industrial city was established at 1973, there are two industrial cities. There are more than 1100 factories and more than 120000 workers.

- Riyadh 1st

Riyadh 1st. Industrial City was established in 1973. There are more than 50 existing factories, producing different products representing electrical industries, plastic industries, metal industries and wood industries. The industrial city is characterized by its location, as it is located near the dry port and behind the Riyadh Railway Station.

- Riyadh 2nd

Riyadh 2nd. Industrial City was established in 1976. In order to satisfy the growing demand for industrial lands in Riyadh, the development of the industrial city was carried out on a total area of more than 18 million square meters in four stages.

Jubail Industrial City

The Jubail industrial city is one of the most modern and biggest industrial complexes in Asia. Construction operations in the city were stepped up in 1975; the latest technologies were used in building it to be a modern industrial city. Jubail industrial comprises a group of major companies which produce petrochemicals, chemical fertilizers, industrial gases, steel, iron and oil.

Yanbu Industrial City

The new industrial city of Yanbu was planned as the spearhead for the modernization of the whole of Saudi Arabia's rural northwestern coastal region. It would also provide a new strategic outlet on Red Sea shipping lanes, to handle most of the Kingdom's sea-borne trade. Planners envisaged a city with housing and lifestyle facilities second to none, and an urban population, which would exceed 100,000 by the year 2020.

These three are chosen because of they are the biggest industrial areas in Saudi Arabia. Also, all the utilities are provided.

The site allocation for Tire Recycling plan is considering the following criteria:

Raw material availability

The raw material for tire recycling is naturally tires. So, this criterion will be taking in consideration due to the expensive of collecting and transporting tires and the present of tires in the location. In general, the presence of tires is depending on the population of region. In characteristic, minimally one tire for each person.

Market availability

The products of tire recycling are char, liquid oil and gas. The gas is recycled in the process. The other products need further processes to be used. So, the char and liquid will be sold to a customer.

Land Available and Cost

Due to the two processes – Size reduction and Pyrolysis – and scrap tire storage the need for a large land is necessary. So, the cost of land will affect the location of plant.

Utilities

Of course, most of manufacturing are needed utilities such as fuel, power and water. So, the presenting of these utilities at low cost will encourage the plant to be established.

Weather

Weather is at some times playing an important role with location of facility. Saudi Arabia in general has same climate at most of cities. The problem is about the humidity. Humidity will affect the environment because raw material which is tires provides ideal conditions for the spreading of mosquitoes and other insects or animals.

In the table below, it will be comparison between the three locations Riyadh, Jubail and Yanbu depending on the previous criteria.

The evaluation shown in Table 10.1 will be from 1 to 10. 10 for Best and 1 for Worst.

Table 10.1 Comparison between Industrial Cities.

Criteria	Riyadh	Jubail	Yanbu
Raw material	10	5	5
Market availability	5	10	10
Land Available and Cost	7	3	3
Utilities	10	10	10
Weather	10	5	5
Total	42	33	33

From the comparison, Riyadh is the ideal choice to locate the plant. In table 10.2 the prices of rent and utilities are mentioned.

Table 10.2 Prices at Riyadh 2nd Industrial City

Development Charges(paid only once)	50 SR/m ²
Total customer invoicing per annum	1 SR/m ²
Electricity	0.15 SR/KWh
Diesel	0.36 SR/L
Water	1.71 SR/m ³

Because of the large number of units are used in the plant, a large land is needed. The land is chosen at Riyadh 2nd industrial. Total area for the land is approximately 240,000 m². The dimensions of land are about 770 m long and 310 m in width.



Figure 10.1 Location of Riyadh 2nd Industrial City.

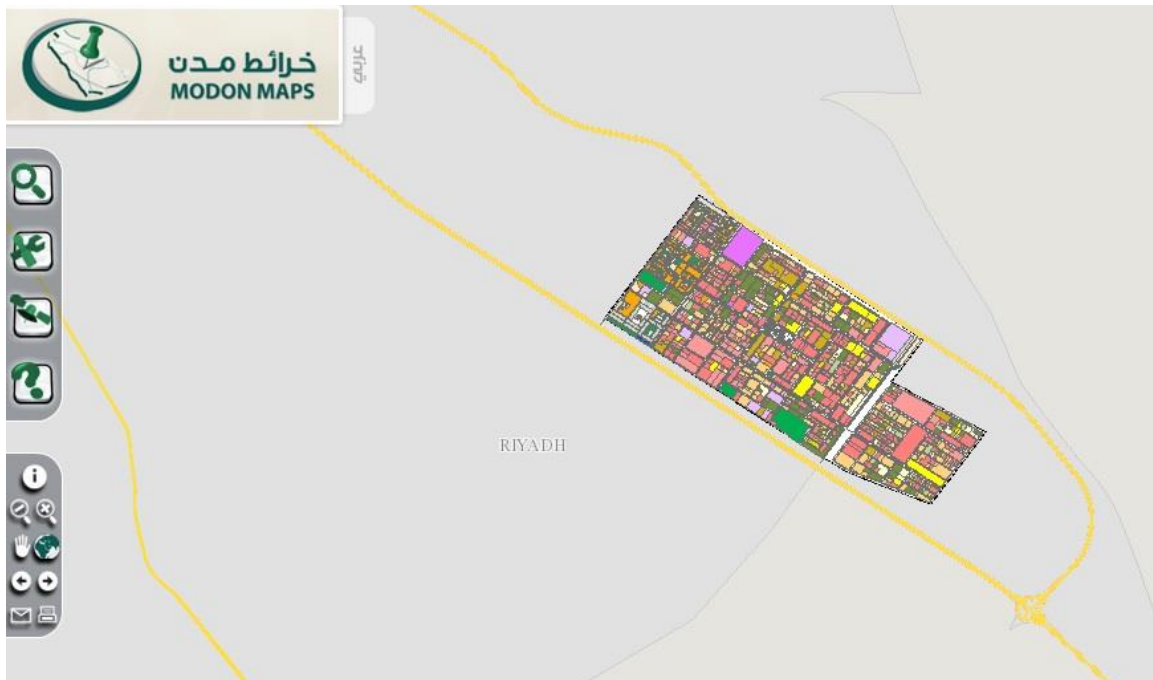


Figure 10.2 Location of Riyadh 2nd Industrial City.



Figure 10.3 Land Chosen and Dimensions.

10.3 Site Layout

The process units and buildings should be laid out to give the most economical flow of materials and personnel around the site. Hazardous processes must be located at a safe distance from other buildings. Consideration must also be given to future expansion of the site. The utilities buildings and service required on a site in addition to the main processing unit include:

- Storage for raw materials and products
- Maintenance workshops
- Warehouse
- Lab for process quality control
- Fire station and other emergency services
- Administration building.
- Restaurant.

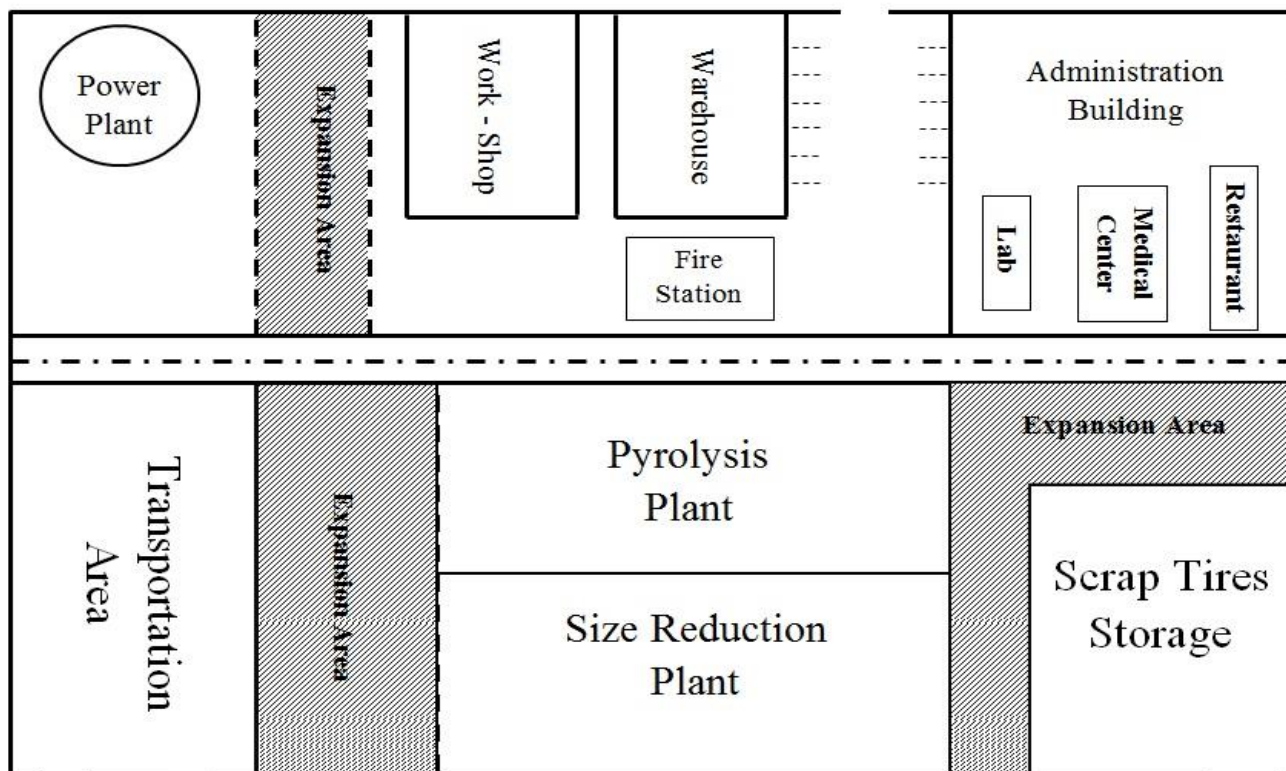


Figure 10.4 Site Layout for the Plant.

CONCLUSION & RECOMMENDATION

Conclusion

At the end of the project, Tires are neglected treasure. More than 20 million tires are disposal every year in Saudi Arabia. The recycle is always better than disposal. For scrap tires, there are many ways to recycle such as using them as whole tires in structural projects or in cement industries as TDF. Also, Scrap tires have wide applications after the tires shredded and grinded to get a crumb rubber besides extracting the steel and fabrics which they have their own commercial prices. Some of the applications of crumb rubber are athletic fields, automotive parts, playgrounds and molding industry.

In addition, there are further processes after having a granules rubber free of steel and fabrics. One of these processes is devulcanization. Devulcanization is a process where returning rubber from its thermoset, elastic state back into plastic, moldable state. There are many methods to devulcanized rubber such as by using chemicals, ultrasonic or microwave. The end product of devulcanization is a rubber has similar characteristics of virgin rubber. The other process is liquefaction the scrap tires where tires are conjunction with coal to enhance the properties of coal.

There is Pyrolysis process which is studied in this report. Pyrolysis is a thermal decomposition of organic material in the absence of air. There are mainly three products from pyrolysis process gas, liquid and char. The yield of each product depends on the formation conditions; it is different from author to other. Temperature, pressure and particles size are main conditions affect the yields of products. Gas is mostly recycled in the process to generate the heat. Liquid is contains many components such as benzene, toluene and xylene. Liquid product can be used as a fuel or as feed to distillation process to separate the components. Char is contains different minerals and components, manly carbon. Char need further process to be commercially used such as activated the carbon.

Finally, scrap tires are very pollutant and dangerous if just disposal in the lands. The recycling is very attractive project and the suitable solution for scrap tires. Hopefully, this project will be enlightened to solve the problem of disposal tires.

Recommendation

As known, tires are a source for pollution. But can be used to produce useful products. Tire recycling in general goes into various methods, such as using them as they are, grinding them or decompose the tires.

It is recommended if the government is issued a regulations that organizing the tires disposal. In addition, it will be helpful if the project is supported by a governmental organization. Also, it is must be there a corporation between this project and the refinery plants to use the product of the pyrolysis plant.

Mainly, there are two fields for crumb rubber. First, is as an additive to asphalt to enhance the properties. Second, is for playgrounds field to protect the industrial grass. It is suitable if there are in Saudi Arabia another fields can crumb rubber be used in such as mold rubber, insulation film or in the manufacturing of rubber instead of natural rubber.

The minerals that extracted from tires can be used as additives in the manufacturing iron and steel. Also, can be recycled and used again in tires. In addition, it can be melt and then mold into different shapes.

Fabrics are still having no clear market or further processes. However, they can be used as reinforcing material for new tires.

About the third product of pyrolysis Ash, it is mainly carbon. In general, it is classified as deactivated carbon. So, one of the important processes is ash activation to produce activated carbon which has many usage in industrial. On the other hand, the ash can be burned to get the benefit from its calorific value which is about 32.81 MJ/Kg if considered as carbon.

When talking about the pyrolytic oil, it has different methods to be used. The main use of oil is to be a feed stock for a refinery plant because it consists of hydrocarbons. In addition, it is easy to be separated due to the light components in pyrolytic oil comparing with crude oil. The other usage is by using it as fuel to be burned. Also, it can be used as fuel in motors due to its characteristics which similar to diesel.

The gas produced will be used as a fuel for the burner, by calculations the quantity will be enough for heating. Taking in consideration the losses of heat and the startup, another source of fuel should be installed. In addition, the stack's effluents must be cooled down to meet the regulations.

References

- [1] <http://www.jags.org>
- [2] <http://www.jalopyjournal.com/forum/archive/index.php/t-612393.html>
- [3] <http://www.mydailynewswatchng.com/tyre-great-invention-taken-granted/>
- [4] Kaster & Lynch, P.A., "Tire Manufacturing Processes"
- [5] <http://www.townfairtire.com>
- [6] Office of Permitting, Waste Tire Recycling Program, tnrc information, , 1999
- [7] "The Pneumatic Tire", 2006
- [8] The Japan Automobile Tyre Manufacturers Association, Inc. Tire Industry of Japan, 2013
- [9] <http://www.researchandmarkets.com>
- [10] S. Mavridou, N. Oikonomou, A. Kalofotias, "Integration of end-of-life tires in the life cycle of road construction", December 2010
- [11] Effects Of Waste Tires, Waste Tire Facilities, And Waste Tire Projects On The Environment, May 1996
- [12] Ahmet . Turer , " Recycling of Scrap Tires"
- [13] www.tceq.state.tx.us
- [14] United States Environmental Protection Agency (EPA)
- [15] W.J. ROFF & J.R. SCOTT, "Fibers, Films, Plastics and Rubbers", First edition, London Butter Worths, 1971.
- [16] Fred W. Barlow, "Rubber Compounding", Second edition, Marcel Dekker, 1993.
- [17] Maurice Morton, "Rubber Technology", Second edition, Van Nostrand Reinhold Company, 1973.
- [18] www.chemistryexplained.com
- [19] Claude Hepburn, "Rubber Technology and Manufacture", Third edition, Butterworths for the Institution of the Rubber Industry, 1971.
- [20] David A. Katz, "Preparation of Synthetic Rubber", 2010
- [21] Alexandra Pehlken and Elhachmic Essadiqi, "Scrap tire Recycling in Canada" CANMET Materials Technology Laboratory, 2005.
- [22] Synthetic Polyisoprene.
- [23] International Carbon Black Association.

- [24] <http://www.kolonindustries.com>
- [25] United State Environmental Protection Agency (EPA), Scrap Tires: Handbook on Recycling Applications and Management for the U.S. and Mexico, 2010.
- [26] M. Juma*, Z. Koreňová, J. Markoš, J. Annus, Ľ. Jelemenský, “PYROLYSIS AND COMBUSTION OF SCRAP TIRE”, 2006
- [27] “Evaluation of Waste Tire Devulcanization Technologies”, 2004.
- [28] Ramesh K. Sharma, Dady B. Dadyburjor, John W. Zondlo, Zhenyu Liu and Alfred H. Stiller, “COAL-TIRE CO-LIQUEFACTION”
- [29] Liberty tire recycle, www.libertytire.com
- [30] “THE USE OF SCRAP TIRES IN CEMENT ROTARY KILNS”, 1992
- [31] Stefan Flanderijn, “Mechanochemical devulcanization of butadiene rubber with DPDS as a devulcanization aid”, 2012
- [32] “Dynamic Devulcanization and Dynamic Vulcanization for Recycling of Crosslinked Rubber”, 2006
- [33] “pyrolysis, thermal gasification, And liquefaction of solid wastes and residues Worldwide Status of Processes”, 1977
- [34] Eldho Abraham, Bibin M Cherian, Elbi P A, Laly A Pothen and Sabu Thomas, “Recent advances in the recycling of rubber waste”
- [35] <http://www.dgengineering.de/Economy-scrap-tires-pyrolysis.html>
- [36] <http://www.scraptirenews.com/crumb.php#manufacturing>
- [37] http://www.crumbrubbersite.com/crumb_rubber.html
- [38] Andrea Corti, Lidia Lombardi, “End life tyres: Alternative final disposal processes compared by LCA”, published by Elsevier, 2004.
- [39] Kurt Reschner, “Scrap Tire Recycling A Summary of Prevalent Disposal and Recycling Methods”, 2008.
- [40] McCabe, W.L., smith, J.C. and Harriott, p. "Unit Operations of Chemical Engineering", 7th eddition, McGraw- Hill, New York, 2005.
- [41] Brad Swenson, “ECO-RP-1000 Tire Recycling System”, ECO GREEN EQUIPMNET, 2013.
- [42] <http://www.uttamrubtech.com/cracker-mill.html>
- [43] http://www.ritec.fr/doc%20ritec%20pdf/zigzag_miner_En.pdf

- [44] <http://people.engr.ncsu.edu/barlaz/Lectures/9%20mrf2.pdf>
- [45] http://www.puritanmagnetics.com/1/magnet/drum_magnets.asp
- [46] <http://www.911metallurgist.com/blog/bond-work-index-formula-equation>
- [47] Tyre Recovery Association, “Specification for the manufacture and storage of size reduced tyre materials”, 2012.
- [48] <http://www.ecomena.org/crumb-rubber-production-and-uses/>
- [49] M. Rofiqul Islam, M. Parveen, H. Haniu and M. R. Islam Saker, “ Innovation in Pyrolysis Technology for Management of Scrap Tire: a Solution of Energy and Environment”, 2010.
- [50] Mahmood M, Barbooti, Thamer J. Mohamed, Alaa A. Hussain, Falak O. Abas, “ Optimization of pyrolysis condition of scrap tires under inert gas atmosphere”, 2004.
- [51] Faisal M. Khan and Dr Tariq Mahmud, “Modelling of Gas Absorbers for Carbon Dioxide Capture Applications”
- [52] Jitao Yangab and Guoxin Hu, “Absorption of SO₂ from flue gas by aqueous fulvic acid solution”, 2012
- [53] Gordon Mckay, “Process Safety Management and Risk Hazard Analysis”.

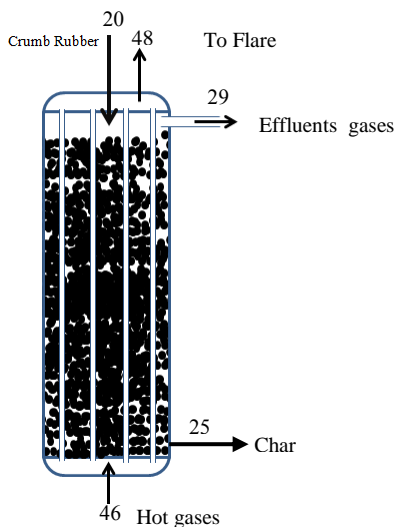
Appendix A

Detailed Calculations of Material & Energy Balances

APPENDIX A

DETAILED CALCULATIONS OF MATERIAL & ENERGY BALANCES

Material and Energy Balance for the Decomposition unit (DU-201 & DU-202):



$$M_{in}=M_{out}$$

$$M_{20}=M_{25}+ M_{29}$$

$$0.595 M_{20}$$

$$M_{25}=0.405 M_{20}$$

$$M_{20}=3027.5\text{Kg/hr}$$

$$M_{29}=1801.36265\text{Kg/hr}$$

$$M_{25}=1226.1375\text{Kg/hr}$$

Stream	Component	T (°C)	N (mol/hr)	H (J/mol)
20	Crumb Rubber	25	442664.516	0
48	Hot gases	534.873045	49467.3915	16578.9025
29	Gas + Vapor oil	475	34825.67428	105093.704
46	Hot gases	1956.13	49467.3915	1952.304202
25	Char	475	102178.125	8719.929017

Component and mole fraction of stream number 20

Component	C	H	N	S	O
mole fraction	0.457661153	0.491059588	0.0024426	0.002543354	0.046293

Component and mole fraction of stream number 25

Component	C	H	S
mole fraction	0.999999874	1.1543E-07	1.0983E-08

Component and mole fraction of stream number 29

Component	CO2	H2S	C3H6	H2	CH4	C2H4	CO	Toluene	Benzene	Hexene	Hexane	Styrene	Ethyl Benzene	Cyclopentane
Mol fraction	0.0209	0.011	0.03	0.2198	0.16828	0.0321	0.0172	0.13024	0.1040	0.0689	0.0479	0.0357	0.0885	0.01744

	A	B	C	D
Cp_{mix20}	23.15408155	0.005197964	-5.96426E-06	3.23245E-09
Cp_{mix25}	18.3195011	0.001524001	-1.50002E-07	5.00087E-12
Cp_{mix29}	18.90471826	0.254477	-0.000147616	3.30646E-08

$$Q = \Delta H = H_{29} + H_{25} - H_{20} + \Delta H_r$$

$$Q = n_{29} * \left(y_i * \Delta H_f + \int_{297}^{(475+273)} Cp_{mix29} dT \right) + n_{25} * \left(y_i * \Delta H_f + \int_{297}^{(475+273)} Cp_{mix25} dT \right)$$

$$- n_{20} * \left(y_i * \Delta H_f + \int_{297}^{297} Cp_{mix19} dT \right)$$

$$Q_{product} = 34825.67428 * (y_i * \Delta H_f + 371934.9255) + 49467.3915 * (y_i * \Delta H_f + 3823.3376) - 442664.516 * (y_i * \Delta H_f + \int_{297}^{297} Cp_{mix20} dT) = 9.55 \times 10^6 \text{ KJ/h}$$

$$Q_{of \text{ Hot gases}} = n \int_{25}^{T_{48}} Cp_{mix_{48}} - n \int_{297}^{1543.747} Cp_{mix_{46}}$$

$$Q = 49467.3915 \int_{25}^{T_{48}} Cp_{mix_{48}} - 49467.3915 \int_{297}^{1543.747} Cp_{mix_{46}} =$$

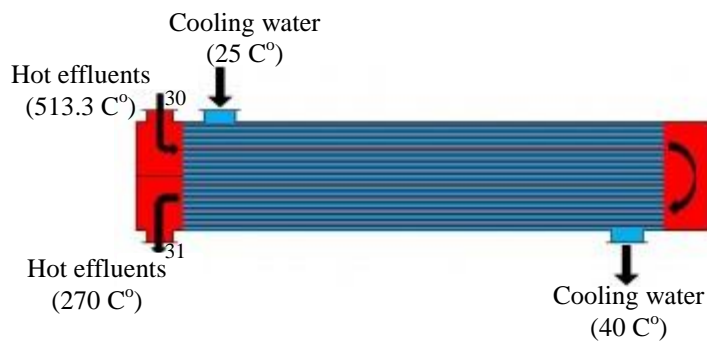
$$Q_{of\ decomposition\ unit} = 0$$

$$Q_{of\ Hot\ gases} = Q_{product}$$

$$9.55 \times 10^6 \frac{\text{KJ}}{\text{h}} = 49467.3915 \int_{25}^{T_{48}} C_{pmix_{48}} - 49467.3915 \int_{297}^{1543.747} C_{pmix_{46}}$$

$$T_{48} = 534.87\text{ }^{\circ}\text{C}$$

Energy Balance for the cooler (H-201)

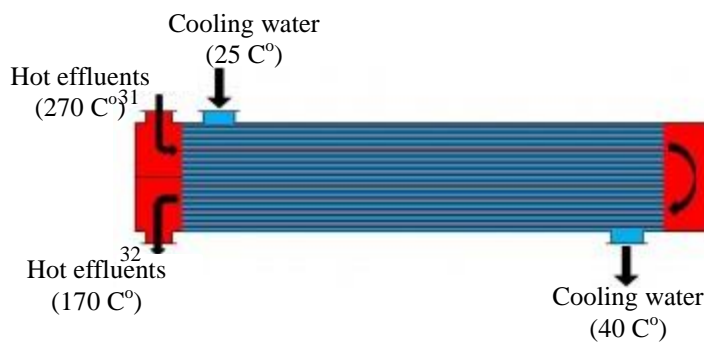


Component	CO2	H2S	C3H6	H2	CH4	C2H4	CO	Toluene	Benzene	Hexene	Hexane	Styrene	Ethyl Benzene	Cyclopentane
Mol fraction	0.0209	0.011	0.03	0.2198	0.16828	0.0321	0.0172	0.13024	0.1040	0.0689	0.0479	0.0357	0.0885	0.01744

Stream	Component	T (C)	N (mol/hr)	H (J/mol)
30	Gas + Vapor oil	513.3	34825.67	105093.704
31	Gas + Vapor oil	270	34825.67	29119.4851

$$Q = n_{31}\Delta H_{31} - n_{30}\Delta H_{30} = 1106076\text{ kJ/h}$$

Energy Balance for the cooler (H-202)

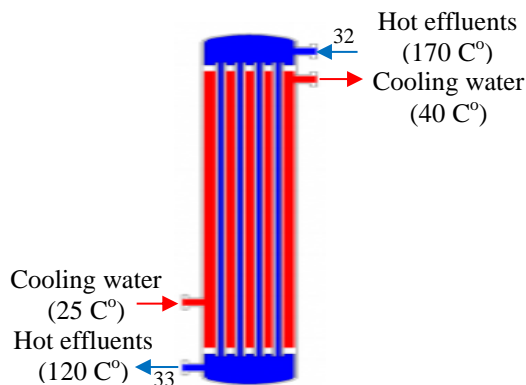


Component	CO2	H2S	C3H6	H2	CH4	C2H4	CO	Toluene	Benzene	Hexene	Hexane	Styrene	Ethyl Benzene	Cyclopentane
Mol fraction	0.0209	0.011	0.03	0.2198	0.16828	0.0321	0.0172	0.13024	0.1040	0.0689	0.0479	0.0357	0.0885	0.01744

Stream	Component	T (C)	N (mol/hr)	H (J/mol)
31	Gas + Vapor oil	270	34825.67	29119.4851
32	Gas + Vapor oil	170	34825.67	303342

$$Q = n_{32}\Delta H_{32} - n_{31}\Delta H_{31} = 9.55 \times 10^6 \text{ kJ/h}$$

Energy Balance for the condenser (H-203)



Component	CO2	H2S	C3H6	H2	CH4	C2H4	CO	Toluene	Benzene	Hexene	Hexane	Styrene	Ethyl Benzene	Cyclopentane
Mol fraction	0.0209	0.011	0.03	0.2198	0.16828	0.0321	0.0172	0.13024	0.1040	0.0689	0.0479	0.0357	0.0885	0.01744

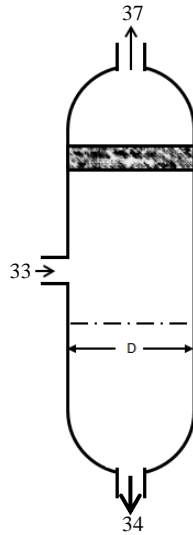
Stream	Component	T (C)	N (mol/hr)
32	Gas + Vapor oil	170	34825.67
33	Gas + Vapor oil+liquid	120	34825.67

$$Q = n_{33}(\Delta H_{33(gas)} + \Delta H_{33(liquid)} - n_{32}\Delta H_{32} =$$

$$Q_{(non-condensable\ mixture)} + Q_{(condensable)} = (378918.3 + 97105.02)$$

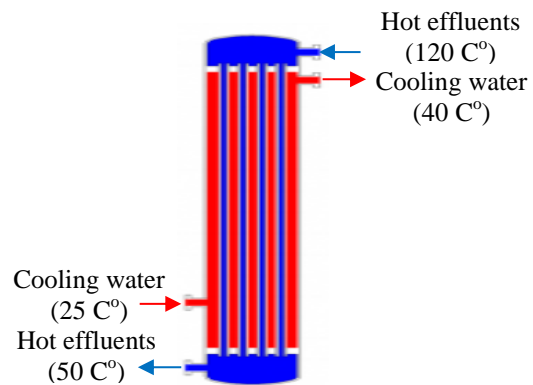
$$476023.3 \text{ kJ/h}$$

Material balance for the flash drum (V-201)



Stream	Component	T (C)	M (Kg/hr)
33	Gas + Vapor oil+liquid	120	1801.3626
37	Gas + Vapor oil	120	929.7158
34	liquid	120	871.6462

Energy Balance for the condenser (H-204)



Component	CO2	H2S	C3H6	H2	CH4	C2H4	CO	Benzene	Hexene	Hexane	Cyclopentane
Mole fraction	0.028	0.15	0.041	0.3	0.223	0.0435	0.023	0.1041	0.093	0.065	0.024

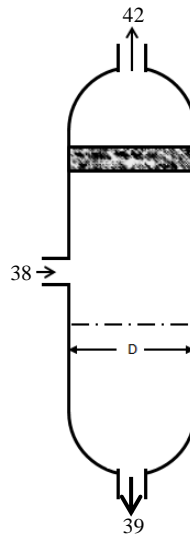
Stream	Component	T (C)	N (mol/hr)
37	Gas + Vapor oil	120	27094.9
38	Gas + liquid	50	27094.9

$$Q = n_{38}(\Delta H_{38(gas)} + \Delta H_{38(liquid)}) - n_{37}\Delta H_{37} =$$

$$Q_{(non-condensable\ mixture)} + Q_{(condensable)} = (332324 + 49535.66) =$$

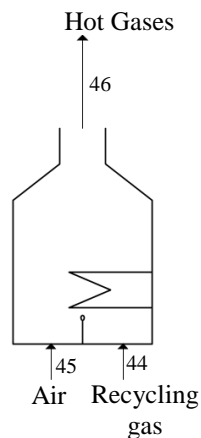
$$381859.66 \text{ kJ/h}$$

Material balance for the flash drum (V-202)



Stream	Component	T (C)	M (Kg/hr)
38	Gas +liquid	50	929.7158
42	gas	50	257.9154
39	liquid	50	671.8

Material Balance for the Furnace (F-201)



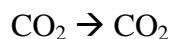
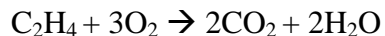
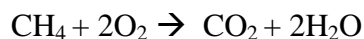
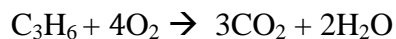
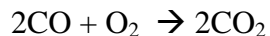
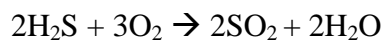
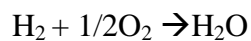
Component	CO ₂	H ₂ S	C ₃ H ₆	H ₂	CH ₄	C ₂ H ₄	CO	sum
Mw	44	34	42	2	16	28	28	
mole fraction (y _i)	0.0413576	0.0221049	0.0737307	0.4335424	0.3318596	0.0634626	0.033941	1
y _i * Mw _i	1.8197375	0.7515687	3.0966913	0.8670849	5.3097547	1.7769537	0.950370	14.57216

$$M_w(\text{average}) = \sum y_i \times M_{w_i} = 14.57216 \text{ g/mol}$$

Total number of moles = 17659.52779 mole / hr

moles of each component (mole/hr)	730.35696	390.36320	1302.0501	7656.1558	5860.4850	1120.7201	599.3964	17659.53
mass of each component (g/hr)	32135.70	13272.349	54686.10	15312.311	93767.760	31380.164	16783.09	257337.5
mass fractions (X _i)	0.1248776	0.0515756	0.212507	0.0595028	0.364376	0.1219416	0.065218	1

Combustion Equations:



The inlet flow gases at stream number (44)

Component	Flow rate (Kg/h)	Mass fraction	LHV (KJ/Kg)
CO	16.78	0.065	10112
CO ₂	32.1	0.125	---
CH ₄	94.02	0.365	50000
C ₂ H ₄	31.33	0.122	47195
H ₂	15.43	0.06	120000
C ₃ H ₆	54.8	0.212	45800
H ₂ S	13.3	0.052	15191

Total Gas flow rate at stream number (44) 257.92 Kg/h

The Air required = 3370 Kg/h with excess 20% = 4044 Kg/h

“inlet at stream number (45)”

The total heating value = 4.23×10^4 KJ/Kg

The total heat generated by combustion = $(4.23 \times 10^4 \text{ KJ/Kg}) * (225.76 \text{ Kg/h})$
 $= 9.55 \times 10^6 \text{ KJ/h}$

The outlet temperature at stream number (46) = 1956.13 °C

The Outlet flow gases at stream number (46)

Component	Flow rate (Kg/h)	Mass fraction
CO ₂	587	0.96
SO ₂	25	0.04

Appendix B

Detailed Calculation of Design and Sizing of Equipment

APPENDIX B

DETAILED CALCULATION OF DESIGN AND SIZING OF EQUIPMENT

1- heat exchanger (E-201):

Problem Statement

The objective is to design a cooler for the decomposition unit's effluents (Condensable and non-condensable gases) with a flow rate 1801.363 Kg/h to cool the mixture down from 513.1 °C to 270 °C using water coming at 25 °C and leaves at 40 °C.

Physical properties at T_{av} And P_{av}

Where T_{av} for Mixture = $(513.1 + 270) / 2 = 391.55$ °C

T_{av} for water = $(40+25) / 2 = 32.5$ °C

<i>Component</i>	Cp (kJ/kg.K)	ui (mN-s/m ²)	ρ (kg/m ³)	K (W/m.K)
<i>Mixture</i>	2.5258	1.62×10^{-02}	0.9794	0.0698
<i>H₂O</i>	4.1867	0.7865	994.5747	0.6163

Heat Load (Q)

$$Q = mC_{p_{Mix}} \Delta T = 1106076 \text{ kJ/h} = 307243.5 \text{ J/s}$$

Finding Water flow required

$$Q = mC_{p_{Mix}} \Delta T = 1106076 \text{ kJ/h} = 307243.5 \text{ J/s} = mC_{p_{water}} \Delta T$$

$$m(\text{water}) = 17612.54 \text{ kg/h} = 4.892 \text{ kg/s}$$

Finding ΔT_{lm}

$$\Delta T_{out} = T_1 - t_2 = (270 - 25) = 245 \text{ } ^\circ\text{C}$$

$$\Delta T_{in} = T_2 - t_1 = (513.1 - 40) = 473.1 \text{ } ^\circ\text{C}$$

$$\Delta T_{lm} = \frac{\Delta T_{out} - \Delta T_{in}}{\ln \frac{\Delta T_{out}}{\Delta T_{in}}} = \mathbf{346.63 \text{ } ^\circ\text{C}}$$

- The heat exchanger will consist of one shell pass and two tube passes.
- The correction factor will be = 1

$$\Delta T_m = F_t (\Delta T_{lm}) = (1) * 346.63 = \mathbf{346.63 \text{ } ^\circ\text{C}}$$

- The following value of overall heat transfer coefficient U can be assumed based on the cold and hot fluids:

$$\mathbf{U = 250 \text{ W/m}^2 \cdot \text{C}}$$

Required Area for Heat transfer

$$Q = UA \Delta T_m \rightarrow A = Q / U \Delta T_m$$

$$\mathbf{A = 3.545 \text{ m}^2}$$

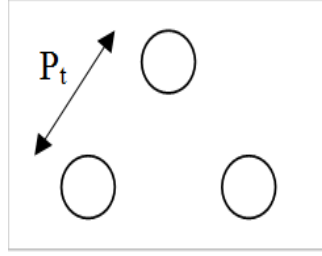
- Choosing 25 mm “O.D”, 21 mm “I.D” Cupro-Nickel (10% Nickel) tubes to resist corrosion problems. Placing water in the shell side and the mixture in the tube side. Take Tube length L=1 m

Calculation of Number of tubes

$$N_t = \frac{Area}{\pi * d_o * L}$$

$$\mathbf{N_t = 45.17 = 46 \text{ tubes}}$$

- A triangular pitch arrangement with **pt= 1.25d_o** will be used:



Calculation of bundle diameter D_b

$$D_b = d_o \left[\frac{N_t}{K_1} \right]^{\frac{1}{n_1}}$$

K_1 , n_1 are constants.

$K_1 = 0.249$, $n_1 = 2.207$

$$D_b = 25 \times 10^{-3} \left[\frac{45.17}{0.249} \right]^{\frac{1}{2.207}}$$

$$\rightarrow D_b = 0.2628 \text{ m}$$

Calculating of The shell diameter D_s

$$D_s = D_b + \text{clearance}$$

For split-ring floated heat type of heat exchanger, clearance= **0.054 m**

$$\rightarrow D_s = 0.2628 + 0.054 = 0.3178 \text{ m}$$

Calculating the heat transfer coefficients for tube side (hi)

$$\text{Cross sectional area of one tube} = \frac{\pi}{4} d_i^2 = \frac{\pi}{4} (21)^2 = 3.46 \times 10^{-4} \text{ m}^2$$

$$\text{Number of tube per pass} = \frac{N_t}{NO. pass} = 46 / 2 = 23 \text{ tube/pass}$$

$$\text{Total cross sectional area for mixture} = \left(\frac{N_t}{NO. pass} \right) * \frac{\pi}{4} d_i^2 = 7.818 \times 10^{-3} \text{ m}^2$$

$$\text{Mass velocity } (G_{\text{mixture}}) = \frac{m(\text{mixture})}{\text{flow area}} = \frac{4.892}{7.818 \times 10^{-3}} = \mathbf{64.005 \text{ kg/m}^2 \cdot \text{s}}$$

$$\text{Linear velocity } (v_{\text{mixture}}) = \frac{G_{\text{mixture}}}{\rho(\text{mixture})} = \frac{64.005}{0.9794} = \mathbf{65.35138 \text{ m/s}}$$

Average mixture Temperature = 391.55 °C.

To calculate h_i :

$$\mathbf{Re = 8.28 \times 10^4}$$

$$\mathbf{Pr = 0.587303}$$

$$\mathbf{Jh = 2.95 \times 10^{-3}}$$

$$h_i = (Jh \times Re \times Pr^{0.33} \times k) / d_i$$

$$\Rightarrow \mathbf{h_i = 681.237 \text{ W/m}^2 \cdot \text{°C}}$$

Calculate heat transfer coefficients for shell side (h_o)

Area for cross flow of the shell side A_s , using Kern Method

$$A_s = \left[\frac{P_t - d_o}{P_t} \right] (D_s)(L_B)$$

Where : P_t = tube pitch

d_o = tube outside diameter

D_s = shell inside diameter

L_B = Baffle spacing (usually one fifth of Shell diameter)

$$d_o = 25 \times 10^{-3} \text{ m}$$

$$P_t = 1.25 d_o \text{ mm} = 31.25 \times 10^{-3} \text{ m}$$

$$L_b = \frac{D_s}{5} = \frac{0.3178}{5} = 0.0636 \text{ m}$$

$$A_s = \left[\frac{P_t - d_o}{P_t} \right] (D_s)(L_B) = \frac{31.25-25}{31.25} (0.3178) (0.0636) = \mathbf{4.041 \times 10^{-3} m^2}$$

mass velocity (G_s) and liner velocity (v_s)

$$G_s = \left[\frac{m_{shell}}{A_s} \right] \quad \text{and} \quad v_s = \left[\frac{G_s}{\rho_{f,shell}} \right]$$

$$m_{shell} = \text{mass flow rate of water} = \mathbf{17612.54 \text{ kg/h}}$$

$$\rightarrow G_s = \frac{4.892}{4.041 \times 10^{-3}} = \mathbf{1210.798 \text{ kg/m}^2.s}$$

$$\rightarrow v_s = \frac{1210.798}{994.5747} = \mathbf{1.217 \text{ m/s}}$$

the equivalent (Hydraulic) diameter d_e :

$$d_e = \frac{1.10}{d_o} [P_t^2 - 0.917 d_o^2]$$

$$d_e = \frac{1.10}{25} [(31.25)^2 - 0.917(25)^2] = \mathbf{17.75 \text{ mm}}$$

Re & Pr for shell side

Average water Temperature = 32.5 °C.

$$Re = \frac{G_s d_e}{\mu_v} = \frac{(1210.798)(0.01775)}{0.7865} = 2.73 \times 10^4 \text{ "Turbulent Flow"}$$

$$Pr = \frac{c_p u}{K} = \frac{(4.1867) \times (0.7865)}{0.6163} = 5.343$$

the shell side coefficient (h_s or h_o)

$$h_o = (Jh \times Re \times Pr^{0.33} \times K) / de$$

$$Jh = 3.9 \times 10^{-3}$$

$$h_o = (3.9 \times 10^{-3} \times 2.73 \times 10^4 \times 0.5343^{0.33} \times 0.6163) / 17.75 \times 10^{-3}$$

$$\rightarrow h_o = 728.55 \text{ W/m}^2 \cdot ^\circ\text{C}$$

Calculating the overall heat transfer coefficient (U)

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o / d_i)}{2K_w} + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right) + \frac{1}{h_{id}} \left(\frac{d_o}{d_i} \right)$$

Where : U_o = overall coefficient based on outside area of the tubes

h_o = outside fluid film coefficient

h_i = inside fluid film coefficient

d_o = tube outside diameter

d_i = tube inside diameter

K_w = thermal conductivity of tube wall material = 45 (W/m. $^\circ\text{C}$) for "Cupro-Nickel"

h_{od} = outside dirt " fouling " coefficient = 6000 (W/m 2 . $^\circ\text{C}$)

h_{id} = inside dirt " fouling " coefficient = 5000 (W/m 2 . $^\circ\text{C}$)

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o / d_i)}{2K_w} + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right) + \frac{1}{h_{id}} \left(\frac{d_o}{d_i} \right)$$

$$\frac{1}{U_o} = \frac{1}{728.55} + \frac{1}{6000} + \frac{25 \times 10^{-3} \ln(\frac{25}{21})}{2 (45)} + \frac{1}{681.237} \left(\frac{25}{21} \right) + \frac{1}{5000} \left(\frac{25}{21} \right)$$

$$\rightarrow U_o = 279.85 \text{ W/m}^2 \cdot ^\circ\text{C}$$

The value of 279.85 W/m².°C is above the estimated value of 250 W/m².°C.

Hence, the current design satisfactory. (ok)

Calculating the pressure drop (ΔP) for side tube and shell tube:

The tube side ΔP_t

$$\Delta P_t = N_p \left[8 j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \left[\frac{\rho v_t^2}{2} \right]$$

Where : ΔP_t = tube side pressure drop (N/m²)

N_p = Number of tube passes

j_f = friction factor ' ' depending on Re ' '

L = length of one tube = 1 m

v_t = flow velocity inside the tube

m = exponent value depending on type of flow

at laminar (Re<2100) ➔ m = 0.25

at Turblent (R>10000) ➔ m = 0.14

now;

$$\Delta P_t = N_p \left[8 j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \left[\frac{\rho v_t^2}{2} \right]$$

$$\Delta P_t = 2 \left[8(2.9 \times 10^{-3}) \left(\frac{1}{21 \times 10^{-3}} \right) + 2.5 \right] \left[\frac{0.9794 * (65.35138)^2}{2} \right]$$

$$\Rightarrow \Delta P_t = 15078.084 \text{ Pa} = \mathbf{15.078 \text{ kPa}} \text{ (Acceptable)}$$

The shell side ΔP_s

$$\Delta P_s = 8J_f \left(\frac{D_s}{D_e} \right) \left(\frac{L}{L_B} \right) \left(\frac{\rho v_s^2}{2} \right) \left(\frac{\mu}{\mu_w} \right)^{-0.14}$$

Where : ΔP_s = shell side pressure drop (N/m²)

J_f = fraction factor ' depending on Re ,

D_s = shell diameter = 0.3178 m

D_e = equivalent diameter for shell side = 0.01775 m

L = length of one tube = 1 m

Re= 27327.63

v_s = flow velocity in shell = 1.217 m/s

L_B = Baffle spacing = 0.0636 m

$\rho_{\text{shell}} = 994.5747 \text{ kg/m}^3$

$$\Delta P_s = 8 * (0.043) \left(\frac{0.3178}{0.01775} \right) \left(\frac{1}{0.0636} \right) \left(\frac{(994.5747)(1.217)^2}{2} \right)$$

$$\Rightarrow \Delta P_s = 71412.71 \text{ Pa} = \mathbf{71.412 \text{ KPa}} \text{ (acceptable)}$$

2- heat exchanger (E-202):

Problem Statement

The objective is to design a cooler for the decomposition unit's effluents (Condensable and non-condensable gases) with a flow rate 1801.363 Kg/h to cool the mixture down from 270 °C to 175 °C using water coming at 25 °C and leaves at 40 °C.

Physical properties at T_{av} And P_{av}

Where T_{av} for Mixture = $(270 + 175) / 2 = 222.5$ °C

T_{av} for water = $(40+25) / 2 = 32.5$ °C

<i>Component</i>	Cp (kJ/kg.K)	ui (mN-s/m ²)	ρ (kg/m ³)	K (W/m.K)
<i>Mixture</i>	2.0612	1.26×10^{-02}	1.3127	0.0472
<i>H₂O</i>	4.1867	0.7865	994.5747	0.6163

Heat Load (Q)

$$Q = mC_{p_{\text{Mix}}} \Delta T = 352732.1 \text{ kJ/h} = 97981.14 \text{ J/s}$$

Finding Water flow required

$$Q = mC_{p_{\text{Mix}}} \Delta T = 352732.1 \text{ kJ/h} = 97981.14 \text{ J/s} = mC_{p_{\text{water}}} \Delta T$$

$$m(\text{water}) = 5616.708 \text{ kg/h} = 1.56 \text{ kg/s}$$

Finding ΔT_{lm}

$$\Delta T_{\text{out}} = T_1 - t_2 = (175 - 25) = 150 \text{ °C}$$

$$\Delta T_{\text{in}} = T_2 - t_1 = (270 - 40) = 30 \text{ °C}$$

$$\Delta T_{\text{lm}} = \frac{\Delta T_{\text{out}} - \Delta T_{\text{in}}}{\ln \frac{\Delta T_{\text{out}}}{\Delta T_{\text{in}}}} = 187.159 \text{ °C}$$

- The heat exchanger will consist of one shell pass and two tube passes.

- The correction factor will be = 1

$$\Delta T_m = F_t (\Delta T_{lm}) = (1) * 187.159 = \mathbf{187.159} \text{ } ^\circ\text{C}$$

- The following value of overall heat transfer coefficient U can be assumed based on the cold and hot fluids:

$$\mathbf{U = 100 \text{ W/m}^2.\text{C}}$$

Required Area for Heat transfer

$$Q = UA \Delta T_m \rightarrow A = Q / U \Delta T_m$$

$$\mathbf{A = 5.235 \text{ m}^2}$$

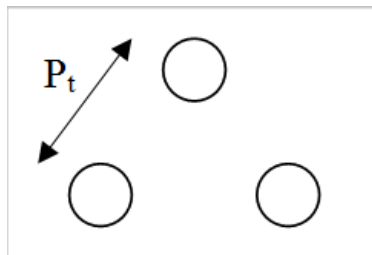
- Choosing 25 mm “O.D”, 21 mm “I.D” Cupro-Nickel (10% Nickel) tubes to resist corrosion problems. Placing water in the shell side and the mixture in the tube side. Take Tube length L=1 m

Calculation of Number of tubes

$$N_t = \frac{\text{Area}}{\pi * d_o * L}$$

$$\mathbf{N_t = 66.69 = 67 \text{ tubes}}$$

- A triangular pitch arrangement with **pt= 1.25d_o** will be used:



Calculation of bundle diameter D_b

$$D_b = d_o \left[\frac{N_t}{K_1} \right]^{\frac{1}{n_1}}$$

K₁ , n₁ are constants.

$$K_1 = 0.249 \text{ , } n_1 = 2.207$$

$$D_b = 25 \times 10^{-3} \left[\frac{66.69}{0.249} \right]^{\frac{1}{2.207}}$$

$$\rightarrow D_b = 0.315 \text{ m}$$

Calculating of The shell diameter D_s

$$D_s = D_b + \text{clearance}$$

For split-ring floated heat type of heat exchanger, clearance= **0.054 m**

$$\rightarrow D_s = 0.315 + 0.054 = \mathbf{0.369 \text{ m}}$$

Calculating the heat transfer coefficients for tube side (h_i)

$$\text{Cross sectional area of one tube} = \frac{\pi}{4} d_i^2 = \frac{\pi}{4} (21)^2 = \mathbf{3.46 \times 10^{-4} \text{ m}^2}$$

$$\text{Number of tube per pass} = \frac{N_t}{NO. pass} = 66.96 / 2 = \mathbf{34 \text{ tube/pass}}$$

$$\text{Total cross sectional area for mixture} = \left(\frac{N_t}{NO. pass} \right) * \frac{\pi}{4} d_i^2 = \mathbf{11.544 \times 10^{-3} \text{ m}^2}$$

$$\text{Mass velocity } (G_{\text{mixture}}) = \frac{m(\text{mixture})}{\text{flow area}} = \frac{1.56}{11.544 \times 10^{-3}} = \mathbf{43.347 \text{ kg/m}^2 \cdot \text{s}}$$

$$\text{Linear velocity } (v_{\text{mixture}}) = \frac{G_{\text{mixture}}}{\rho(\text{mixture})} = \frac{43.347}{1.3127} = \mathbf{33.021 \text{ m/s}}$$

Average mixture Temperature = 222.5 °C.

To calculate h_i :

$$\mathbf{Re = 7.21 \times 10^4}$$

$$\mathbf{Pr = 0.5511}$$

$$\mathbf{Jh = 3 \times 10^{-3}}$$

$$h_i = (Jh \times Re \times Pr^{0.33} \times k) / d_i$$

$$\rightarrow h_i = 399.55 \text{ W/m}^2 \cdot ^\circ\text{C}$$

Calculate heat transfer coefficients for shell side (h_o)

Area for cross flow of the shell side A_s , using Kern Method

$$A_s = \left[\frac{P_t - d_o}{P_t} \right] (D_s)(L_B)$$

Where: P_t = tube pitch

d_o = tube outside diameter

D_s = shell inside diameter

L_B = Baffle spacing (usually one fifth of Shell diameter)

$$d_o = 25 \times 10^{-3} \text{ m}$$

$$P_t = 1.25 d_o \text{ mm} = 31.25 \times 10^{-3} \text{ m}$$

$$L_b = \frac{D_s}{5} = \frac{0.369}{5} = 0.07376 \text{ m}$$

$$A_s = \left[\frac{P_t - d_o}{P_t} \right] (D_s)(L_B) = \frac{31.25 - 25}{31.25} (0.369) (0.07376) = 5.44 \times 10^{-3} \text{ m}^2$$

mass velocity (G_s) and liner velocity (v_s)

$$G_s = \left[\frac{m_{shell}}{A_s} \right] \quad \text{and} \quad v_s = \left[\frac{G_s}{\rho_{f,shell}} \right]$$

$$m_{shell} = \text{mass flow rate of water} = 5616.708 \text{ kg/h} = 1.56 \text{ Kg/s}$$

$$\rightarrow G_s = \frac{1.56}{5.44 \times 10^{-3}} = 286.796 \text{ kg/m}^2 \cdot \text{s}$$

$$\rightarrow v_s = \frac{286.796}{994.5747} = 0.288 \text{ m/s}$$

the equivalent (Hydraulic) diameter d_e :

$$d_e = \frac{1.10}{d_o} [P_t^2 - 0.917 d_o^2]$$

$$d_e = \frac{1.10}{25} [(31.25)^2 - 0.917(25)^2] = \mathbf{17.75 \text{ mm}}$$

Re & Pr for shell side

Average water Temperature = 32.5 °C.

$$Re = \frac{Gs \, de}{\mu_v} = \frac{(286.796)(0.01775)}{0.7865} = 6.47 \times 10^3 \text{ "Turbulent Flow"}$$

$$Pr = \frac{Cp \, u}{K} = \frac{(4.1867) \times (0.7865)}{0.6163} = 5.343$$

the shell side coefficient (h_s or h_o)

$$h_o = (Jh \times Re \times Pr^{0.33} \times K) / de$$

$$Jh = 7.5 \times 10^{-3}$$

$$h_o = (7.5 \times 10^{-3} \times 6.47 \times 10^3 \times 0.5.343^{0.33} \times 0.6163) / 17.75 \times 10^{-3}$$

$$\rightarrow \mathbf{h_o = 224.411 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Calculating the overall heat transfer coefficient (U)

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o / d_i)}{2K_w} + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right) + \frac{1}{h_{id}} \left(\frac{d_o}{d_i} \right)$$

Where: U_o = overall coefficient based on outside area of the tubes

h_o = outside fluid film coefficient

h_i = outside fluid film coefficient

d_o = tube outside diameter

d_i = tube inside diameter

K_w = thermal conductivity of tube wall material = 45 (W/m.°C) for "Cupro-Nickel"

h_{od} = outside dirt " fouling " coefficient = 6000 (W/m².°C)

h_{id} = inside dirt " fouling " coefficient = 5000 (W/m².°C)

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o / d_i)}{2K_w} + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right) + \frac{1}{h_{id}} \left(\frac{d_o}{d_i} \right)$$

$$\frac{1}{U_o} = \frac{1}{224.411} + \frac{1}{6000} + \frac{25 \times 10^{-3} \ln\left(\frac{25}{21}\right)}{2 (45)} + \frac{1}{399.55} \left(\frac{25}{21} \right) + \frac{1}{5000} \left(\frac{25}{21} \right)$$

$$\rightarrow U_o = 126.76 \text{ W/m}^2.\text{°C}$$

The value of 126.76 W/m².°C is above the estimated value of 100 W/m².°C.

Hence, the current design satisfactory. (ok)

Calculating the pressure drop (ΔP) for side tube and shell tube:

The tube side ΔP_t

$$\Delta P_t = N_p \left[8 j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \left[\frac{\rho v_t^2}{2} \right]$$

Where: ΔP_t = tube side pressure drop (N/m²)

N_p = Number of tube passes

j_f = friction factor ' depending on Re '

L = length of one tube = 1 m

v_t = flow velocity inside the tube

m = exponent value depending on type of flow

at laminar (Re<2100) $\rightarrow m = 0.25$

at Turblent (R>10000) $\rightarrow m = 0.14$

now;

$$\Delta P_t = N_p \left[8j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \left[\frac{\rho v_t^2}{2} \right]$$

$$\Delta P_t = 2 \left[8(2.9 \times 10^{-3}) \left(\frac{1}{21 \times 10^{-3}} \right) + 2.5 \right] \left[\frac{1.3127 * (33.021)^2}{2} \right]$$

$$\Rightarrow \Delta P_t = 5159.74 \text{ Pa} = \mathbf{5.16 \text{ kPa}} \text{ (Acceptable)}$$

The shell side ΔP_s

$$\Delta P_s = 8J_f \left(\frac{D_s}{D_e} \right) \left(\frac{L}{L_B} \right) \left(\frac{\rho v_s^2}{2} \right) \left(\frac{\mu}{\mu_w} \right)^{-0.14}$$

Where: ΔP_s = shell side pressure drop (N/m²)

j_f = friction factor ' ' depending on Re ,

D_s = shell diameter = 0.369 m

D_e = equivalent diameter for shell side = 0.01775 m

L = length of one tube = 1 m

Re= 6472.97

v_s = flow velocity in shell = 0.288 m/s

L_B = Baffle spacing = 0.07376 m

$\rho_{\text{shell}} = 994.5747 \text{ kg/m}^3$

$$\Delta P_s = 8 * (0.055) \left(\frac{0.369}{0.01775} \right) \left(\frac{1}{0.07376} \right) \left(\frac{(994.5747)(0.288)^2}{2} \right)$$

$$\Rightarrow \Delta P_s = 5124.755 \text{ Pa} = \mathbf{5.125 \text{ KPa}} \text{ (acceptable)}$$

3- heat exchanger “condenser “ (E-203):

Problem Statement

The objective is to design a condenser for the decomposition unit's effluents (Condensable and non-condensable gases) with a flow rate 1801.363 Kg/h to condensate the heavy liquid vaporized in the mixture at temperature from 175 °C to 120 °C using water coming at 25 °C and leaves at 40 °C.

Physical properties at T_{av} And P_{av}

Where T_{av} for Mixture = $(175 + 125) / 2 = 150$ °C

T_{av} for water = $(40+25) / 2 = 32.5$ °C

<i>Component</i>	Cp (kJ/kg.K)	ui (mN-s/m2)	ρ (kg/m3)		K (W/m.K)
<i>Condensable mixture</i>	2.1227	0.1986	ρ_l	ρ_v	0.1031
			752	5.3978	
<i>Non-condensable mixture</i>	0.0517	0.0124	1.8658		2.0901
<i>H₂O</i>	4.1867	0.7865	994.5747		0.6163

Heat Load (Q)

$$Q = mC_{p_{\text{Mix}}} \Delta T = Q_{(\text{non-condensable mixture})} + Q_{(\text{condensable mixture})} = (378918.3 + 97105.02) =$$

$$476023.3 \text{ kJ/h} = 132228.6936 \text{ J/s}$$

Finding Water flow required

$$Q = mC_{p_{\text{Mix}}} \Delta T = 476023.3 \text{ kJ/h} = 132228.6936 \text{ J/s} = mC_{p_{\text{water}}} \Delta T$$

$$m(\text{water}) = 7579.92 \text{ kg/h} = 2.105 \text{ kg/s}$$

Finding ΔT_{lm}

$$\Delta T_{out} = T_1 - t_2 = (125 - 25) = 100 \text{ }^\circ\text{C}$$

$$\Delta T_{in} = T_2 - t_1 = (175 - 40) = 135 \text{ }^\circ\text{C}$$

$$\Delta T_{lm} = \frac{\Delta T_{out} - \Delta T_{in}}{\ln \frac{\Delta T_{out}}{\Delta T_{in}}} = \mathbf{116.62 \text{ }^\circ\text{C}}$$

- The heat exchanger will consist of one shell pass and two tube passes.
- The correction factor will be = 1

$$\Delta T_m = F_t (\Delta T_{lm}) = (1) * 116.62 = \mathbf{116.62 \text{ }^\circ\text{C}}$$

- The following value of overall heat transfer coefficient U can be assumed based on the cold and hot fluids:

$$\mathbf{U = 150 \text{ W/m}^2.\text{C}}$$

Required Area for Heat transfer

$$Q = UA \Delta T_m \rightarrow A = Q / U \Delta T_m$$

$$\mathbf{A = 7.56 \text{ m}^2}$$

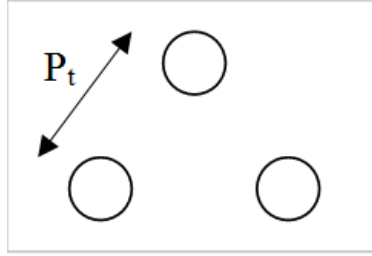
- Choosing 25 mm “O.D”, 21 mm “I.D” Cupro-Nickel (10% Nickel) tubes to resist corrosion problems. Placing water in the shell side and the mixture in the tube side. Take Tube length L=1 m

Calculation of Number of tubes

$$N_t = \frac{Area}{\pi * d_o * L}$$

$$\mathbf{N_t = 96.28 = 97 \text{ tubes}}$$

- A triangular pitch arrangement with $\mathbf{pt = 1.25d_o}$ will be used:



Calculation of bundle diameter D_b

$$D_b = d_o \left[\frac{N_t}{K_1} \right]^{\frac{1}{n_1}}$$

K_1 , n_1 are constants.

$K_1 = 0.249$, $n_1 = 2.207$

$$D_b = 25 \times 10^{-3} \left[\frac{96.28}{0.249} \right]^{\frac{1}{2.207}}$$

$$\rightarrow D_b = 0.371 \text{ m}$$

Calculating of The shell diameter D_s

$$D_s = D_b + \text{clearance}$$

For split-ring floated heat type of heat exchanger, clearance= **0.054 m**

$$\rightarrow D_s = 0.2628 + 0.054 = \mathbf{0.426 \text{ m}}$$

Calculating the heat transfer coefficients for tube side (hi)

- **First : heat transfer coefficients for non-condensable mixture**

$$\text{Cross sectional area of one tube} = \frac{\pi}{4} d_i^2 = \frac{\pi}{4} (21)^2 = \mathbf{3.46 \times 10^{-4} \text{ m}^2}$$

$$\text{Number of tube per pass} = \frac{N_t}{NO.pass} = 97 / 1 = \mathbf{96.28 \text{ tube/pass}}$$

$$\text{Total cross sectional area for mixture} = \left(\frac{N_t}{NO_{pass}} \right) * \frac{\pi}{4} d_i^2 = \mathbf{0.033 \, m^2}$$

$$\text{Mass velocity (G}_{\text{non-condensable mixture}}) = \frac{m(\text{non-condensable mixture})}{\text{flow area}} = \frac{0.258255}{0.033} = \mathbf{7.748 \, kg/m^2.s}$$

$$\text{Linear velocity (v}_{\text{non-condensable mixture}}) = \frac{G_{\text{non-condensable mixture}}}{\rho(\text{mixture})} = \frac{7.748}{1.8658} = \mathbf{4.152 \, m/s}$$

Average mixture Temperature = 150 °C.

To calculate $h_{i(\text{non-condensable mixture})}$:

$$\mathbf{Re = 1.31 \times 10^4}$$

$$\mathbf{Pr = 0.50049}$$

$$\mathbf{Jh = 3.60 \times 10^{-3}}$$

$$h_i = (Jh \times Re \times Pr^{0.33} \times k) / d_i$$

$$\rightarrow \mathbf{h_{i(\text{non-condensable mixture})} = 92.69 \, W/m^2.^{\circ}C}$$

- **Second : the heat transfer coefficients for condensable mixture**

The Prandtl number for the condensate film is given by :

$$Pr_c = \frac{c_p u_l}{k_l}$$

$$Pr_c = \frac{2.1227 * 0.1986}{0.1031} = \mathbf{4.0889}$$

$$r_v = \frac{W_c}{\pi d_i}$$

Where : r_v = vertical tube loading

W_c = total condensate flow

$$r_v = \frac{0.2421}{\pi * 0.021} = \mathbf{3.671 \, kg/m.s}$$

The Reynolds number for the condensate film is given by :

$$Re_c = \frac{4r_v}{u_l} = 73955.34$$

From figure 12.39. $\frac{h_c}{k_l} \left(\frac{u_l^2}{\rho_l(\rho_l - \rho_v)g} \right)^{\frac{1}{3}} = \mathbf{0.7}$

The heat transfer coefficients for condensable mixture inside tube :

$$h_c = 0.7k_l / \left(\frac{u_l^2}{\rho_l(\rho_l - \rho_v)g} \right)^{\frac{1}{3}} = \mathbf{3743.9 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Boyko-kruzhilin method :

Cross sectional area of one tube = $\frac{\pi}{4} d_i^2 = \frac{\pi}{4} (21)^2 = \mathbf{3.46 \times 10^{-4} \text{ m}^2}$

Fluid velocity , total condensation :

$$u_t = \frac{W_c}{A_s \rho_L} = \mathbf{0.93 \text{ m/s}}$$

$$Re = \frac{\rho_l u_t d_i}{\mu_l} = 73955.34$$

The force convection in the tube :

$$h'_t = 0.021 \left(\frac{k_l}{d_i} \right) Re^{0.8} Pr^{0.43} = \mathbf{1483.974 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

The heat transfer coefficients by Boyko-kruzhilin method for condensable mixture inside tube :

$$h_c = h'_t \left(\frac{1 + \sqrt{\rho_L / \rho_v}}{2} \right) = \mathbf{9499.24 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Take the maximum of h_c to be the heat transfer coefficients for condensable mixture inside tube.

$$\Rightarrow \mathbf{h_{i(consensable mixture)} = 9499.24 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

$$\Rightarrow \mathbf{h_i = h_{i(non-consensable mixture)} + h_{i(consensable mixture)} = 9591.93 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Calculate heat transfer coefficients for shell side (h_o)

Area for cross flow of the shell side A_s , using Kern Method

$$A_s = \left[\frac{P_t - d_o}{P_t} \right] (D_s)(L_B)$$

Where: P_t = tube pitch

d_o = tube outside diameter

D_s = shell inside diameter

L_B = Baffle spacing (usually one fifth of Shell diameter)

$$d_o = 25 \times 10^{-3} \text{ m}$$

$$P_t = 1.25 d_o \text{ mm} = 31.25 \times 10^{-3} \text{ m}$$

$$L_b = \frac{D_s}{5} = \frac{0.4258}{5} = 0.08516 \text{ m}$$

$$A_s = \left[\frac{P_t - d_o}{P_t} \right] (D_s)(L_B) = \frac{31.25 - 25}{31.25} (0.4258) (0.08516) = \mathbf{0.007251 \text{ m}^2}$$

mass velocity (G_s) and liner velocity (v_s)

$$G_s = \left[\frac{m_{shell}}{A_s} \right] \quad \text{and} \quad v_s = \left[\frac{G_s}{\rho_{f,shell}} \right]$$

$$m_{shell} = \text{mass flow rate of water} = \mathbf{7579.92 \text{ kg/h}}$$

$$\rightarrow G_s = \frac{2.105536}{0.007251} = \mathbf{290.356 \text{ kg/m}^2 \cdot \text{s}}$$

$$\rightarrow v_s = \frac{290.356}{994.5747} = \mathbf{0.292 \text{ m/s}}$$

the equivalent (Hydraulic) diameter d_e :

$$d_e = \frac{1.10}{d_o} [P_t^2 - 0.917 d_o^2]$$

$$d_e = \frac{1.10}{25} [(31.25)^2 - 0.917(25)^2] = \mathbf{17.75 \text{ mm}}$$

Re & Pr for shell side

Average water Temperature = 32.5 °C.

$$Re = \frac{Gs \, d_e}{\mu_v} = \frac{(290.356)(0.01775)}{0.7865} = 6.55 \times 10^3 \text{ "Turbulent Flow"}$$

$$Pr = \frac{c_p u}{K} = \frac{(4.1867) \times (0.7865)}{0.6163} = 5.343$$

the shell side coefficient (h_s or h_o)

$$h_o = (Jh \times Re \times Pr^{0.33} \times K) / d_e$$

$$Jh = 5.6 \times 10^{-3}$$

$$h_o = (5.6 \times 10^{-3} \times 6.55 \times 10^3 \times 5.343^{0.33} \times 0.6163) / 17.75 \times 10^{-3}$$

$$\rightarrow \mathbf{h_o = 185.813 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Calculating the overall heat transfer coefficient (U)

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o / d_i)}{2K_w} + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right) + \frac{1}{h_{id}} \left(\frac{d_o}{d_i} \right)$$

Where: U_o = overall coefficient based on outside area of the tubes

h_o = outside fluid film coefficient

h_i = inside fluid film coefficient

d_o = tube outside diameter

d_i = tube inside diameter

K_w = thermal conductivity of tube wall material = 45 (W/m.°C) for "Cupro-Nickel"

h_{od} = outside dirt " fouling " coefficient = 6000 (W/m².°C)

h_{id} = inside dirt " fouling " coefficient = 5000 (W/m².°C)

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o / d_i)}{2K_w} + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right) + \frac{1}{h_{id}} \left(\frac{d_o}{d_i} \right)$$

$$\frac{1}{U_o} = 0.00596$$

$$\rightarrow U_o = 167.81 \text{ W/m}^2 \cdot ^\circ\text{C}$$

The value of 167.81 W/m².°C is above the estimated value of 150 W/m².°C.

Hence, the current design satisfactory. (ok)

Calculating the pressure drop (ΔP) for side tube and shell tube:

The tube side ΔP_t

$$\Delta P_t = N_p \left[8 j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \left[\frac{\rho v_t^2}{2} \right]$$

ΔP_t = tube side pressure drop (N/m²)

N_p = Number of tube passes

j_f = friction factor ' depending on Re '

L = length of one tube = 1 m

v_t = flow velocity inside the tube

m = exponent value depending on type of flow

at laminar (Re < 2100) $\rightarrow m = 0.25$

at Turblent (R>10000) → m = 0.14

now;

$$\Delta P_t = N_p \left[8j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \left[\frac{\rho v_t^2}{2} \right]$$

$$\Delta P_t = 1 \left[8(3 \times 10^{-3}) \left(\frac{1}{21 \times 10^{-3}} \right) + 2.5 \right] \left[\frac{752 * (0.93)^2}{2} \right]$$

$$\rightarrow \Delta P_t = 1184.98 \text{ Pa} = \mathbf{1.185 \text{ kPa}} \text{ (Acceptable)}$$

The shell side ΔP_s

$$\Delta P_s = 8J_f \left(\frac{D_s}{D_e} \right) \left(\frac{L}{L_B} \right) \left(\frac{\rho v_s^2}{2} \right) \left(\frac{\mu}{\mu_w} \right)^{-0.14}$$

Where: ΔP_s = shell side pressure drop (N/m²)

j_f = fraction factor ' depending on Re ,

D_s = shell diameter = 0.3178 m

D_e = equivalent diameter for shell side = 0.01775 m

L = length of one tube = 1 m

Re= 6553.305638

v_s = flow velocity in shell = 0.291 m/s

L_B = Baffle spacing = 0.0851 m

$\rho_{\text{shell}} = 994.5747 \text{ kg/m}^3$

$$\rightarrow \Delta P_s = 4297.70 \text{ Pa} = \mathbf{4.3 \text{ KPa}} \text{ (acceptable)}$$

4- heat exchanger “condenser “ (E-204):

Problem Statement

The objective is to design a condenser for the decomposition unit's effluents (Condensable and non-condensable gases) with a flow rate 929.72 Kg/h to condensate the light liquid vaporized in the mixture at temperature from 125 °C to 50 °C using water coming at 25 °C and leaves at 40 °C.

Physical properties at T_{av} And P_{av}

Where T_{av} for Mixture = $(125 + 50) / 2 = 87.5$ °C

T_{av} for water = $(40+25) / 2 = 32.5$ °C

<i>Component</i>	Cp (kJ/kg.K)	ui (mN-s/m ²)	ρ (kg/m ³)		K (W/m.K)
<i>Condensable mixture</i>	2.2144	0.2199	ρ_l	ρ_v	0.108
			677.18	5.1089	
<i>Non-condensable mixture</i>	2.563	0.0137	0.8791		0.0766
<i>H₂O</i>	4.1867	0.7865	994.5747		0.6163

Heat Load (Q)

$$Q = mC_{p_{MIX}} \Delta T = Q_{(non-condensable\ mixture)} + Q_{(condensable\ mixture)} = (332324 + 49535.66) =$$

$$381859.66 \text{ kJ/h} = 106072.13 \text{ J/s}$$

Finding Water flow required

$$Q = mC_{p_{MIX}} \Delta T = 381859.66 \text{ kJ/h} = 106072.13 \text{ J/s} = mC_{p_{water}} \Delta T$$

$$m(\text{water}) = 6080.52 \text{ kg/h} = 1.689 \text{ kg/s}$$

Finding ΔT_{lm}

$$\Delta T_{out} = T_1 - t_2 = (50 - 25) = 25 \text{ }^{\circ}\text{C}$$

$$\Delta T_{in} = T_2 - t_1 = (125 - 40) = 85 \text{ }^{\circ}\text{C}$$

$$\Delta T_{lm} = \frac{\Delta T_{out} - \Delta T_{in}}{\ln \frac{\Delta T_{out}}{\Delta T_{in}}} = 49.03 \text{ }^{\circ}\text{C}$$

- The heat exchanger will consist of one shell pass and two tube passes.
- The correction factor will be = 1

$$\Delta T_m = F_t (\Delta T_{lm}) = (1) * 49.03 = 49.03 \text{ }^{\circ}\text{C}$$

- The following value of overall heat transfer coefficient U can be assumed based on the cold and hot fluids:

$$U = 500 \text{ W/m}^2 \cdot \text{C} \quad (\text{reference})$$

Required Area for Heat transfer

$$Q = UA \Delta T_m \rightarrow A = Q / U \Delta T_m$$

$$A = 4.33 \text{ m}^2$$

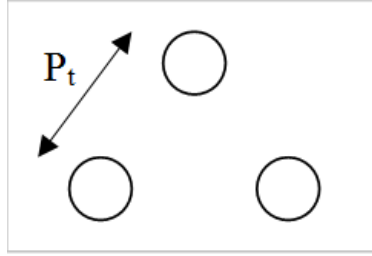
- Choosing 25 mm “O.D”, 21 mm “I.D” Cupro-Nickel (10% Nickel) tubes to resist corrosion problems. Placing water in the shell side and the mixture in the tube side. Take Tube length L=3 m

Calculation of Number of tubes

$$N_t = \frac{Area}{\pi * d_o * L}$$

$$N_t = 18.373 = 19 \text{ tubes}$$

- A triangular pitch arrangement with $pt = 1.25d_o$ will be used:



Calculation of bundle diameter D_b

$$D_b = d_o \left[\frac{N_t}{K_1} \right]^{\frac{1}{n_1}}$$

K_1 , n_1 are constants.

$K_1 = 0.249$, $n_1 = 2.207$

$$D_b = 25 \times 10^{-3} \left[\frac{18.373}{0.249} \right]^{\frac{1}{2.207}}$$

$$\rightarrow D_b = 0.18 \text{ m}$$

Calculating of The shell diameter D_s

$$D_s = D_b + \text{clearance}$$

For split-ring floated heat type of heat exchanger, clearance= **0.054 m**

$$\rightarrow D_s = 0.18 + 0.054 = \mathbf{0.23 \text{ m}}$$

Calculating the heat transfer coefficients for tube side (hi)

- **First : heat transfer coefficients for non-condensable mixture**

$$\text{Cross sectional area of one tube} = \frac{\pi}{4} d_i^2 = \frac{\pi}{4} (21)^2 = \mathbf{3.46 \times 10^{-4} \text{ m}^2}$$

$$\text{Number of tube per pass} = \frac{N_t}{NO.pass} = 18.373 / 1 = \mathbf{18.373 \text{ tube/pass}}$$

$$\text{Total cross sectional area for mixture} = \left(\frac{N_t}{NO_{pass}} \right) * \frac{\pi}{4} d_i^2 = \mathbf{0.0064 \text{ m}^2}$$

$$\text{Mass velocity (G}_{\text{non-condensable mixture}}) = \frac{m(\text{non-condensable mixture})}{\text{flow area}} = \frac{0.071644}{0.0064} = \mathbf{11.26 \text{ kg/m}^2.\text{s}}$$

$$\text{Linear velocity (v}_{\text{non-condensable mixture}}) = \frac{G_{\text{non-condensable mixture}}}{\rho(\text{mixture})} = \frac{11.26}{0.8971} = \mathbf{12.8 \text{ m/s}}$$

Average mixture Temperature = 87.5 °C.

To calculate $h_{i(\text{non-condensable mixture})}$:

$$\mathbf{Re = 1.73 \times 10^4}$$

$$\mathbf{Pr = 0.4584}$$

$$\mathbf{Jh = 4.0 \times 10^{-3}}$$

$$h_i = (Jh \times Re \times Pr^{0.33} \times k) / d_i$$

$$\Rightarrow \mathbf{h_{i(\text{non-condensable mixture})} = 194.74 \text{ W/m}^2.\text{°C}}$$

- **Second : the heat transfer coefficients for condensable mixture**

The Prandtl number for the condensate film is given by

$$Pr_c = \frac{c_p u_l}{k_l}$$

$$Pr_c = \frac{2.1227 * 0.1986}{0.1031} = \mathbf{4.509}$$

$$r_v = \frac{W_c}{\pi d_i}$$

Where : r_v = vertical tube loading

W_c = total condensate flow

$$r_v = \frac{0.1866}{\pi * 0.021} = \mathbf{2.83 \text{ kg/m.s}}$$

The Reynolds number for the condensate film is given by :

$$Re_c = \frac{4r_v}{u_l} = 51478.2$$

From figure 12.39. $\frac{h_c}{k_l} \left(\frac{u_l^2}{\rho_l(\rho_l - \rho_v)g} \right)^{\frac{1}{3}} = \mathbf{0.57}$

The heat transfer coefficients for condensable mixture inside tube :

$$h_c = 0.57k_l / \left(\frac{u_l^2}{\rho_l(\rho_l - \rho_v)g} \right)^{\frac{1}{3}} = \mathbf{2782.35 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Boyko-kruzhilin method :

$$\text{Cross sectional area of one tube} = \frac{\pi}{4} d_i^2 = \frac{\pi}{4} (21)^2 = \mathbf{3.46 \times 10^{-4} \text{ m}^2}$$

Fluid velocity , total condensation :

$$u_t = \frac{W_c}{A_s \rho_L} = \mathbf{0.796 \text{ m/s}}$$

$$Re = \frac{\rho_l u_t d_i}{u_l} = 51478.2$$

The force convection in the tube :

$$h'_t = 0.021 \left(\frac{k_l}{d_i} \right) Re^{0.8} p_r^{0.43} = \mathbf{1213.3 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

The heat transfer coefficients by Boyko-kruzhilin method for condensable mixture inside tube :

$$h_c = h'_t \left(\frac{1 + \sqrt{\rho_L / \rho_v}}{2} \right) = \mathbf{7591 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Take the maximum of h_c to be the heat transfer coefficients for condensable mixture inside tube.

$$\rightarrow \mathbf{h_{i(consensable mixture)} = 7591 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

$$\rightarrow \mathbf{h_i = h_{i(non-consensable mixture)} + h_{i(consensable mixture)} = 7785.73 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Calculate heat transfer coefficients for shell side (h_o)

Area for cross flow of the shell side A_s , using Kern Method

$$A_s = \left[\frac{P_t - d_o}{P_t} \right] (D_s)(L_B)$$

Where: P_t = tube pitch

d_o = tube outside diameter

D_s = shell inside diameter

L_B = Baffle spacing (usually one fifth of Shell diameter)

$$d_o = 25 \times 10^{-3} \text{ m}$$

$$P_t = 1.25 d_o \text{ mm} = 31.25 \times 10^{-3} \text{ m}$$

$$L_b = \frac{D_s}{5} = \frac{0.23}{5} = 0.0459 \text{ m}$$

$$A_s = \left[\frac{P_t - d_o}{P_t} \right] (D_s)(L_B) = \frac{31.25 - 25}{31.25} (0.23) (0.0459) = \mathbf{0.002107 \text{ m}^2}$$

mass velocity (G_s) and liner velocity (v_s)

$$G_s = \left[\frac{m_{shell}}{A_s} \right] \quad \text{and} \quad v_s = \left[\frac{G_s}{\rho_{f.shell}} \right]$$

$$m_{shell} = \text{mass flow rate of water} = \mathbf{6080.52 \text{ kg/h}}$$

$$\rightarrow G_s = \frac{1.689}{0.002107} = \mathbf{801.54 \text{ kg/m}^2 \cdot \text{s}}$$

$$\rightarrow v_s = \frac{801.54}{994.5747} = \mathbf{0.806 \text{ m/s}}$$

the equivalent (Hydraulic) diameter d_e :

$$d_e = \frac{1.10}{d_o} [P_t^2 - 0.917 d_o^2]$$

$$d_e = \frac{1.10}{25} [(31.25)^2 - 0.917(25)^2] = \mathbf{17.75 \text{ mm}}$$

Re & Pr for shell side

Average water Temperature = 32.5 °C.

$$Re = \frac{Gs \, d_e}{\mu_v} = \frac{(801.54)(0.01775)}{0.806} = 1.81 \times 10^4 \text{ "Turbulent Flow"}$$

$$Pr = \frac{Cp \, u}{K} = \frac{(4.1867) \times (0.7865)}{0.6163} = 5.343$$

the shell side coefficient (h_s or h_o)

$$h_o = (Jh \times Re \times Pr^{0.33} \times K) / d_e$$

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

$$h_o = (5.5 \times 10^{-3} \times 1.81 \times 10^4 \times 5.343^{0.33} \times 0.6163) / 17.75 \times 10^{-3}$$

$$\Rightarrow \mathbf{h_o = 746.42 \text{ W/m}^2 \cdot ^\circ\text{C}}$$

Calculating the overall heat transfer coefficient (U)

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o / d_i)}{2K_w} + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right) + \frac{1}{h_{id}} \left(\frac{d_o}{d_i} \right)$$

Where: U_o = overall coefficient based on outside area of the tubes

h_o = outside fluid film coefficient

h_i = inside fluid film coefficient

d_o = tube outside diameter

d_i = tube inside diameter

K_w = thermal conductivity of tube wall material = 45 (W/m.°C) for "Cupro-Nickel"

h_{od} = outside dirt " fouling " coefficient = 6000 (W/m².°C)

h_{id} = inside dirt " fouling " coefficient = 5000 (W/m².°C)

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o / d_i)}{2K_w} + \frac{1}{h_i} \left(\frac{d_o}{d_i} \right) + \frac{1}{h_{id}} \left(\frac{d_o}{d_i} \right)$$

$$\frac{1}{U_o} = 0.00195$$

$$\rightarrow U_o = 513.922 \text{ W/m}^2 \cdot ^\circ\text{C}$$

The value of 513.922 W/m².°C is above the estimated value of 500 W/m².°C.

Hence, the current design satisfactory. (ok)

Calculating the pressure drop (ΔP) for side tube and shell tube:

The tube side ΔP_t

$$\Delta P_t = N_p \left[8 j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \left[\frac{\rho v_t^2}{2} \right]$$

Where: ΔP_t = tube side pressure drop (N/m²)

N_p = Number of tube passes

j_f = friction factor ' depending on Re '

L = length of one tube = 1 m

v_t = flow velocity inside the tube

m = exponent value depending on type of flow

at laminar (Re<2100) $\rightarrow m = 0.25$

at Turblent (R>10000) $\rightarrow m = 0.14$

now;

$$\Delta P_t = N_p \left[8j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \left[\frac{\rho v_t^2}{2} \right]$$

$$\Delta P_t = 1 \left[8(3.15 \times 10^{-3}) \left(\frac{1}{21 \times 10^{-3}} \right) + 2.5 \right] \left[\frac{677 * (0.769)^2}{2} \right]$$

$$\Rightarrow \Delta P_t = 1308.74 \text{ Pa} = \mathbf{1.31 \text{ kPa}} \text{ (Acceptable)}$$

The shell side ΔP_s

$$\Delta P_s = 8J_f \left(\frac{D_s}{D_e} \right) \left(\frac{L}{L_B} \right) \left(\frac{\rho v_s^2}{2} \right) \left(\frac{\mu}{\mu_w} \right)^{-0.14}$$

Where: ΔP_s = shell side pressure drop (N/m²)

j_f = fraction factor ' ' depending on Re , = 0.09

D_s = shell diameter = 0.3178 m

D_e = equivalent diameter for shell side = 0.01775 m

L = length of one tube = 1 m

Re = 18100

v_s = flow velocity in shell = 0.8059 m/s

L_B = Baffle spacing = 0.0851 m

$\rho_{\text{shell}} = 994.5747 \text{ kg/m}^3$

$$\Rightarrow \Delta P_s = 65502.5 \text{ Pa} = \mathbf{65.5 \text{ KPa}} \text{ (acceptable)}$$

5- Flash Drum (V-201):

Problem statement

A liquid-gas phase separator (Flash Drum) will be used to separate the first condenser effluent which has a flow of 1801.363 kg/hr at 50 °C and 1.84 atm . The flash drum will be with mist eliminator to prevent the liquid droplets from rising with the vapor.

Taking $k_v = 0.0107$ m/s (with mist eliminator)

Where k_v is an empirical constant that depends on the properties of the fluids, the design of the separator, the size of the drops, the vapor velocity, and the degree of separation required. This value is an approximating one for flash drums with mist eliminator.

$$\text{The maximum gas velocity (v}_v\text{): } v_v = k_v \left(\frac{\rho_L - \rho_v}{\rho_v} \right)^{\frac{1}{2}}$$

Where, ρ_v : The density of the vapor phase = 1.8658 Kg/m³

ρ_L : The density of the liquid phase = 752 Kg/m³

$$v_v = 0.0107 \left(\frac{752 - 1.8658}{1.8658} \right)^{\frac{1}{2}} = 0.215 \text{ m/s}$$

The cross sectional area (A): $A = \frac{V_v}{v_v}$

Where, V_v : The volumetric flow rate of the vapor.

$$V_v = \frac{\text{mass flow rate of the vapor}}{\text{density of the vapor}} = \frac{929.7168}{1.8658} = 498.2939 \text{ m}^3/\text{hr} = 0.13842 \text{ m}^3/\text{s}$$

$$\rightarrow A = 0.13842 / 0.215 = 0.6452 \text{ m}^2$$

Now, calculating the diameter of the flash drum (D):

$$D = \sqrt{\frac{4 \times A}{\pi}} = \sqrt{\frac{4 \times 0.6452}{\pi}} = 0.907 \text{ m}$$

Now, calculating the liquid level height (L_L): $L_L \times A = V_L \times t_s$

Where, t_s : The liquid phase surge time which taking as 5 min.

V_L : The volumetric flow rate of the liquid phase.

$$V_L = \frac{\text{mass flow rate of the liquid}}{\text{density of the liquid}} = \frac{871.6462}{752} = 1.1591 \text{ m}^3/\text{hr} = 0.000322 \text{ m}^3/\text{s}$$

$$L_L = (0.000322 \times 300) / 0.6452 = 0.14972 \text{ m}$$

So, the total height (L): $L = L_L + 1.5D + 0.4572$

$$L = 0.14972 + 1.5 (0.907) + 0.4572 = 1.967 \text{ m}$$

The following heights are based on Gerunda's recommendation:

Droplet settling length = $D = 0.907$

Which is the length from the center line of the inlet nozzle to the bottom of the mist eliminator.

The height from the bottom of the nozzle to the liquid surface = $0.5 \times D = 0.453 \text{ m}$

The thickness of the mist eliminator = 0.152 m (typically)

Finally, an additional height above the eliminator is added to obtain uniform flow distribution across the eliminator = 0.305 m

For the thickness of the vessel:

Design pressure (P) = $P_0 + 25 \text{ psi}$

Where, P_0 is the operating pressure, $P_0 = 12.34 \text{ psi}$

$$\rightarrow P = 12.34 + 25 = 37.34 \text{ psi}$$

The Shell is with a Longitudinal Weld, so the efficiencies for the head and the shell are 0.8 and 0.7 respectively.

$$\text{The shell factor } \alpha_s = \frac{P}{2\varepsilon_s S - 1.2P}$$

Where, S: the hoop stress.

The material of construction is stainless steel 316, so $S = 15200 \text{ psi}$

$$\alpha_s = \frac{37.34}{2(0.8)(15200) - 1.2(37.34)} = 0.001758$$

$$\text{and the head factor } \alpha_h = \frac{1.104 P}{2\varepsilon_h S - 0.2P} = \frac{1.104 (37.34)}{2(0.7)(15200) - 0.2(37.34)} = 0.001696 \text{ (for a torispherical head)}$$

The shell thickness = $\alpha_s D + tc$

The head thickness = $\alpha_h D + tc$

Where, tc : the minimum corrosion allowance = 0.00318 m

The shell thickness = $\alpha_s D + tc = 0.001758 (0.907) + 0.00318 = 0.004774 \text{ m} = 4.77 \text{ mm}$

The head thickness = $\alpha_h D + tc = 0.001696 (0.907) + 0.00318 = 0.004717 \text{ m} = 4.77 \text{ mm}$

6- Flash Drum (V-202):

Problem statement

A liquid-gas phase separator (Flash Drum) will be used to separate the first condenser effluent which has a flow of 929.72 Kg/hr at 50 °C and 1.84 atm . The flash drum will be with mist eliminator to prevent the liquid droplets from rising with the vapor.

Taking $k_v = 0.0107 \text{ m/s}$ (with mist eliminator)

Where k_v is an empirical constant that depends on the properties of the fluids, the design of the separator, the size of the drops, the vapor velocity, and the degree of separation required. This value is an approximating one for flash drums with mist eliminator.

The maximum gas velocity (v_v): $v_v = k_v \left(\frac{\rho_L - \rho_v}{\rho_v} \right)^{\frac{1}{2}}$

Where, ρ_v : The density of the vapor phase = 0.8791 Kg/m³

ρ_L : The density of the liquid phase = 677 Kg/m³

$$v_v = 0.0107 \left(\frac{677 - 0.8791}{0.8791} \right)^{\frac{1}{2}} = 0.29674 \text{ m/s}$$

The cross sectional area (A): $A = \frac{V_v}{v_v}$

Where, V_v : The volumetric flow rate of the vapor.

$$V_v = \frac{\text{mass flow rate of the vapor}}{\text{density of the vapor}} = \frac{257.92}{0.8791} = 293.391 \text{ m}^3/\text{hr} = 0.0815 \text{ m}^3/\text{s}$$

$$\rightarrow A = 0.0815 / 0.29674 = 0.275 \text{ m}^2$$

Now, calculating the diameter of the flash drum (D):

$$D = \sqrt{\frac{4 \times A}{\pi}} = \sqrt{\frac{4 \times 0.275}{\pi}} = 0.5915 \text{ m}$$

Now, calculating the liquid level height (L_L): $L_L \times A = V_L \times t_s$

Where, t_s : The liquid phase surge time which taking as 5 min.

V_L : The volumetric flow rate of the liquid phase.

$$V_L = \frac{\text{mass flow rate of the liquid}}{\text{density of the liquid}} = \frac{671.8}{677} = 0.9923 \text{ m}^3/\text{hr} = 0.000276 \text{ m}^3/\text{s}$$

$$L_L = (0.000276 \times 300) / 0.275 = 0.3011 \text{ m}$$

So, the total height (L): $L = L_L + 1.5D + 0.4572$

$$L = 0.3011 + 1.5 (0.5915) + 0.4572 = 1.646 \text{ m}$$

The following heights are based on Gerunda's recommendation:

Droplet settling length = D = 0.5915

Which is the length from the center line of the inlet nozzle to the bottom of the mist eliminator.

The height from the bottom of the nozzle to the liquid surface = $0.5 \times D = 0.296 \text{ m}$

The thickness of the mist eliminator = 0.152 m (typically)

Finally, an additional height above the eliminator is added to obtain uniform flow distribution across the eliminator = 0.305 m

For the thickness of the vessel:

Design pressure (P) = $P_0 + 25 \text{ psi}$

Where, P_0 is the operating pressure, $P_0 = 12.34 \text{ psi}$

$$\rightarrow P = 12.34 + 25 = 37.34 \text{ psi}$$

The Shell is with a Longitudinal Weld, so the efficiencies for the head and the shell are 0.8 and 0.7 respectively.

$$\text{The shell factor } \alpha_s = \frac{P}{2\epsilon_s S - 1.2P}$$

Where, S: the hoop stress.

The material of construction is stainless steel 316, so S= 15200 psi

$$\alpha_s = \frac{37.34}{2(0.8)(15200) - 1.2(37.34)} = 0.001758$$

$$\text{and the head factor } \alpha_h = \frac{1.104 P}{2\epsilon_h S - 0.2P} = \frac{1.104(37.34)}{2(0.7)(15200) - 0.2(37.34)} = 0.001696 \text{ (for a torispherical head)}$$

$$\text{The shell thickness} = \alpha_s D + tc$$

$$\text{The head thickness} = \alpha_h D + tc$$

Where, tc: the minimum corrosion allowance = 0.00318 m

$$\text{The shell thickness} = \alpha_s D + tc = 0.001758 (0.907) + 0.00318 = 0.004774 \text{ m} = 4.77 \text{ mm}$$

$$\text{The head thickness} = \alpha_h D + tc = 0.001696 (0.907) + 0.00318 = 0.004717 \text{ m} = 4.77 \text{ mm}$$

Sizing of Equipment

1- Decomposition unit (DU-201&202) :

- Density of crumb rubber = 389 Kg/m³
- Flow of crumb rubber per batch = 3027.5 Kg

The volume needed for the crumb rubber is;

$$V = \frac{m}{\rho}$$

$$V = \frac{3027.5}{389} = 7.8 \text{ m}^3 = 8 \text{ m}^3$$

$$\text{Volume of cylinder} = \frac{\pi d^2 h}{4}$$

Assumptions:

- Diameter = 2 m
- Height = 2.6 m
- There are eight pipes are used to transfer the heat with OD 0.03 m.
- Add 0.5 m at the top of crumb rubber for the produced gases.
- Add 0.5 m at the top of the unit for discharging the combustion gases.
- Add 0.5 m at the bottom of the unit for inlet the combustion gases.

The total height = 2.6 m + 0.5 m + 0.5 m + 0.5 m = 4.1 m

The new Volume;

$$V = \frac{\pi (2)^2 (4.1)}{4} = 12.9 \text{ m}^3$$

Volume of pipes

$$\text{Volume of one pipe} = V = \frac{\pi (0.03)^2 (3.1)}{4} = 0.0022 \text{ m}^3$$

$$\text{Volume of pipes} = N * V \text{ of one} = 8 * 0.0022 = 0.0175 \text{ m}^3$$

$$\text{The Total volume of Decomposition unit} = 12.9 \text{ m}^3 + 0.0175 \text{ m}^3 = 12.92 \text{ m}^3 = 13 \text{ m}^3$$

2- Compressors Sizing.

A compressor is one of the most complicated and costly device which is used to raise the pressure for gas line. Each compressor is generally a function of the gas capacity, action and discharge head. Centrifugal compressor is used. For sizing a compressor only work need to be calculated.

To calculate the work, the following equation is used;

$$W_{rev \& \text{ adiab}} = \frac{mzRT_1 \left[\left(\frac{P_2}{P_1} \right)^a - 1 \right]}{a}$$

Where;

- m: Flow rate of inlet (mol/s)
- z : compressibility factor
- R : Gas constant (J/mol . K)
- T1 : Temperature inlet (K)
- P1 : Pressure inlet (bar)
- P2: Pressure outlet (bar)
- $a = \frac{(k-1)}{k}$
- $k : \frac{c_p}{c_v}$

The temperature will increase because the pressure has increased, to calculate the output pressure the following equation is used;

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^a$$

Where;

- T2 : Temperature outlet (K)
- T1 : Temperature inlet (K)
- P1 : Pressure inlet (bar)
- P2: Pressure outlet (bar)
- $a = \frac{(k-1)}{k}$

❖ C-201

This compressor is used to raise the pressure of the flow of nitrogen from its source to the reactor from 1 bar to 2 bars. Also the temperature will increase while the pressure increases.

Use	Discharge the char from reactor.
Compressed component	Nitrogen
Type of Compressor	Blower compressor
Inlet Pressure	1 bar
Outlet Pressure	2 bar
Inlet Temperature	25 C°
Flow	0.7 mol/s
Compressibility factor, z	1
C _p /C _v , k	1.4
Gas constant, R	8.314 J/mol.K
a	0.29

$$W_{Theoretical} = \frac{mzRT_1 \left[\left(\frac{P_2}{P_1} \right)^a - 1 \right]}{a}$$

$$W_{Theoretical} = 1.32 \text{ KW}$$

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^a = 363.47 \text{ K} = 90.3 \text{ C}^\circ$$

$$\text{Efficiency} = \eta = 0.8$$

$$W_{\text{Actual}} = \frac{W_{\text{Theoretical}}}{\text{Efficiency}}$$

$$W_{\text{Actual}} = \frac{1.32 \text{ KW}}{0.8}$$

$$W_{\text{Actual}} = 1.65 \text{ KW}$$

❖ C-202

This compressor is used to raise the pressure of the flow of Air from its source to the reactor to discharge the char after the run finish from 1 bar to 15 bars. Also the temperature will increase while the pressure increases.

Use	Discharge the char from reactor.
Compressed component	Air
Type of Compressor	Centrifugal
Inlet Pressure	1 bar
Outlet Pressure	15 bar
Inlet Temperature	25 C°
Flow	50 mol/s
Compressibility factor, z	1
C _p /C _v , k	1.4
Gas constant, R	8.314 J/mol.K
a	0.29

$$W_{\text{rev \& adiab}} = \frac{mzRT_1 \left[\left(\frac{P_2}{P_1} \right)^a - 1 \right]}{a} = 506.6 \text{ KW}$$

$$T_2 = T_1 \left(\left(\frac{P_2}{P_1} \right)^a \right) = 363.47 \text{ K} = 90.3 \text{ C}^\circ$$

$$T_2 = T_1 \left(\left(\frac{P_2}{P_1} \right)^a \right) = 363.47 \text{ K} = 90.3 \text{ C}^\circ$$

$$\text{Efficiency} = \eta = 0.8$$

$$W_{\text{Actual}} = \frac{W_{\text{Theoretical}}}{\text{Efficiency}}$$

$$W_{\text{Actual}} = \frac{506.6 \text{ KW}}{0.8}$$

$$W_{\text{Actual}} = 633.24 \text{ KW}$$

❖ C-203

This compressor is used to raise the pressure of the flow of gases from the reactor to the cooler from 1 bar to 2 bars. Also the temperature will increase while the pressure increases.

Use	Compress the gas to the cooler
Compressed component	Gases
Type of Compressor	Blower compressor
Inlet Pressure	1 bar
Outlet Pressure	2 bar
Inlet Temperature	475 C°
Flow	9.67 mol/s
Compressibility factor, z	0.99
C _p /C _v , k	1.06
Gas constant, R	8.314 J/mol.K
a	0.06

$$W_{\text{rev \& adiab}} = \frac{mzRT_1 \left[\left(\left(\frac{P_2}{P_1} \right)^a \right) - 1 \right]}{a}$$

$$W_{\text{Theoretical}} = 42.5 \text{ KW}$$

$$T_2 = T_1 \left(\left(\frac{P_2}{P_1} \right)^a \right) = 779.09 \text{ K} = 505.9 \text{ C}^\circ$$

$$\text{Efficiency} = \eta = 0.8$$

$$W_{Actual} = \frac{W_{Theoretical}}{Efficiency}$$

$$W_{Actual} = \frac{42.5 \text{ KW}}{0.8}$$

$$W_{Actual} = 53.18 \text{ KW}$$

❖ C-204

This compressor is used to raise the pressure of the flow of gases from the gas tank to the burner from 1 bar to 2 bars. Also the temperature will increase while the pressure increases.

Use	Compress the gas to the burner
Compressed component	Gases
Type of Compressor	Blower compressor
Inlet Pressure	1 bar
Outlet Pressure	2 bar
Inlet Temperature	50 C°
Flow	4.91 mol/s
Compressibility factor, z	0.99
C _p /C _v , k	1.3
Gas constant, R	8.314 J/mol.K
a	0.23

$$W_{rev \& \text{adiab}} = \frac{mzRT_1 \left[\left(\left(\frac{P_2}{P_1} \right)^a \right) - 1 \right]}{a}$$

$$W_{Theoretical} = 9.9 \text{ KW}$$

$$T_2 = T_1 \left(\left(\frac{P_2}{P_1} \right)^a \right) = 379.9 \text{ K} = 106.75 \text{ C}^\circ$$

$$Efficiency = \eta = 0.8$$

$$W_{Actual} = \frac{W_{Theoretical}}{Efficiency}$$

$$W_{Actual} = \frac{9.9 \text{ KW}}{0.8}$$

$$W_{Actual} = 12.4 \text{ KW}$$

- **C-205**

This compressor is used to compress the air to the burner from 1 bar to 2 bars. Also the temperature will increase while the pressure increases.

Use	Compress the air to the burner
Compressed component	Gases
Type of Compressor	Blower compressor
Inlet Pressure	1 bar
Outlet Pressure	2 bar
Inlet Temperature	25 C°
Flow	4.91 mol/s
Compressibility factor, z	0.99
C _p /C _v , k	1.4
Gas constant, R	8.314 J/mol.K
A	0.29

$$W_{rev \& \text{adiab}} = \frac{mzRT_1 \left[\left(\left(\frac{P_2}{P_1} \right)^a \right) - 1 \right]}{a}$$

$$W_{Theoretical} = 73.9 \text{ KW}$$

$$T_2 = T_1 \left(\left(\frac{P_2}{P_1} \right)^a \right) = 363.4 \text{ K} = 90.3 \text{ C}^\circ$$

$$\text{Efficiency} = \eta = 0.8$$

$$W_{Actual} = \frac{W_{Theoretical}}{\text{Efficiency}}$$

$$W_{Actual} = \frac{73.9 \text{ KW}}{0.8}$$

$$W_{\text{Actual}} = 92.4 \text{ KW}$$

3- Sizing of Burner (F-201):

In the burner, the flow of gases from the second flash (V-202) is burned in the burner with a 20% excess air. The combustion products then will enter the decomposition units (DU-201, DU-202) to heat the crumb rubber.

Data for calculation;

- Gas flow rate 225.76 Kg/h
- The Air flow rate 4044 Kg/h
- Inlet Temperature 30 C°
- Inlet Pressure 2 bar

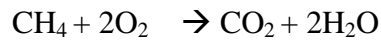
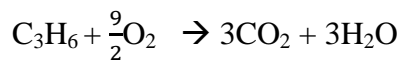
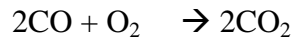
Inlet flow gases describe

Component	Flow rate (Kg/h)	Mass fraction	LHV (KJ/Kg)
CO	16.78	0.065	10112
CO ₂	32.1	0.125	---
CH ₄	94.02	0.365	50000
C ₂ H ₄	31.33	0.122	47195
H ₂	15.43	0.06	120000
C ₃ H ₆	54.8	0.212	45800
H ₂ S	13.3	0.052	15191

The heat capacity for inlet and outlet streams of the burner

	A	B	C	D
$C_{pmix_{44}}$	21.27364	0.051058995	-1.63466E-05	2.10672E-09
$C_{pmix_{45}}$	30.5116	-0.01072093	2.48386E-05	-1.14637E-08
$C_{pmix_{46}}$	30.30877925	0.00628978	-1.4945E-06	-1.5E-11

The reactions are:



The total heating value = 4.23×10^4 KJ/Kg

The total heat generated by combustion = $(4.23 \times 10^4 \text{ KJ/Kg}) * (225.76 \text{ Kg/h})$
 $= 9.55 \times 10^6 \text{ KJ/h}$

Outlet flow gases describe

Component	Flow rate (Kg/h)	Mass fraction
CO ₂	587	0.544
H ₂ O	466.9	0.432
SO ₂	25	0.023

Calculation of outlet temperature:

$$Q = 0 = \Delta H = H_{46} - H_{44} - H_{45}$$

$$H = n_i * (y_i * \Delta H_f + \int C_{p_{mix}} dT)$$

$$T_{46} = 1940\text{ }^{\circ}\text{C}$$

4- Sizing of storage tanks :

- **Gas storage**

Used to	Storage the gases after the 2 nd condenser (E-204)
Flow	257.9 Kg/h
Density	1.0887 Kg/m ³
Volumetric Flow rate	236.88 m ³ /h
Maximum Storage Time	2 Hours
Volume required	500 m ³
Storage type	Horizontal
Length	13 m
Height	7m

- **Liquid storage**

1-The storage after first flash drum

Used to	Storage the liquid produces from 1 st flash drum (V-203)
Flow	874.75 Kg/h
Density	772.73 Kg/m ³
Volumetric Flow rate	1.132 m ³ /h
Maximum Storage Time	4 days
Volume required	120 m ³
Storage type	Vertical
Length	6 m
Diameter	5m

1-The storage after second flash drum

Used to	Storage the liquid produces from 2 nd flash drum (V-202)
Flow	671.8 Kg/h
Density	717.46 Kg/m ³
Volumetric Flow rate	0.94 m ³ /h
Maximum Storage Time	4 days
Volume required	120 m ³
Storage type	Vertical
Length	6 m
Diameter	5 m

Appendix C

Heat Capacities

APPENDIX C

HEAT CAPACITIES

$$C_p = A + BT + CT^2 + DT^3 = \text{J/gmol-K}$$

	A	B* 10²	C* 10⁴	D* 10⁸
H ₂ S	33.3525	-0.7109	0.4022	-2.1178
C ₃ H ₆	3.71	23.54	-1.16	2.205
H ₂	27.14	0.9274	-0.1381	0.7645
C ₂ H ₄	3.806	15.66	-0.8348	1.755
H ₂ O	32.24	0.1924	0.1055	-0.3596
N ₂	31.15	-1.357	0.268	-1.168
Hexane	-4.413	58.2	-3.119	6.494
CH ₄	19.25	5.213	0.1197	-1.132
CO	30.87	-1.285	0.2789	-1.272
Ethyl benzene	-43.1	70.72	-4.811	13.01
C ₇ H ₈	-24.35	51.25	-2.765	4.911
C ₂ H ₄ O	-9.4394	23.2857	-1.4446	3.6226
Styrene	-28.25	61.59	-4.023	9.935
C ₆ H ₆	-33.92	47.39	-3.017	7.13
C	18.3195	0.1524	-0.0015	0.0005
O ₂	28.11	-0.0003	0.1746	-1.065
CO ₂	19.8	7.344	-0.5602	1.715

Appendix D

Figures Used in Calculations

APPENDIX D

FIGURES USED IN CALCULATIONS

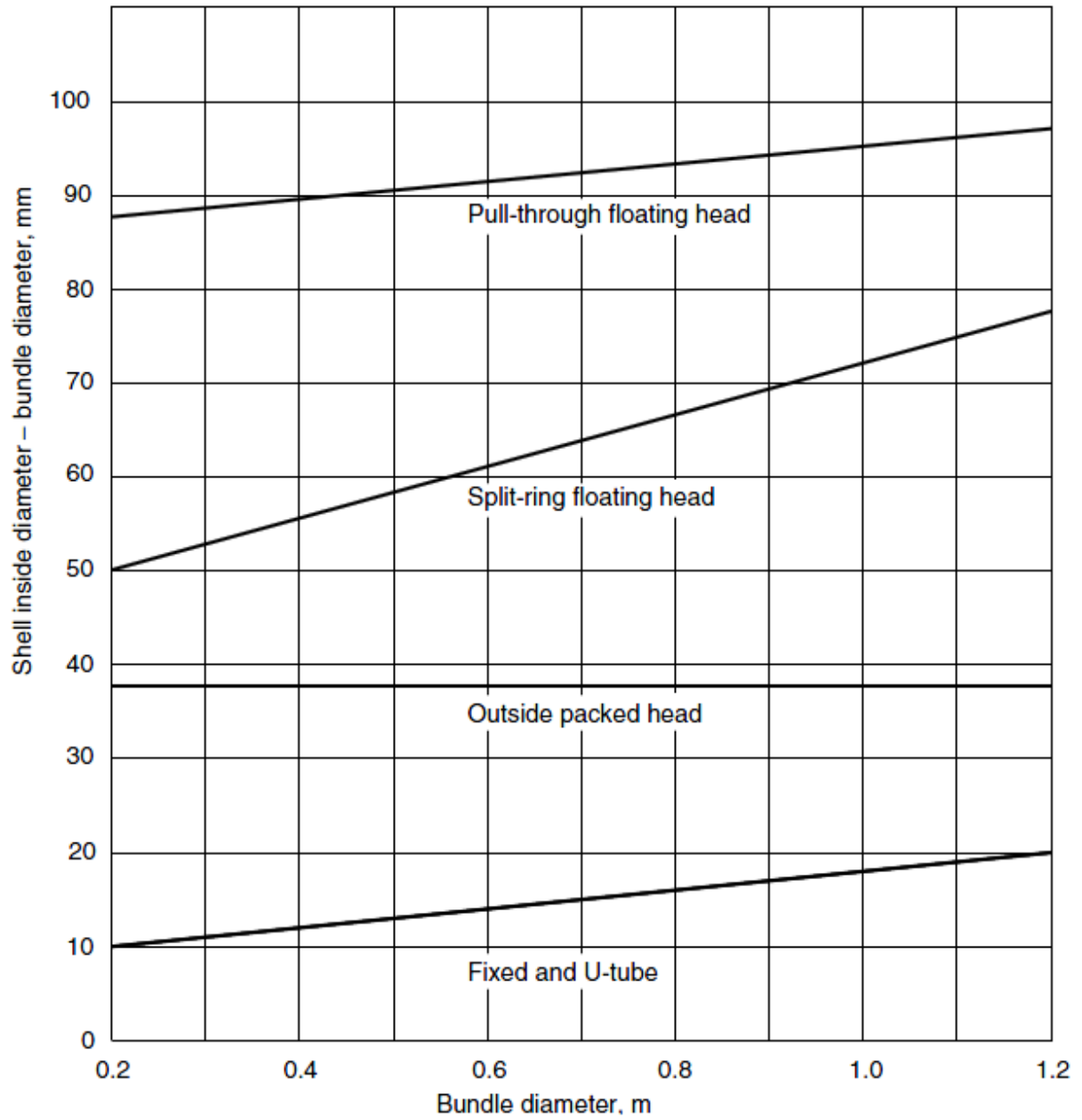
Constant K & n for bundle diameter:

Triangular pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.319	0.249	0.175	0.0743	0.0365
n_1	2.142	2.207	2.285	2.499	2.675
Square pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.215	0.156	0.158	0.0402	0.0331
n_1	2.207	2.291	2.263	2.617	2.643

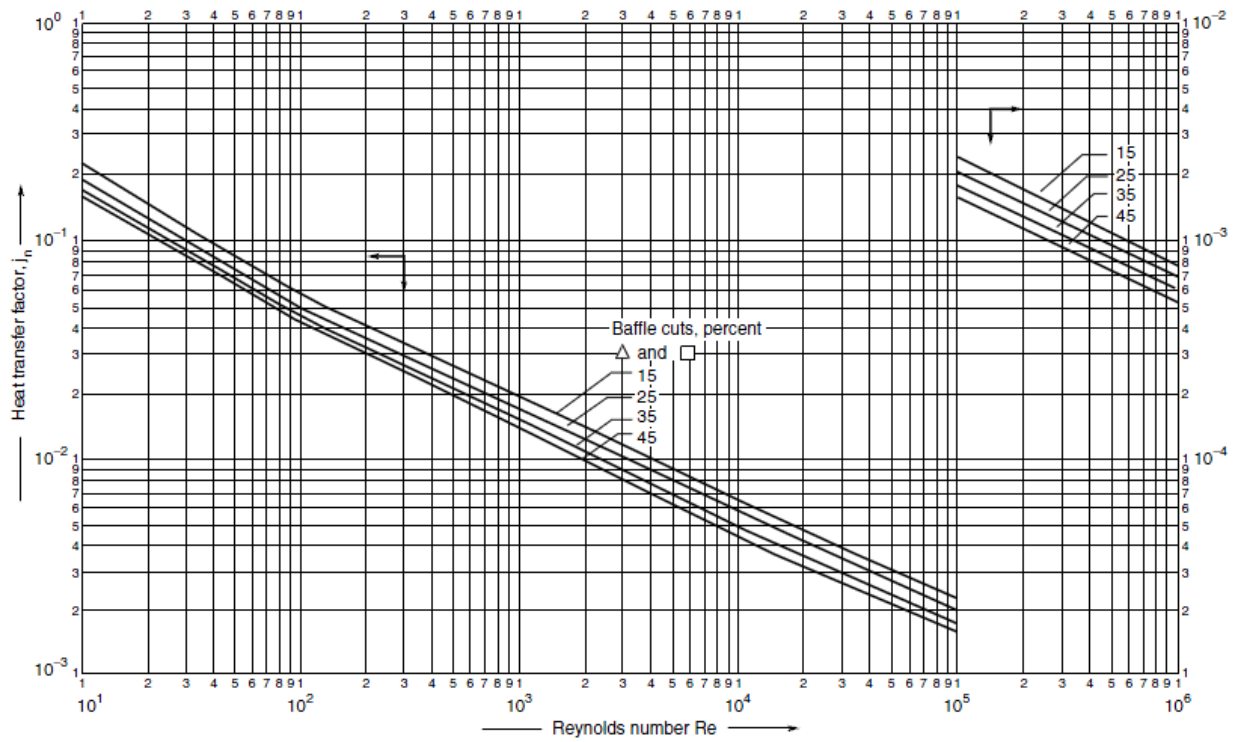
Minimum mechanical properties for 70-30 Cu-Ni(CW 354H) based on Euronorm Standards:

Form	Condition	Thickness t^*	Tensile Strength	0.2% Proof Strength	Elongation	Hardness
		mm	N/mm ²	N/mm ²	%	HV
Tube EN 12449: 1999	R370	10 max	370	120	35	-
	H085	10 max	-	-	-	85-120
	R480	5 max	480	300	12	-
	H135	5 max	-	-	-	135
Sheet/plate EN 1652: 1997	R350	0.3-15	350-420	(120)	35 for $t > 2.5\text{mm}$	-
	H080	0.3-15	-	-	-	80-120
	R410	0.3-15	410	(300)	14 for $t > 2.5\text{mm}$	-
	H110	0.3-15	-	-	-	110
Heavy PlateFor pressure vessels EN 1653:1997	R320	2.5-125	320	120	30	(100)
	R410	10-40	410	300	14	(140)

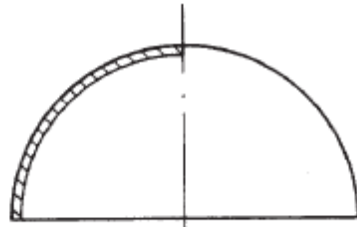
Shell-bundle clearance



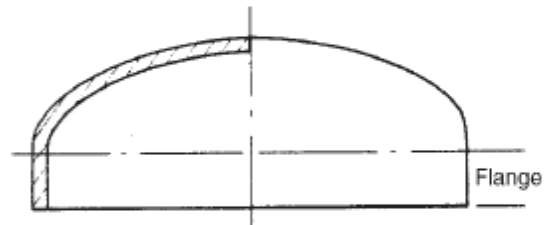
Shell side heat transfer factors



Domed Heads



(a)



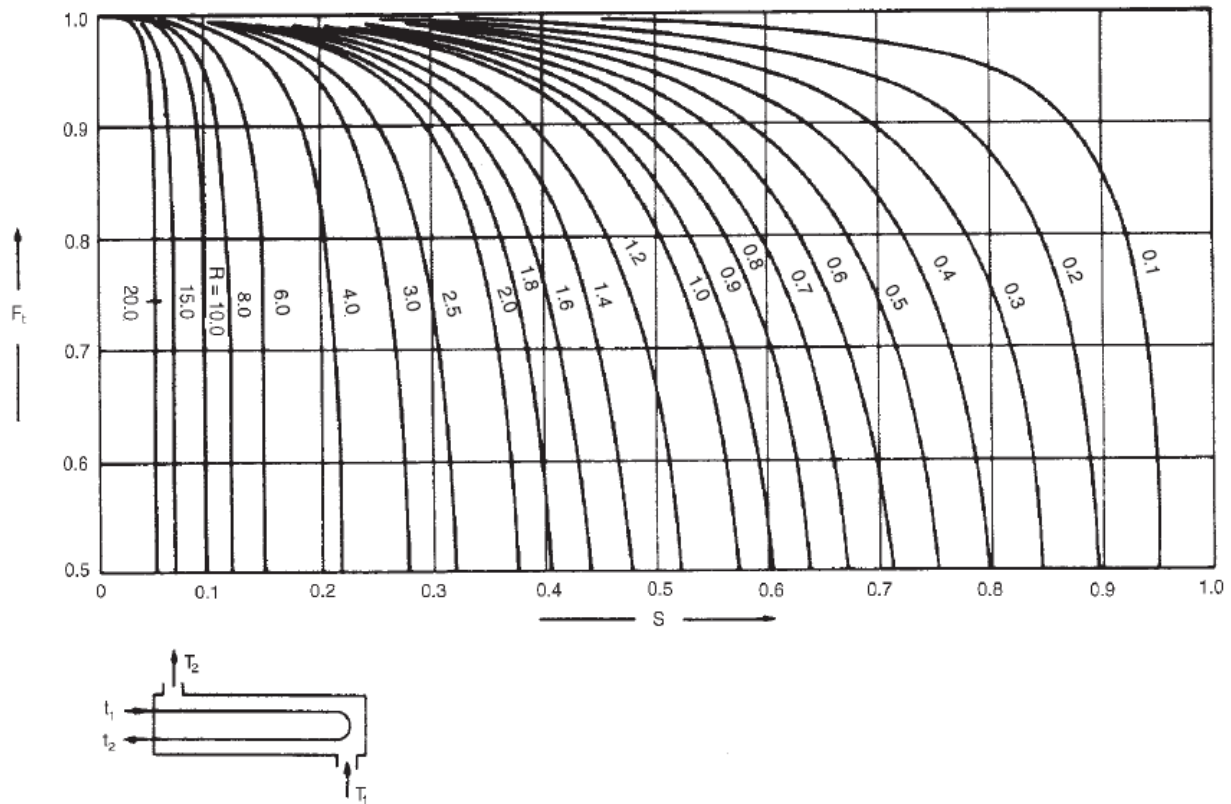
(b)



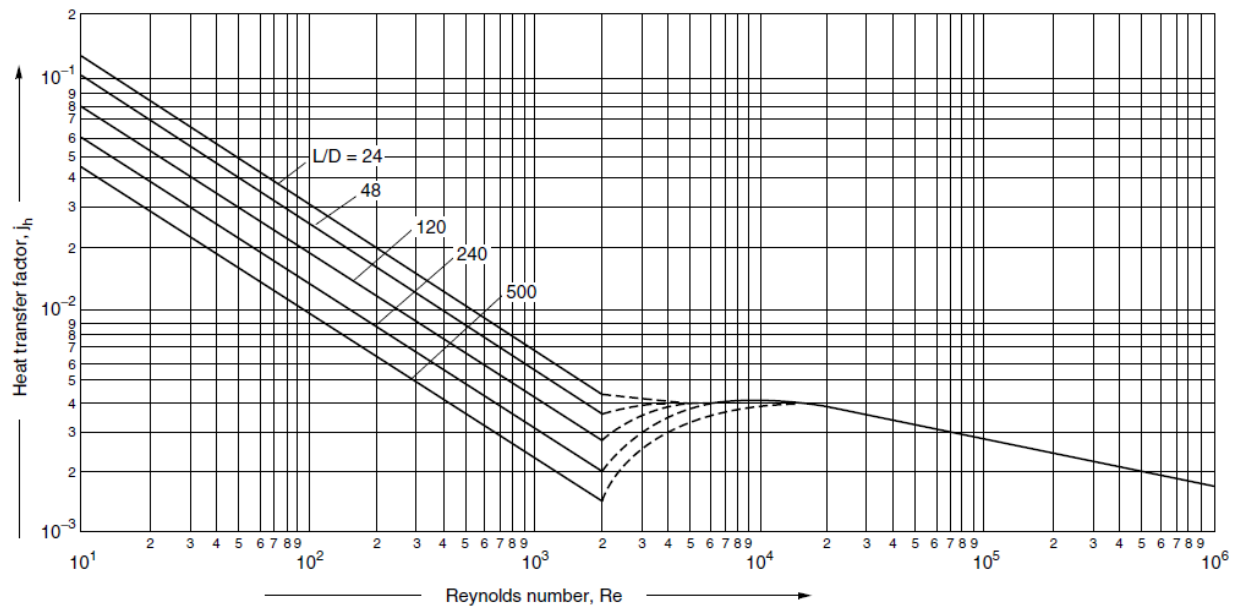
(c)

Domed heads (a) Hemispherical (b) Ellipsoidal (c) Torispherical

Temperature factor



Tube side heat transfer coefficient

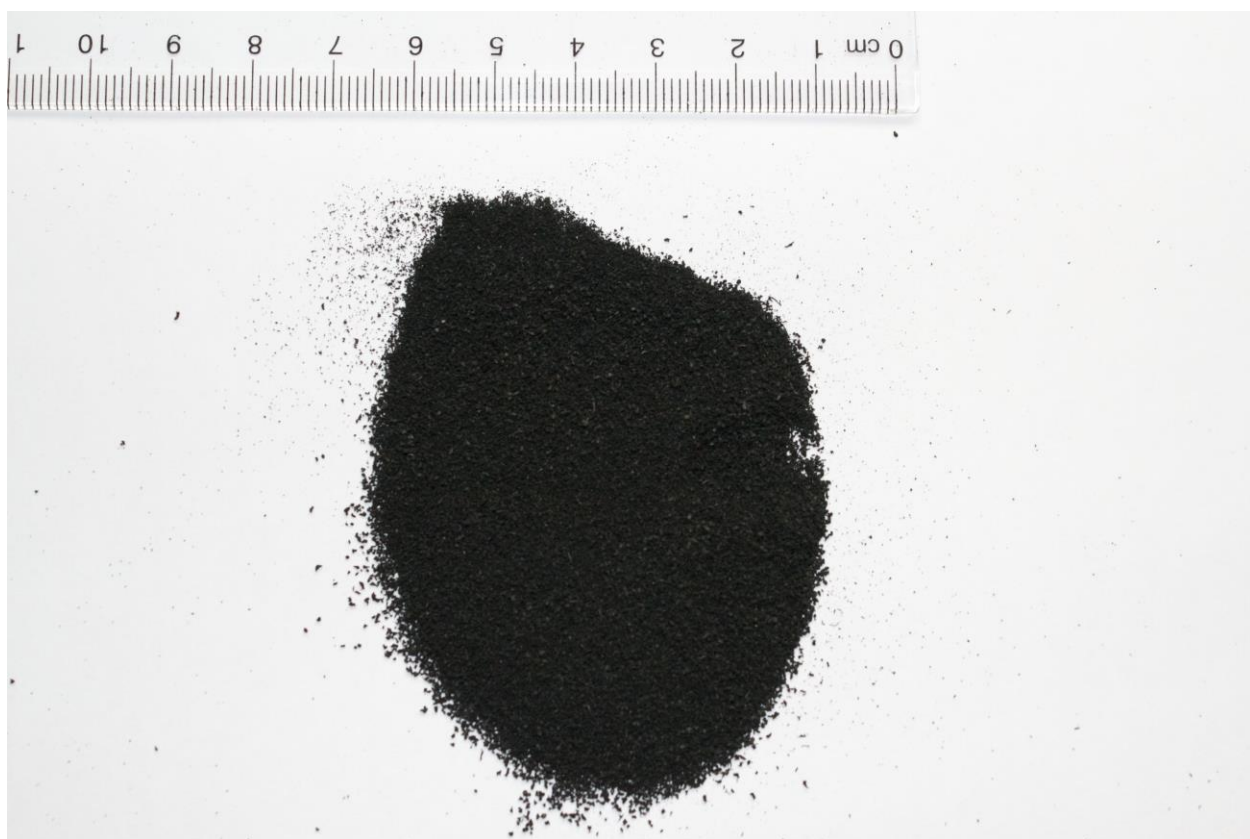


Appendix E

Crumb Rubber Samples

APPENDIX E
CRUMB RUBBER SAMPLES





Appendix F

Thermal Gravimetric Analysis (TGA)

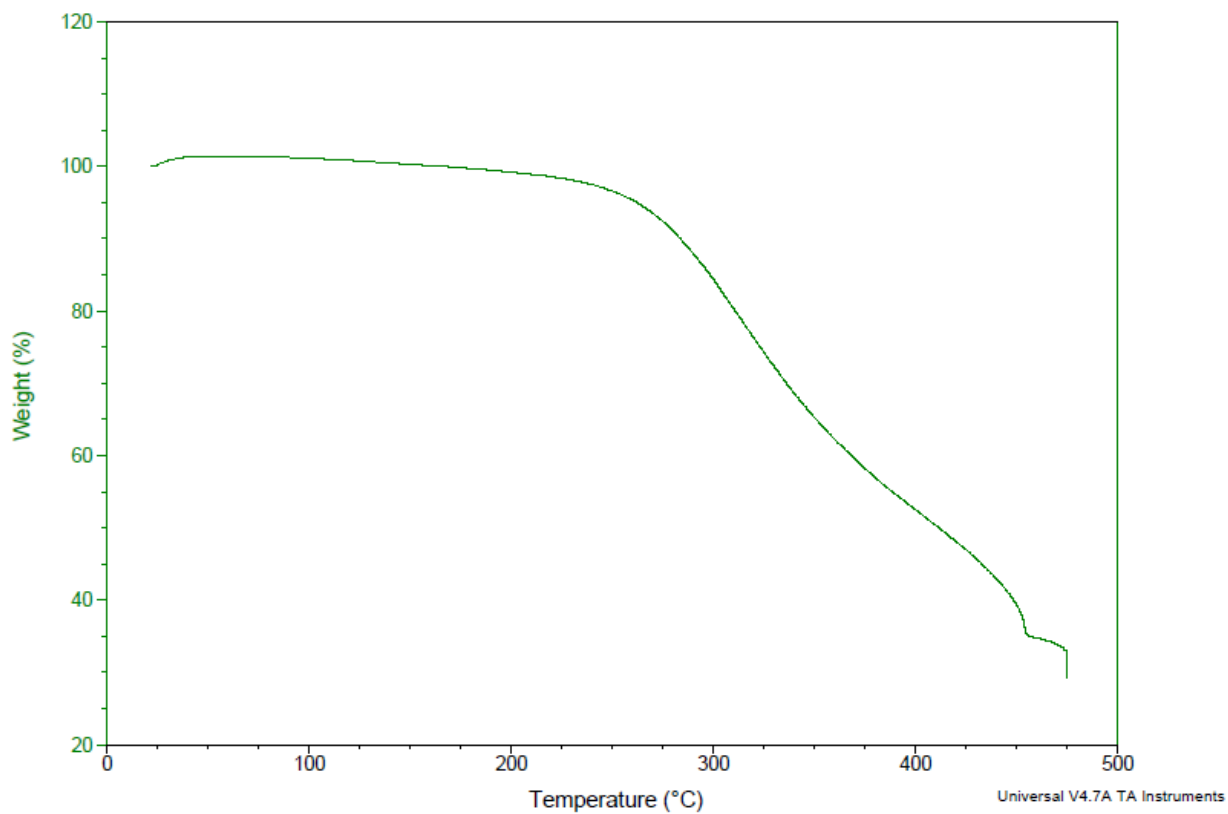
APPENDIX F

THERMAL GRAVIMETRIC ANALYSIS (TGA)

Sample: dunlop isothermal at 475
Size: 2.2860 mg
Method: Ramp 10 c/min
Comment: dunlop at 475

TGA

File: C:\...\dunlop\dunlop isothermal.001
Operator: omer
Run Date: 17-Oct-2014 10:29
Instrument: TGA Q50 V20.10 Build 36



Appendix G

Material Safety Data Sheet (MSDS)

Material Safety Data Sheet



Carbon Dioxide

Section 1. Chemical product and company identification

Product name	: Carbon Dioxide
Supplier	: AIRGAS INC., on behalf of its subsidiaries 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
Product use	: Synthetic/Analytical chemistry.
Synonym	: Carbonic Acid, Carbon Dioxide Liquid, Carbon Dioxide, Refrigerated Liquid, Carbonic Anhydride
MSDS #	: 001013
Date of Preparation/Revision	: 1/20/2012.
In case of emergency	: 1-866-734-3438

Section 2. Hazards identification

Physical state	: Gas or Liquid.
Emergency overview	: WARNING! GAS: CONTENTS UNDER PRESURE. MAY CAUSE RESPIRATORY TRACT, EYE, AND SKIN IRRITATION. CAN CAUSE TARGET ORGAN DAMAGE. Do not puncture or incinerate container. Can cause rapid suffocation. LIQUID: MAY CAUSE RESPIRATORY TRACT, EYE, AND SKIN IRRITATION. CAN CAUSE TARGET ORGAN DAMAGE. Extremely cold liquid and gas under pressure. Can cause rapid suffocation. May cause severe frostbite. Do not puncture or incinerate container. Avoid contact with eyes, skin and clothing. May cause target organ damage, based on animal data. Wash thoroughly after handling. Keep container closed. Avoid breathing gas. Use with adequate ventilation. Contact with rapidly expanding gas, liquid, or solid can cause frostbite.
Target organs	: May cause damage to the following organs: lungs.
Routes of entry	: Inhalation Dermal Eyes
Potential acute health effects	
Eyes	: Moderately irritating to eyes. Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Skin	: Moderately irritating to the skin. Contact with rapidly expanding gas may cause burns or frostbite. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Inhalation	: Moderately irritating to the respiratory system.
Ingestion	: Ingestion is not a normal route of exposure for gases. Contact with cryogenic liquid can cause frostbite and cryogenic burns.
Potential chronic health effects	
Chronic effects	: May cause target organ damage, based on animal data.
Target organs	: May cause damage to the following organs: lungs.
Medical conditions aggravated by over-exposure	: Pre-existing disorders involving any target organs mentioned in this MSDS as being at risk may be aggravated by over-exposure to this product.
See toxicological information (Section 11)	

Carbon Dioxide

Section 3. Composition, Information on Ingredients

<u>Name</u>	<u>CAS number</u>	<u>% Volume</u>	<u>Exposure limits</u>
Carbon Dioxide	124-38-9	100	ACGIH TLV (United States, 2/2010). STEL: 54000 mg/m ³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 9000 mg/m ³ 8 hour(s). TWA: 5000 ppm 8 hour(s). NIOSH REL (United States, 6/2009). STEL: 54000 mg/m ³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 9000 mg/m ³ 10 hour(s). TWA: 5000 ppm 10 hour(s). OSHA PEL (United States, 6/2010). TWA: 9000 mg/m ³ 8 hour(s). TWA: 5000 ppm 8 hour(s). OSHA PEL 1989 (United States, 3/1989). STEL: 54000 mg/m ³ 15 minute(s). STEL: 30000 ppm 15 minute(s). TWA: 18000 mg/m ³ 8 hour(s). TWA: 10000 ppm 8 hour(s).

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training. If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact	: Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.
Skin contact	: In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.
Frostbite	: Try to warm up the frozen tissues and seek medical attention.
Inhalation	: Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.
Ingestion	: As this product is a gas, refer to the inhalation section.

Section 5. Fire-fighting measures

Flammability of the product	: Non-flammable.
Products of combustion	: Decomposition products may include the following materials: carbon dioxide carbon monoxide
Fire-fighting media and instructions	: Use an extinguishing agent suitable for the surrounding fire. Apply water from a safe distance to cool container and protect surrounding area. If involved in fire, shut off flow immediately if it can be done without risk. Contains gas under pressure. In a fire or if heated, a pressure increase will occur and the container may burst or explode.
Special protective equipment for fire-fighters	: Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

- Personal precautions** : Immediately contact emergency personnel. Keep unnecessary personnel away. Use suitable protective equipment (section 8). Shut off gas supply if this can be done safely. Isolate area until gas has dispersed.
- Environmental precautions** : Avoid dispersal of spilled material and runoff and contact with soil, waterways, drains and sewers.
- Methods for cleaning up** : Immediately contact emergency personnel. Stop leak if without risk. Note: see section 1 for emergency contact information and section 13 for waste disposal.

Section 7. Handling and storage

- Handling** : Wash thoroughly after handling. High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Keep container closed. Avoid contact with skin and clothing. Use with adequate ventilation. Avoid contact with eyes. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement. Never allow any unprotected part of the body to touch uninsulated pipes or vessels that contain cryogenic liquids. Prevent entrapment of liquid in closed systems or piping without pressure relief devices. Some materials may become brittle at low temperatures and will easily fracture.
- Storage** : Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F). For additional information concerning storage and handling refer to Compressed Gas Association pamphlets P-1 Safe Handling of Compressed Gases in Containers and P-12 Safe Handling of Cryogenic Liquids available from the Compressed Gas Association, Inc.

Section 8. Exposure controls/personal protection

- Engineering controls** : Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits.
- Personal protection**
- Eyes** : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists or dusts.
- When working with cryogenic liquids, wear a full face shield.
- Skin** : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.
- Respiratory** : Use a properly fitted, air-purifying or air-fed respirator complying with an approved standard if a risk assessment indicates this is necessary. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.
- The applicable standards are (US) 29 CFR 1910.134 and (Canada) Z94.4-93
- Hands** : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary.
- Insulated gloves suitable for low temperatures
- Personal protection in case of a large spill** : Self-contained breathing apparatus (SCBA) should be used to avoid inhalation of the product. Full chemical-resistant suit and self-contained breathing apparatus should be worn only by trained and authorized persons.

Product name

Carbon Dioxide

Carbon dioxide

ACGIH TLV (United States, 2/2010).

STEL: 54000 mg/m³ 15 minute(s).

STEL: 30000 ppm 15 minute(s).

TWA: 9000 mg/m³ 8 hour(s).

TWA: 5000 ppm 8 hour(s).

NIOSH REL (United States, 6/2009).

STEL: 54000 mg/m³ 15 minute(s).

STEL: 30000 ppm 15 minute(s).

TWA: 9000 mg/m³ 10 hour(s).

TWA: 5000 ppm 10 hour(s).

OSHA PEL (United States, 6/2010).

TWA: 9000 mg/m³ 8 hour(s).

TWA: 5000 ppm 8 hour(s).

OSHA PEL 1989 (United States, 3/1989).

STEL: 54000 mg/m³ 15 minute(s).

STEL: 30000 ppm 15 minute(s).

TWA: 18000 mg/m³ 8 hour(s).

TWA: 10000 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

Molecular weight	: 44.01 g/mole	
Molecular formula	: C-O ₂	
Melting/freezing point	: Sublimation temperature: -79°C (-110.2 to °F)	
Critical temperature	: 30.9°C (87.6°F)	
Vapor pressure	: 830 (psig)	
Vapor density	: 1.53 (Air = 1)	Liquid Density@BP: Solid density = 97.5 lb/ft ³ (1562 kg/m ³)
Specific Volume (ft³/lb)	: 8.7719	
Gas Density (lb/ft³)	: 0.114	

Section 10. Stability and reactivity

Stability and reactivity	: The product is stable.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

Product/ingredient name	Result	Species	Dose	Exposure
Carbon dioxide	LC50 Inhalation Gas.	Rat	470000 ppm	30 minutes

IDLH	: 40000 ppm
Chronic effects on humans	: May cause damage to the following organs: lungs.
Other toxic effects on humans	: No specific information is available in our database regarding the other toxic effects of this material to humans.
Specific effects	
Carcinogenic effects	: No known significant effects or critical hazards.
Mutagenic effects	: No known significant effects or critical hazards.
Reproduction toxicity	: No known significant effects or critical hazards.

Carbon Dioxide

Section 12. Ecological information

Aquatic ecotoxicity

Not available.

Toxicity of the products of biodegradation : not available

Environmental fate : Not available.




Environmental hazards : This product shows a low bioaccumulation potential.

Toxicity to the environment : Not available.

Section 13. Disposal considerations

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, local regulation. Return cylinders with residual product to Airgas, Inc. Do not dispose of locally.

Section 14. Transport information

Regulatory information	UN number	Proper shipping name	Class	Packing group	Label	Additional information
DOT Classification	UN1013	CARBON DIOXIDE	2.2	Not applicable (gas).		Limited quantity Yes.
	UN2187	Carbon dioxide, refrigerated liquid				Packaging Instruction Passenger aircraft Quantity limitation: 75 kg Cargo aircraft Quantity limitation: 150 kg
TDG Classification	UN1013	CARBON DIOXIDE	2.2	Not applicable (gas).		Explosive Limit and Limited Quantity Index 0.125
	UN2187	Carbon dioxide, refrigerated liquid				Passenger Carrying Road or Rail Index 75
Mexico Classification	UN1013	CARBON DIOXIDE	2.2	Not applicable (gas).		-
	UN2187	Carbon dioxide, refrigerated liquid				

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Section 15. Regulatory information

United States

U.S. Federal regulations : TSCA 8(a) IUR: This material is listed or exempted.
United States inventory (TSCA 8b): This material is listed or exempted.
SARA 302/304/311/312 **extremely hazardous substances**: No products were found.
SARA 302/304 **emergency planning and notification**: No products were found.
SARA 302/304/311/312 **hazardous chemicals**: Carbon dioxide
SARA 311/312 **MSDS distribution - chemical inventory - hazard identification**:
Carbon dioxide: Sudden release of pressure, Immediate (acute) health hazard, Delayed (chronic) health hazard

State regulations

: **Connecticut Carcinogen Reporting**: This material is not listed.
Connecticut Hazardous Material Survey: This material is not listed.
Florida substances: This material is not listed.
Illinois Chemical Safety Act: This material is not listed.
Illinois Toxic Substances Disclosure to Employee Act: This material is not listed.
Louisiana Reporting: This material is not listed.
Louisiana Spill: This material is not listed.
Massachusetts Spill: This material is not listed.
Massachusetts Substances: This material is listed.
Michigan Critical Material: This material is not listed.
Minnesota Hazardous Substances: This material is not listed.
New Jersey Hazardous Substances: This material is listed.
New Jersey Spill: This material is not listed.
New Jersey Toxic Catastrophe Prevention Act: This material is not listed.
New York Acutely Hazardous Substances: This material is not listed.
New York Toxic Chemical Release Reporting: This material is not listed.
Pennsylvania RTK Hazardous Substances: This material is listed.
Rhode Island Hazardous Substances: This material is not listed.

Canada

WHMIS (Canada)

: Class A: Compressed gas.
CEPA Toxic substances: This material is listed.
Canadian ARET: This material is not listed.
Canadian NPRI: This material is not listed.
Alberta Designated Substances: This material is not listed.
Ontario Designated Substances: This material is not listed.
Quebec Designated Substances: This material is not listed.

Section 16. Other information

United States

Label requirements

: GAS:
CONTENTS UNDER PRESURE.
MAY CAUSE RESPIRATORY TRACT, EYE, AND SKIN IRRITATION.
CAN CAUSE TARGET ORGAN DAMAGE.
Do not puncture or incinerate container.
Can cause rapid suffocation.
LIQUID:
MAY CAUSE RESPIRATORY TRACT, EYE, AND SKIN IRRITATION.
CAN CAUSE TARGET ORGAN DAMAGE.
Extremely cold liquid and gas under pressure.
Can cause rapid suffocation.
May cause severe frostbite.

Canada

Label requirements

: Class A: Compressed gas.

Carbon Dioxide

Hazardous Material
Information System (U.S.A.)

Health	*	1
Flammability		0
Physical hazards		0

liquid:

Health		3
Fire hazard		0
Reactivity		0
Personal protection		

National Fire Protection
Association (U.S.A.)



liquid:



Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.

Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

Material Safety Data Sheet

Sulfur Dioxide

Airgas

Section 1. Chemical product and company identification

Product name	: Sulfur Dioxide
Supplier	: AIRGAS INC., on behalf of its subsidiaries 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
Product use	: Synthetic/Analytical chemistry.
Synonym	: Sulfurous acid anhydride; Fermenticide powder; Fermenticide liquid; Sulfur oxide (SO ₂); Sulfurous anhydride; Sulfurous oxide; SO ₂ ; Sulphur dioxide; Fermenticide liquid; Schwefeldioxyd; Siarki dwutlenek; Sulfur oxide; UN 1079; Oxosulfane oxide
MSDS #	: 001047
Date of Preparation/Revision	: 3/20/2012.
In case of emergency	: 1-866-734-3438

Section 2. Hazards identification

Physical state	: Gas. [COLORLESS LIQUEFIED COMPRESSED GAS WITH A SHARP IRRITATING ODOR. [NOTE: A LIQUID BELOW 14 F. SHIPPED AS A LIQUEFIED COMPRESSED GAS.]
Emergency overview	: DANGER! CAUSES SEVERE RESPIRATORY TRACT, EYE AND SKIN BURNS. MAY CAUSE TARGET ORGAN DAMAGE, BASED ON ANIMAL DATA. CONTENTS UNDER PRESSURE. Do not puncture or incinerate container. Do not breathe gas. Do not get on skin or clothing. Use only with adequate ventilation. Keep container closed. Wash thoroughly after handling. Contact with rapidly expanding gases can cause frostbite.
Target organs	: May cause damage to the following organs: lungs, upper respiratory tract, skin, eyes.
Routes of entry	: Inhalation Dermal Eyes
<u>Potential acute health effects</u>	
Eyes	: Severely corrosive to the eyes. Causes severe burns. Contact with rapidly expanding gas may cause burns or frostbite.
Skin	: Severely corrosive to the skin. Causes severe burns. Contact with rapidly expanding gas may cause burns or frostbite.
Inhalation	: Severely corrosive to the respiratory system.
Ingestion	: Ingestion is not a normal route of exposure for gases
<u>Potential chronic health effects</u>	
Target organs	: May cause damage to the following organs: lungs, upper respiratory tract, skin, eyes.
Medical conditions aggravated by over-exposure	: Pre-existing disorders involving any target organs mentioned in this MSDS as being at risk may be aggravated by over-exposure to this product.
See toxicological information (Section 11)	

Sulfur Dioxide

Section 3. Composition, Information on Ingredients

Name	CAS number	% Volume	Exposure limits
Sulfur Dioxide	7446-09-5	100	ACGIH TLV (United States, 1/2009). STEL: 0.25 ppm 15 minute(s). OSHA PEL 1989 (United States, 3/1989). TWA: 2 ppm 8 hour(s). TWA: 5 mg/m ³ 8 hour(s). STEL: 5 ppm 15 minute(s). STEL: 10 mg/m ³ 15 minute(s). NIOSH REL (United States, 6/2009). TWA: 2 ppm 10 hour(s). TWA: 5 mg/m ³ 10 hour(s). STEL: 5 ppm 15 minute(s). STEL: 13 mg/m ³ 15 minute(s). OSHA PEL (United States, 11/2006). TWA: 5 ppm 8 hour(s). TWA: 13 mg/m ³ 8 hour(s).

Section 4. First aid measures

No action shall be taken involving any personal risk or without suitable training. If it is suspected that fumes are still present, the rescuer should wear an appropriate mask or self-contained breathing apparatus. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Eye contact	: Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.
Skin contact	: In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.
Frostbite	: Try to warm up the frozen tissues and seek medical attention.
Inhalation	: Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.
Ingestion	: As this product is a gas, refer to the inhalation section.

Section 5. Fire-fighting measures

Flammability of the product	: Non-flammable.
Products of combustion	: Decomposition products may include the following materials: sulfur oxides
Fire-fighting media and instructions	: Use an extinguishing agent suitable for the surrounding fire. Apply water from a safe distance to cool container and protect surrounding area. If involved in fire, shut off flow immediately if it can be done without risk. Contains gas under pressure. In a fire or if heated, a pressure increase will occur and the container may burst or explode.
Special protective equipment for fire-fighters	: Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions	: Immediately contact emergency personnel. Keep unnecessary personnel away. Use suitable protective equipment (section 8). Shut off gas supply if this can be done safely. Isolate area until gas has dispersed.
Environmental precautions	: Avoid dispersal of spilled material and runoff and contact with soil, waterways, drains and sewers.
Methods for cleaning up	: Immediately contact emergency personnel. Stop leak if without risk. Note: see section 1 for emergency contact information and section 13 for waste disposal.

Sulfur Dioxide

Section 7. Handling and storage

- Handling** : Use only with adequate ventilation. Wash thoroughly after handling. High pressure gas. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Keep container closed. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
- Storage** : Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F).

Section 8. Exposure controls/personal protection

- Engineering controls** : Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits.

Personal protection

- Eyes** : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists or dusts.
- Skin** : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.
- Respiratory** : Use a properly fitted, air-purifying or air-fed respirator complying with an approved standard if a risk assessment indicates this is necessary. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.
- The applicable standards are (US) 29 CFR 1910.134 and (Canada) Z94.4-93
- Hands** : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary.
- Personal protection in case of a large spill** : Self-contained breathing apparatus (SCBA) should be used to avoid inhalation of the product. Full chemical-resistant suit and self-contained breathing apparatus should be worn only by trained and authorized persons.

Product name

sulphur dioxide

ACGIH TLV (United States, 1/2009).

STEL: 0.25 ppm 15 minute(s).

OSHA PEL 1989 (United States, 3/1989).

TWA: 2 ppm 8 hour(s).

TWA: 5 mg/m³ 8 hour(s).

STEL: 5 ppm 15 minute(s).

STEL: 10 mg/m³ 15 minute(s).

NIOSH REL (United States, 6/2009).

TWA: 2 ppm 10 hour(s).

TWA: 5 mg/m³ 10 hour(s).

STEL: 5 ppm 15 minute(s).

STEL: 13 mg/m³ 15 minute(s).

OSHA PEL (United States, 11/2006).

TWA: 5 ppm 8 hour(s).

TWA: 13 mg/m³ 8 hour(s).

Consult local authorities for acceptable exposure limits.

Sulfur Dioxide

Section 9. Physical and chemical properties

Molecular weight	: 64.06 g/mole
Molecular formula	: O ₂ -S
Boiling/condensation point	: -10°C (14°F)
Melting/freezing point	: -75.6°C (-104.1°F)
Critical temperature	: 156.9°C (314.4°F)
Vapor pressure	: 34 (psig)
Vapor density	: 2.2 (Air = 1)
Specific Volume (ft ³ /lb)	: 5.9172
Gas Density (lb/ft ³)	: 0.169

Section 10. Stability and reactivity

Stability and reactivity	: The product is stable.
Incompatibility with various substances	: Extremely reactive or incompatible with the following materials: alkalis and moisture. Reactive or incompatible with the following materials: metals.
Hazardous decomposition products	: Under normal conditions of storage and use, hazardous decomposition products should not be produced.
Hazardous polymerization	: Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Toxicity data

Product/ingredient name	Result	Species	Dose	Exposure
sulphur dioxide	LC50 Inhalation Gas.	Mouse	3000 ppm	0.5 hours
	LC50 Inhalation Gas.	Rat	2520 ppm	1 hours
	LC50 Inhalation Gas.	Rat	2520 ppm	1 hours

IDLH : 100 ppm

Chronic effects on humans : **CARCINOGENIC EFFECTS:** A4 (Not classifiable for humans or animals.) by ACGIH, 3 (Not classifiable for humans.) by IARC.
May cause damage to the following organs: lungs, upper respiratory tract, skin, eyes.

Other toxic effects on humans : Hazardous by the following route of exposure: of skin contact (corrosive), of eye contact (corrosive), of inhalation (lung corrosive).

Specific effects

Carcinogenic effects	: No known significant effects or critical hazards.
Mutagenic effects	: No known significant effects or critical hazards.
Reproduction toxicity	: No known significant effects or critical hazards.

Section 12. Ecological information

Aquatic ecotoxicity

Not available.







Products of degradation	:
Environmental fate	: Not available.
Environmental hazards	: No known significant effects or critical hazards.
Toxicity to the environment	: Not available.

Sulfur Dioxide

Section 13. Disposal considerations

Product removed from the cylinder must be disposed of in accordance with appropriate Federal, State, local regulation. Return cylinders with residual product to Algas, Inc. Do not dispose of locally.

Section 14. Transport information

Regulatory Information	UN number	Proper shipping name	Class	Packing group	Label	Additional Information
DOT Classification	UN1079	SULFUR DIOXIDE	2.3	Not applicable (gas).	 	<p><u>Limited quantity</u> Yes.</p> <p><u>Packaging instruction</u> Passenger aircraft Quantity limitation: Forbidden.</p> <p>Cargo aircraft Quantity limitation: Forbidden.</p> <p><u>Special provisions</u> 3, B14, T50, TP19</p>
TDG Classification	UN1079	SULFUR DIOXIDE; OR SULPHUR DIOXIDE	2.3	Not applicable (gas).	 	<p><u>Explosive Limit and Limited Quantity Index</u> 0</p> <p><u>ERAP Index</u> 500</p> <p><u>Passenger Carrying Ship Index</u> Forbidden</p> <p><u>Passenger Carrying Road or Rail Index</u> Forbidden</p>
Mexico Classification	UN1079	SULFUR DIOXIDE	2.3	Not applicable (gas).	 	-

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Sulfur Dioxide

Section 15. Regulatory information

United States

U.S. Federal regulations : **United States Inventory (TSCA 8b)**: This material is listed or exempted.
SARA 302/304/311/312 extremely hazardous substances: sulphur dioxide
SARA 302/304 emergency planning and notification: sulphur dioxide
SARA 302/304/311/312 hazardous chemicals: sulphur dioxide
SARA 311/312 MSDS distribution - chemical inventory - hazard identification:
sulphur dioxide: Sudden release of pressure, Immediate (acute) health hazard, Delayed (chronic) health hazard
Clean Water Act (CWA) 307: No products were found.
Clean Water Act (CWA) 311: No products were found.

State regulations

Clean Air Act (CAA) 112 regulated flammable substances: No products were found.
Clean Air Act (CAA) 112 regulated toxic substances: sulphur dioxide
Connecticut Carcinogen Reporting: This material is not listed.
Connecticut Hazardous Material Survey: This material is not listed.
Florida substances: This material is not listed.
Illinois Chemical Safety Act: This material is not listed.
Illinois Toxic Substances Disclosure to Employee Act: This material is not listed.
Louisiana Reporting: This material is not listed.
Louisiana Spill: This material is not listed.
Massachusetts Spill: This material is not listed.
Massachusetts Substances: This material is listed.
Michigan Critical Material: This material is not listed.
Minnesota Hazardous Substances: This material is not listed.
New Jersey Hazardous Substances: This material is listed.
New Jersey Spill: This material is not listed.
New Jersey Toxic Catastrophe Prevention Act: This material is listed.
New York Acutely Hazardous Substances: This material is listed.
New York Toxic Chemical Release Reporting: This material is not listed.
Pennsylvania RTK Hazardous Substances: This material is listed.
Rhode Island Hazardous Substances: This material is not listed.

Canada

WHMIS (Canada)

: **Class A**: Compressed gas.
Class D-1A: Material causing immediate and serious toxic effects (Very toxic).
Class E: Corrosive material
CEPA Toxic substances: This material is listed.
Canadian ARET: This material is not listed.
Canadian NPRI: This material is listed.
Alberta Designated Substances: This material is not listed.
Ontario Designated Substances: This material is not listed.
Quebec Designated Substances: This material is not listed.

Section 16. Other information

United States

Label requirements

: **CAUSES SEVERE RESPIRATORY TRACT, EYE AND SKIN BURNS.**
MAY CAUSE TARGET ORGAN DAMAGE, BASED ON ANIMAL DATA.
CONTENTS UNDER PRESSURE.

Canada

Label requirements

: **Class A**: Compressed gas.
Class D-1A: Material causing immediate and serious toxic effects (Very toxic).
Class E: Corrosive material

Sulfur Dioxide

Hazardous Material
Information System (U.S.A.)

Health	3
Flammability	0
Physical hazards	0

National Fire Protection
Association (U.S.A.)



Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.

Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.