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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2nd Semester 1434 - 35 H
2013-14 G
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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 have 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.
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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](image-url)
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]**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage of weight</th>
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<tr>
<td>Natural rubber</td>
<td>14 %</td>
</tr>
<tr>
<td>Synthetic rubber</td>
<td>27%</td>
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<tr>
<td>Carbon black</td>
<td>28%</td>
</tr>
<tr>
<td>Steel</td>
<td>14 - 15%</td>
</tr>
<tr>
<td>Fabric, fillers, accelerators, antiozonants, etc.</td>
<td>16 - 17%</td>
</tr>
<tr>
<td>Average weight</td>
<td>New 25 lbs, Scrap 20 lbs.</td>
</tr>
</tbody>
</table>

**Table 1.2 Truck Tire Components [6]**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage of weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural rubber</td>
<td>27 %</td>
</tr>
<tr>
<td>Synthetic rubber</td>
<td>14%</td>
</tr>
<tr>
<td>Carbon black</td>
<td>28%</td>
</tr>
<tr>
<td>Steel</td>
<td>14 - 15%</td>
</tr>
<tr>
<td>Fabric, fillers, accelerators, antiozonants, etc.</td>
<td>16 - 17%</td>
</tr>
<tr>
<td>Average weight</td>
<td>New 120 lbs., Scrap 100 lbs.</td>
</tr>
</tbody>
</table>
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.

Table 1.3 Share of World Tire Production by Geographic Region [7]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia and Oceania</td>
<td>7,365</td>
<td>97</td>
<td>8,673</td>
<td>118</td>
<td>8,899</td>
<td>103</td>
<td>9,269</td>
<td>104</td>
<td>63</td>
</tr>
<tr>
<td>(China)</td>
<td>(4,090)</td>
<td>(107)</td>
<td>(4,849)</td>
<td>(119)</td>
<td>(4,961)</td>
<td>(102)</td>
<td>(5,261)</td>
<td>(106)</td>
<td>(36)</td>
</tr>
<tr>
<td>(Japan)</td>
<td>(998)</td>
<td>(73)</td>
<td>(1,208)</td>
<td>(121)</td>
<td>(1,225)</td>
<td>(101)</td>
<td>(1,160)</td>
<td>(95)</td>
<td>(8)</td>
</tr>
<tr>
<td>(Korea)</td>
<td>(457)</td>
<td>(88)</td>
<td>(588)</td>
<td>(129)</td>
<td>(614)</td>
<td>(104)</td>
<td>(633)</td>
<td>(103)</td>
<td>(4)</td>
</tr>
<tr>
<td>Europe</td>
<td>2,310</td>
<td>82</td>
<td>2,586</td>
<td>112</td>
<td>2,794</td>
<td>108</td>
<td>2,653</td>
<td>95</td>
<td>18</td>
</tr>
<tr>
<td>North America</td>
<td>1,398</td>
<td>82</td>
<td>1,871</td>
<td>120</td>
<td>1,732</td>
<td>104</td>
<td>1,653</td>
<td>95</td>
<td>11</td>
</tr>
<tr>
<td>South &amp; Central America</td>
<td>761</td>
<td>86</td>
<td>890</td>
<td>117</td>
<td>905</td>
<td>102</td>
<td>905</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td>Middle East and Africa</td>
<td>202</td>
<td>82</td>
<td>201</td>
<td>100</td>
<td>224</td>
<td>111</td>
<td>231</td>
<td>103</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>12,036</td>
<td>91</td>
<td>14,021</td>
<td>117</td>
<td>14,554</td>
<td>104</td>
<td>14,711</td>
<td>101</td>
<td>100</td>
</tr>
</tbody>
</table>

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 ×10⁶) 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 mosquitoes 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]**

<table>
<thead>
<tr>
<th>Composition</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td>Natural rubber, Synthetic rubber</td>
</tr>
<tr>
<td>Compounding ingredients</td>
<td>Vulcanizing agent, Vulcanizing accelerator,</td>
</tr>
<tr>
<td></td>
<td>Vulcanizing accelerator aid, Antioxidant, Filler, Softener</td>
</tr>
<tr>
<td>Reinforcing agent</td>
<td>Carbon black, Silica</td>
</tr>
<tr>
<td>Tire cord</td>
<td>Steel cord, Textile cord</td>
</tr>
</tbody>
</table>
Table 2.2 Material Composition of Tire [10]

<table>
<thead>
<tr>
<th>Material</th>
<th>Avg. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td>46 %</td>
</tr>
<tr>
<td>Carbon black</td>
<td>22 %</td>
</tr>
<tr>
<td>Metal</td>
<td>20.75%</td>
</tr>
<tr>
<td>Textile</td>
<td>5.5 %</td>
</tr>
<tr>
<td>Zinc oxide</td>
<td>1.5 %</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1 %</td>
</tr>
<tr>
<td>Additives</td>
<td>6.25 %</td>
</tr>
</tbody>
</table>

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]

<table>
<thead>
<tr>
<th>Tire Type</th>
<th>Synthetic Rubber</th>
<th>Natural Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger tire</td>
<td>55%</td>
<td>45%</td>
</tr>
<tr>
<td>Light Truck Tire</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Race Tire</td>
<td>65%</td>
<td>35%</td>
</tr>
<tr>
<td>Off Road Tire</td>
<td>20%</td>
<td>80%</td>
</tr>
</tbody>
</table>
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:

\[
\begin{align*}
\text{CH}_2 & \text{C} = \text{C} \text{CH}_2 \text{H} \\
\text{H}_3 & \text{C} \text{H}
\end{align*}
\]

**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 4x10^6. 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 kept below 0°C, rubber gets 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, \(\text{NaOH}\). 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 $5 \times 10^4$ to $5.8 \times 10^6$. The average values of molecular weight of synthetic rubber $2 \times 10^6$ [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 casting 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**

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Heating Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating oil</td>
<td>42 MJ/Kg</td>
</tr>
<tr>
<td>Natural gas</td>
<td>38 MJ/m3</td>
</tr>
<tr>
<td>Coal</td>
<td>25 MJ/Kg</td>
</tr>
<tr>
<td>Wood biomass</td>
<td>20 MJ/Kg</td>
</tr>
<tr>
<td>Tires</td>
<td>36 MJ/Kg</td>
</tr>
<tr>
<td>Mixed Plastic waste</td>
<td>43 MJ/Kg</td>
</tr>
</tbody>
</table>

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 mosquitoes 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 embrittke 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 enters 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]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ambient</th>
<th>Cryogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>Max. 120 °C</td>
<td>Below – 80 °C</td>
</tr>
<tr>
<td>Size Reduction Principle</td>
<td>cutting, tearing, shearing</td>
<td>Braking cryogenically embrittled rubber pieces</td>
</tr>
<tr>
<td>Particle Morphology</td>
<td>spongy and rough, high specific surface</td>
<td>even and smooth, low specific surface</td>
</tr>
<tr>
<td>Particle Size Distribution</td>
<td>relatively narrow particle size distribution, only limited size reduction per grinding step</td>
<td>wide particle size distribution (ranging 10 mm to 0.2 mm) in just one processing step</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Electricity Consumption</td>
<td>Higher</td>
<td>Lower</td>
</tr>
<tr>
<td>Liquid N₂ Consumption</td>
<td>N/A</td>
<td>0.5 – 1.0 kg liquid N₂ per kg tire input</td>
</tr>
</tbody>
</table>

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]**

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Ambient Ground</th>
<th>Cryogenic Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Particle shape</td>
<td>Irregular</td>
<td>Regular</td>
</tr>
<tr>
<td>Fibre content</td>
<td>0.5%</td>
<td>Nil</td>
</tr>
<tr>
<td>Steel content</td>
<td>0.1%</td>
<td>Nil</td>
</tr>
<tr>
<td>Cost</td>
<td>Comparable</td>
<td>Comparable</td>
</tr>
</tbody>
</table>
Table 3.3 Comparison of Environmental Effect of Ambient and Cryogenic Processes [39]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ambient</th>
<th>Cryogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse Effect</td>
<td>122 kg Co2 / t tire</td>
<td>455 kg Co2 / t tire</td>
</tr>
<tr>
<td>Solid Waste Indicator’95</td>
<td>-1196 kg solid waste / t tire</td>
<td>-724 kg solid waste / t tire</td>
</tr>
<tr>
<td>ECO-Point</td>
<td>0.278 ECO-point / t PFU</td>
<td>42.543 ECO-point / t PFU</td>
</tr>
</tbody>
</table>

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. 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. 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
<th>Mass Fraction (x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td>R</td>
<td>0.51</td>
</tr>
<tr>
<td>Steel</td>
<td>S</td>
<td>0.15</td>
</tr>
<tr>
<td>Fabric</td>
<td>F</td>
<td>0.03</td>
</tr>
<tr>
<td>Reinforcing Agent</td>
<td>A</td>
<td>0.25</td>
</tr>
<tr>
<td>Compounding ingredients</td>
<td>I</td>
<td>0.06</td>
</tr>
</tbody>
</table>

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].

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]

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

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 200-350°C [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]

<table>
<thead>
<tr>
<th>Author</th>
<th>Temperature (°C)</th>
<th>Pressure (kPa)</th>
<th>Sample sizes</th>
<th>Solid (wt.%)</th>
<th>Liquid (wt.%)</th>
<th>Gas (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berrueco et al</td>
<td>400-700</td>
<td>101</td>
<td>20 mm</td>
<td>47-63</td>
<td>30-43</td>
<td>2.4-4.4</td>
</tr>
<tr>
<td>Loresgoiti et al</td>
<td>400-700</td>
<td>101</td>
<td>20-30 mm</td>
<td>43-53</td>
<td>28-40</td>
<td>7-9</td>
</tr>
<tr>
<td>Roy et al</td>
<td>25-500</td>
<td>0.8-28</td>
<td>-</td>
<td>35-36</td>
<td>62</td>
<td>1-3</td>
</tr>
<tr>
<td>Barbooti et al</td>
<td>420-450</td>
<td>101</td>
<td>2-20 mm</td>
<td>31.5-51</td>
<td>36-62</td>
<td>7.3-16.8</td>
</tr>
<tr>
<td>M. Rofiqul Islam et al</td>
<td>375-575</td>
<td>101</td>
<td>2-8 cm³</td>
<td>38-48.5</td>
<td>43-51</td>
<td>7.5-19</td>
</tr>
</tbody>
</table>

Pyrolytic char may be used as a solid fuel or as a precursor 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>
<thead>
<tr>
<th>Temperature</th>
<th>475°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow of Nitrogen</td>
<td>4.515 Kg/min</td>
</tr>
<tr>
<td>Size of scrap tire particles</td>
<td>4 cm3</td>
</tr>
<tr>
<td>Feed</td>
<td>3027.5 Kg/h</td>
</tr>
<tr>
<td>Process time</td>
<td>1 h</td>
</tr>
</tbody>
</table>

These factors are taken from an experiment by M. Rofiqul 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>
<thead>
<tr>
<th>Product</th>
<th>Percentage %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid char</td>
<td>40.5</td>
</tr>
<tr>
<td>Liquid</td>
<td>51</td>
</tr>
<tr>
<td>Gas</td>
<td>8.5</td>
</tr>
</tbody>
</table>

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 m$^3$ 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 N$_2$ 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 N$_2$ 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 cm$^3$ 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 475°C, 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](image)

**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**

<table>
<thead>
<tr>
<th>Group</th>
<th>Component</th>
<th>Boiling Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Styrene</td>
<td>145.16</td>
</tr>
<tr>
<td></td>
<td>Ethyl Benzene</td>
<td>136.2</td>
</tr>
<tr>
<td></td>
<td>Toluene</td>
<td>110.63</td>
</tr>
<tr>
<td>B</td>
<td>Benzene</td>
<td>80.09</td>
</tr>
<tr>
<td></td>
<td>Hexene</td>
<td>63.48</td>
</tr>
<tr>
<td></td>
<td>Hexane</td>
<td>68.73</td>
</tr>
<tr>
<td></td>
<td>Cyclopentane</td>
<td>54.3</td>
</tr>
</tbody>
</table>

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.
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 cm³. The optimum temperature for high yield of liquid is at 475 °C [49].

![Temperature VS Wt %](image)

**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 cm³ [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 × 24 × 300 × 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 → 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**

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td>R</td>
</tr>
<tr>
<td>Steel</td>
<td>S</td>
</tr>
<tr>
<td>Fabric</td>
<td>F</td>
</tr>
<tr>
<td>Reinforcing Agent</td>
<td>A</td>
</tr>
<tr>
<td>Compounding ingredients</td>
<td>I</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Stream No.</th>
<th>R</th>
<th>S</th>
<th>F</th>
<th>A</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.55</td>
<td>0.75</td>
<td>0.15</td>
<td>1.25</td>
<td>0.3</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.675</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>1.785</td>
<td>0.0525</td>
<td>0.105</td>
<td>0.875</td>
<td>0.21</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0.03825</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0.0224775</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>0</td>
<td>0.006705</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>0.765</td>
<td>0.0000225</td>
<td>0.000045</td>
<td>0.375</td>
<td>0.09</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Stream No.</th>
<th>R</th>
<th>S</th>
<th>F</th>
<th>A</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.51</td>
<td>0.15</td>
<td>0.03</td>
<td>0.25</td>
<td>0.06</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0.5896</td>
<td>0.0173</td>
<td>0.0347</td>
<td>0.2890</td>
<td>0.0694</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>0.6219</td>
<td>0.02 ×10⁻³</td>
<td>0.04 ×10⁻³</td>
<td>0.3049</td>
<td>0.0732</td>
</tr>
</tbody>
</table>

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 because 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:

\[ M_w(average) = \sum y_i \times M_w_i \] (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
- \( \text{Cp}_i \) (kJ/kg-K) 1.1006
- \( \text{Cp}_o \) (kJ/kg-K) 1.5180

Inlet flow gases described in Table 5.4

**Table 5.4 Inlet Gases to the Burner**

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow rate (Kg/h)</th>
<th>Mass fraction</th>
<th>LHV (KJ/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>16.78</td>
<td>0.065</td>
<td>10112</td>
</tr>
<tr>
<td>( \text{CO}_2 )</td>
<td>32.1</td>
<td>0.125</td>
<td>---</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>94.02</td>
<td>0.365</td>
<td>50000</td>
</tr>
<tr>
<td>C(_2)H(_4)</td>
<td>31.33</td>
<td>0.122</td>
<td>47195</td>
</tr>
<tr>
<td>H(_2)</td>
<td>15.43</td>
<td>0.06</td>
<td>120000</td>
</tr>
<tr>
<td>C(_3)H(_6)</td>
<td>54.8</td>
<td>0.212</td>
<td>45800</td>
</tr>
<tr>
<td>H(_2)S</td>
<td>13.3</td>
<td>0.052</td>
<td>15191</td>
</tr>
</tbody>
</table>

The reactions are:
\[
2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} \\
2\text{H}_2\text{S} + 3\text{O}_2 \rightarrow 2\text{SO}_2 + 2\text{H}_2\text{O} \\
2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2 \\
\text{C}_3\text{H}_6 + \frac{9}{2}\text{O}_2 \rightarrow 3\text{CO}_2 + 3\text{H}_2\text{O} \\
\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \\
\text{C}_2\text{H}_4 + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O}
\]
The total heating value = $4.23 \times 10^4$ KJ/Kg

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

= $9.55 \times 10^6$ KJ/h

Outlet flow gases described in Table 5.5.

**Table 5.5 Outlet Gases from the Burner**

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow rate (Kg/h)</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>587</td>
<td>0.96</td>
</tr>
<tr>
<td>SO₂</td>
<td>25</td>
<td>0.04</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Stream</th>
<th>Flow rate (Kg/hr)</th>
<th>Crumb rubber</th>
<th>Char</th>
<th>Pyrolytic oil</th>
<th>Gas</th>
<th>O₂</th>
<th>N₂</th>
<th>CO₂</th>
<th>SO₂</th>
<th>H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>3027.5</td>
<td>3027.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>3027.5</td>
<td>3027.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>2619000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>549990</td>
<td>2069010</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>22</td>
<td>2619000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>549990</td>
<td>2069010</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>22.575 Kg/5 min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>22.575Kg/5 min</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>24</td>
<td>22.575 Kg/5 min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>22.575Kg/5 min</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>1226.137</td>
<td>0</td>
<td>1226.137</td>
<td>0</td>
<td>0</td>
<td>549990</td>
<td>2069010</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>26</td>
<td>1226.137</td>
<td>0</td>
<td>1226.137</td>
<td>0</td>
<td>0</td>
<td>549990</td>
<td>2069010</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>1801.3625</td>
<td>0</td>
<td>0</td>
<td>1544.025</td>
<td>257.337</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>28</td>
<td>1801.3625</td>
<td>0</td>
<td>0</td>
<td>1544.025</td>
<td>257.337</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>29</td>
<td>1801.3625</td>
<td>0</td>
<td>0</td>
<td>1544.025</td>
<td>257.337</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>1801.3625</td>
<td>0</td>
<td>0</td>
<td>1544.025</td>
<td>257.337</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>31</td>
<td>1801.3625</td>
<td>0</td>
<td>0</td>
<td>1544.025</td>
<td>257.337</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>32</td>
<td>1801.3625</td>
<td>0</td>
<td>0</td>
<td>1544.025</td>
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<td>0</td>
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</tr>
<tr>
<td>Stream</td>
<td>Flow rate (Kg/hr)</td>
<td>Crumb rubber</td>
<td>Char</td>
<td>Pyrolytic oil</td>
<td>Gas</td>
<td>O₂</td>
<td>N₂</td>
<td>CO₂</td>
<td>SO₂</td>
<td>H₂O</td>
</tr>
<tr>
<td>--------</td>
<td>------------------</td>
<td>--------------</td>
<td>------</td>
<td>---------------</td>
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</tr>
<tr>
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<td>929.7158</td>
<td>0</td>
<td>0</td>
<td>672.3788</td>
<td>257.337</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
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<td>672.3788</td>
<td>257.337</td>
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<td>123.02</td>
<td>3100.03</td>
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<td>123.02</td>
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<td>466.86</td>
</tr>
<tr>
<td>48</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>123.02</td>
<td>3100.03</td>
<td>586.98</td>
<td>25</td>
<td>466.86</td>
</tr>
<tr>
<td>49</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>22.575Kg/5min</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>22.575Kg/5min</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>51</td>
<td>3122.605</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>123.02</td>
<td>3122.605</td>
<td>586.98</td>
<td>25</td>
<td>466.86</td>
</tr>
</tbody>
</table>
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].

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

(2)

Where,

$W =$ actual work input (KWhr/ton)

$W_i =$ Bond Work index (KWhr/ton)

$D_p =$ Product diameter in ($\mu$m), 80% passing.

$D_F =$ Feed diameter in ($\mu$m), 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

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

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
\[ Wi = 3898 \text{ KWhr/ton} \]

Cracker mill work index calculations:

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

\[ Wi = 844 \text{ KWhr/ton} \]

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

**Shredder machine work calculations:**

\[ W = 10 (3244 \times 5) \times \left( \frac{1}{\sqrt[6]{1 \times 10^4}} - \frac{1}{\sqrt[1.59]{1 \times 10^4}} \right) = 499.98 \text{ KW} \]

**Granulator machine work calculations:**

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

**Cracker mill work calculations:**

\[ W = 10 (844 \times 5) \times \left( \frac{1}{\sqrt[1.59]{1 \times 10^4}} - \frac{1}{\sqrt[6]{1 \times 10^4}} \right) = 999.81 \text{ KW} \]

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:

\[ H_i = \int_{T_{ref}}^{T} C_p \, dt \]  

(3)

For phase change:

\[ H_i = \int_{T_{ref}}^{TB} C_{p_{ig}} \, dt + \Delta H_v + \int_{TB}^{T} C_{p_{il}} \, dt \]  

(4)

Table 5.7 shows a summary of Streams results:
**Table 5.7** Summary of Enthalpies in all Streams

<table>
<thead>
<tr>
<th>Stream</th>
<th>T (C)</th>
<th>P (atm)</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>25</td>
<td>1</td>
<td>Solid</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
<td>1</td>
<td>Solid</td>
</tr>
<tr>
<td>21</td>
<td>25</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
<td>22</td>
<td>545.3</td>
<td>15</td>
<td>Gas</td>
</tr>
<tr>
<td>23</td>
<td>25</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
<td>24</td>
<td>114.85</td>
<td>2</td>
<td>Gas</td>
</tr>
<tr>
<td>25</td>
<td>475</td>
<td>1</td>
<td>Solid</td>
</tr>
<tr>
<td>26</td>
<td>475</td>
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<td>Solid</td>
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<tr>
<td>27</td>
<td>475</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
<td>28</td>
<td>475</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
<td>29</td>
<td>475</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
<td>30</td>
<td>513.3</td>
<td>2</td>
<td>Gas</td>
</tr>
<tr>
<td>31</td>
<td>270</td>
<td>1.985</td>
<td>Gas</td>
</tr>
<tr>
<td>32</td>
<td>175</td>
<td>1.98</td>
<td>Gas</td>
</tr>
<tr>
<td>33</td>
<td>120</td>
<td>1.79</td>
<td>Gas+liquid</td>
</tr>
<tr>
<td>34</td>
<td>120</td>
<td>1.79</td>
<td>Liquid</td>
</tr>
<tr>
<td>35</td>
<td>120</td>
<td>1.79</td>
<td>Liquid</td>
</tr>
<tr>
<td>36</td>
<td>120</td>
<td>1.79</td>
<td>Liquid</td>
</tr>
<tr>
<td>37</td>
<td>120</td>
<td>1.79</td>
<td>Gas</td>
</tr>
<tr>
<td>38</td>
<td>50</td>
<td>1.789</td>
<td>Gas+liquid</td>
</tr>
<tr>
<td>39</td>
<td>50</td>
<td>1.789</td>
<td>Liquid</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
<td>1.789</td>
<td>Liquid</td>
</tr>
<tr>
<td>41</td>
<td>50</td>
<td>1.789</td>
<td>Liquid</td>
</tr>
<tr>
<td>42</td>
<td>50</td>
<td>1.789</td>
<td>Gas</td>
</tr>
<tr>
<td>43</td>
<td>50</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
<td>44</td>
<td>93</td>
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<td>115.1</td>
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<td>Gas</td>
</tr>
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<td>46</td>
<td>1956.13</td>
<td>2</td>
<td>Gas</td>
</tr>
<tr>
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<td>534.87</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
<td>48</td>
<td>534.87</td>
<td>2</td>
<td>Gas</td>
</tr>
<tr>
<td>49</td>
<td>-----</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
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<td>-----</td>
<td>1</td>
<td>Gas</td>
</tr>
<tr>
<td>51</td>
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<td>1</td>
<td>Gas</td>
</tr>
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</table>
Table 5.8 Summary of Heat loads in all Units

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

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)

![Flow Diagram for Cooler (E-201).](image)

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)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Load (Q)</td>
<td>307243.5 J/s</td>
</tr>
<tr>
<td>Cooling water flow required</td>
<td>17612.54 kg/h</td>
</tr>
<tr>
<td>Overall heat transfer coefficient (U) assumed</td>
<td>250 W/m².°C</td>
</tr>
<tr>
<td>Required Area for Heat transfer</td>
<td>3.545 m²</td>
</tr>
<tr>
<td>Heat transfer coefficients for tube side (hi)</td>
<td>681.237 W/m².°C</td>
</tr>
<tr>
<td>Heat transfer coefficients for shell side (ho)</td>
<td>728.55 W/m².°C</td>
</tr>
<tr>
<td>Overall heat transfer coefficient (U) calculated</td>
<td>279.85 W/m².°C</td>
</tr>
<tr>
<td>Pressure drop for tube side ΔPt</td>
<td>15.078 KPa</td>
</tr>
<tr>
<td>Pressure drop for shell side ΔPs</td>
<td>71.412 KPa</td>
</tr>
</tbody>
</table>
6.1.2 Design of Cooler (E-202)

![Flow Diagram for Cooler (E-202).](image)

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)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Load (Q)</td>
<td>97981.14 J/s</td>
</tr>
<tr>
<td>Overall heat transfer coefficient (U) assumed</td>
<td>100 W/m².°C</td>
</tr>
<tr>
<td>Cooling water flow required</td>
<td>5616.708 kg/h</td>
</tr>
<tr>
<td>Required Area for Heat transfer</td>
<td>5.235 m²</td>
</tr>
<tr>
<td>Heat transfer coefficients for tube side (hi)</td>
<td>399.55 W/m².°C</td>
</tr>
<tr>
<td>Heat transfer coefficients for shell side (ho)</td>
<td>224.411 W/m².°C</td>
</tr>
<tr>
<td>Overall heat transfer coefficient (U) calculated</td>
<td>126.76 W/m².°C</td>
</tr>
<tr>
<td>Pressure drop for tube side ΔPt</td>
<td>5.16 KPa</td>
</tr>
<tr>
<td>Pressure drop for shell side ΔPs</td>
<td>5.125 KPa</td>
</tr>
</tbody>
</table>
6.1.3 Design of Condenser (E-203)

![Figure 6.3 Flow Diagram for Condenser (E-203).](image)

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)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Load (Q)</td>
<td>132228.6936 J/s</td>
</tr>
<tr>
<td>Overall heat transfer coefficient ( U ) assumed</td>
<td>150 W/m².°C</td>
</tr>
<tr>
<td>Cooling water flow required</td>
<td>7579.92 kg/h</td>
</tr>
<tr>
<td>Required Area for Heat transfer</td>
<td>7.56 m²</td>
</tr>
<tr>
<td>Heat transfer coefficients for non-condensable mixture</td>
<td>92.69 W/m².°C</td>
</tr>
<tr>
<td>Heat transfer coefficients for condensable mixture</td>
<td>3743.9 W/m².°C</td>
</tr>
<tr>
<td>Heat transfer coefficients for tube side ( hi )</td>
<td>9591.93 W/m².°C</td>
</tr>
<tr>
<td>Heat transfer coefficients for shell side ( ho)</td>
<td>185.813 W/m².°C</td>
</tr>
<tr>
<td>Overall heat transfer coefficient ( U ) calculated</td>
<td>167.81 W/m².°C</td>
</tr>
<tr>
<td>Pressure drop for tube side ΔPt</td>
<td>1.185 KPa</td>
</tr>
<tr>
<td>Pressure drop for shell side ΔPs</td>
<td>4.3 KPa</td>
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</table>
6.1.4 Design of 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).

![Figure 6.4 Flow Diagram for Condenser (E-204).](image)

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

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Load (Q)</td>
<td>106072.13 J/s</td>
</tr>
<tr>
<td>Overall heat transfer coefficient (U) assumed</td>
<td>500 W/m².°C</td>
</tr>
<tr>
<td>Cooling water flow required</td>
<td>6080.52 kg/h</td>
</tr>
<tr>
<td>Required Area for Heat transfer</td>
<td>4.33 m²</td>
</tr>
<tr>
<td>Heat transfer coefficients for non-condensable mixture</td>
<td>194.74 W/m².°C</td>
</tr>
<tr>
<td>Heat transfer coefficients for condensable mixture</td>
<td>7591 W/m².°C</td>
</tr>
<tr>
<td>Heat transfer coefficients for tube side (hi)</td>
<td>7785.73 W/m².°C</td>
</tr>
<tr>
<td>Heat transfer coefficients for shell side (ho)</td>
<td>746.42 W/m².°C</td>
</tr>
<tr>
<td>Overall heat transfer coefficient (U) calculated</td>
<td>513.922 W/m².°C</td>
</tr>
<tr>
<td>Pressure drop for tube side ΔPt</td>
<td>1.31 KPa</td>
</tr>
<tr>
<td>Pressure drop for shell side ΔPs</td>
<td>65.5 KPa</td>
</tr>
</tbody>
</table>
6.1.5 Design of 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)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sectional area (A)</td>
<td>0.6452 m²</td>
</tr>
<tr>
<td>Diameter of the flash (D)</td>
<td>0.907 m</td>
</tr>
<tr>
<td>Liquid level height (L_L)</td>
<td>0.1497 m</td>
</tr>
<tr>
<td>The total height (L)</td>
<td>1.967 m</td>
</tr>
<tr>
<td>The shell thickness</td>
<td>4.77 mm</td>
</tr>
<tr>
<td>The head thickness</td>
<td>4.77 mm</td>
</tr>
<tr>
<td>Total Volume</td>
<td>1.66 m³</td>
</tr>
</tbody>
</table>
6.1.6 Design of 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)**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sectional area (A)</td>
<td>0.275 m²</td>
</tr>
<tr>
<td>Diameter of the flash (D)</td>
<td>0.5915 m</td>
</tr>
<tr>
<td>Liquid level height (Lₗ)</td>
<td>0.3011 m</td>
</tr>
<tr>
<td>The total height (L)</td>
<td>1.646 m</td>
</tr>
<tr>
<td>The shell thickness</td>
<td>4.77 mm</td>
</tr>
<tr>
<td>The head thickness</td>
<td>4.77 mm</td>
</tr>
<tr>
<td>Total Volume</td>
<td>0.561 m³</td>
</tr>
</tbody>
</table>
6.2 Equipment Sizing

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

![Flow Diagram for Compressors](image)

**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)

<table>
<thead>
<tr>
<th></th>
<th>C-201</th>
<th>C-202</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compressed Flow</td>
<td>Compressed Flow</td>
</tr>
<tr>
<td></td>
<td>0.7 mol/s</td>
<td>50 mol/s</td>
</tr>
<tr>
<td></td>
<td>[W_{\text{theoretical}} ]</td>
<td>[W_{\text{theoretical}} ]</td>
</tr>
<tr>
<td></td>
<td>1.32 KW</td>
<td>633.2 KW</td>
</tr>
<tr>
<td></td>
<td>Outlet Pressure</td>
<td>Outlet Pressure</td>
</tr>
<tr>
<td></td>
<td>2 bar</td>
<td>15 bar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>C-203</th>
<th>C-204</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compressed Flow</td>
<td>Compressed Flow</td>
</tr>
<tr>
<td></td>
<td>9.67 mol/s</td>
<td>4.91 mol/s</td>
</tr>
<tr>
<td></td>
<td>[W_{\text{theoretical}} ]</td>
<td>[W_{\text{theoretical}} ]</td>
</tr>
<tr>
<td></td>
<td>42.5 KW</td>
<td>9.9 KW</td>
</tr>
<tr>
<td></td>
<td>Outlet Pressure</td>
<td>Outlet Pressure</td>
</tr>
<tr>
<td></td>
<td>2 bar</td>
<td>2 bar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>C-205</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compressed Flow</td>
</tr>
<tr>
<td></td>
<td>4.91 mol/s</td>
</tr>
<tr>
<td></td>
<td>[W_{\text{theoretical}} ]</td>
</tr>
<tr>
<td></td>
<td>73.9 KW</td>
</tr>
<tr>
<td></td>
<td>Outlet Pressure</td>
</tr>
<tr>
<td></td>
<td>2 bar</td>
</tr>
</tbody>
</table>
6.2.2 Burner sizing (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)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas flow rate</td>
<td>225.76 Kg/h</td>
</tr>
<tr>
<td>The Air flow rate</td>
<td>4044 Kg/h</td>
</tr>
<tr>
<td>Total heating value</td>
<td>$4.23 \times 10^4$ KJ/Kg</td>
</tr>
<tr>
<td>Total heat generated by combustion</td>
<td>$9.55 \times 10^6$ KJ/h</td>
</tr>
<tr>
<td>The temperature for the outlet gas</td>
<td>1940 °C</td>
</tr>
</tbody>
</table>

**Figure 6.8** Flow Diagram for Burner (H-201).
6.2.3 Decomposition Unit Sizing (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 Summery of Sizing Specifications for the Decomposition Unit (DU-201 & 202)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow of crumb rubber per batch</td>
<td>3027.5 Kg</td>
</tr>
<tr>
<td>Volume needed for the crumb rubber</td>
<td>7.8 m³</td>
</tr>
<tr>
<td>Number of pipes</td>
<td>8 pipes</td>
</tr>
<tr>
<td>Volume of pipes</td>
<td>0.0175 m³</td>
</tr>
<tr>
<td>Total volume of Decomposition unit</td>
<td>13 m³</td>
</tr>
</tbody>
</table>
6.2.4 Storage Tanks Sizing

6.2.4.1 Gas Storage Tank Sizing (TK-201)

![Flow Diagram for Gas Storage (TK-201).](image)

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>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>257.9 Kg/h</td>
</tr>
<tr>
<td>Maximum Storage Time</td>
<td>2 Hours</td>
</tr>
<tr>
<td>Volume required</td>
<td>500 m³</td>
</tr>
</tbody>
</table>

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

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

![Flow Diagram for Liquid Storage (TK 203 --- 206).](image)

**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)

<table>
<thead>
<tr>
<th>Storage Tanks (TK-203 and 204)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>874.75 Kg/h</td>
</tr>
<tr>
<td>Maximum Storage Time</td>
<td>4 days</td>
</tr>
<tr>
<td>Volume required</td>
<td>120 m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Storage Tanks (TK-205 and 206)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>671.8 Kg/h</td>
</tr>
<tr>
<td>Maximum Storage Time</td>
<td>4 days</td>
</tr>
<tr>
<td>Volume required</td>
<td>120 m³</td>
</tr>
</tbody>
</table>
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.](image-url)
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.

![Diagram of process control inputs and outputs](image-url)

**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**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td>Level Control</td>
</tr>
<tr>
<td>TC</td>
<td>Temperature Control</td>
</tr>
<tr>
<td>FC</td>
<td>Flow Control</td>
</tr>
<tr>
<td>TT</td>
<td>Temperature Transmitter</td>
</tr>
<tr>
<td>AC</td>
<td>Analyzer Control</td>
</tr>
<tr>
<td>PC</td>
<td>Pressure Control</td>
</tr>
<tr>
<td>PT</td>
<td>Pressure Transmitter</td>
</tr>
</tbody>
</table>
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.

![Diagram](image)

**Figure 7.3** Control Loop of Heat Exchanger (E-201).
### Table 7.2 Control Specifications of Heat Exchanger (E-201)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Heat exchanger (E-201)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Strategy Selected</td>
<td>Backward Control (Temperature)</td>
</tr>
<tr>
<td>Controlled Variables</td>
<td>Temperature of hot fluid</td>
</tr>
<tr>
<td>Measured variables</td>
<td>Temperature of hot fluid</td>
</tr>
<tr>
<td>Manipulated Variables</td>
<td>Flow of cooling water</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Flow of cooling water</td>
</tr>
<tr>
<td>Set-Points</td>
<td>270 °C</td>
</tr>
</tbody>
</table>

### 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).

![Control Loop of Heat Exchanger (E-202)](image)

**Figure 7.4** Control Loop of Heat Exchanger (E-202).
Table 7.3 Control Specification of Heat Exchanger (E-202)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Heat exchanger (E-202)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Strategy Selected</td>
<td>Backward Control (Temperature)</td>
</tr>
<tr>
<td>Controlled Variables</td>
<td>Temperature of hot fluid</td>
</tr>
<tr>
<td>Measured variables</td>
<td>Temperature of hot fluid</td>
</tr>
<tr>
<td>Manipulated Variables</td>
<td>Flow of cooling water</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Flow of cooling water</td>
</tr>
<tr>
<td>Set-Points</td>
<td>175 °C</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Condenser (E-203)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Strategy Selected</td>
<td>Backward Control (Temperature)</td>
</tr>
<tr>
<td>Controlled Variables</td>
<td>Temperature of hot fluid</td>
</tr>
<tr>
<td>Measured variables</td>
<td>Temperature of hot fluid</td>
</tr>
<tr>
<td>Manipulated Variables</td>
<td>Flow of cooling water</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Flow of cooling water</td>
</tr>
<tr>
<td>Set-Points</td>
<td>125 °C</td>
</tr>
</tbody>
</table>

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).

Figure 7.6 Control Loop of Heat Exchanger (E-204).
Table 7.5 Control Specification of Heat Exchanger (E-204)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Condenser (E-204)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Strategy Selected</td>
<td>Backward Control (Temperature)</td>
</tr>
<tr>
<td>Controlled Variables</td>
<td>Temperature of hot fluid</td>
</tr>
<tr>
<td>Measured variables</td>
<td>Temperature of hot fluid</td>
</tr>
<tr>
<td>Manipulated Variables</td>
<td>Flow of cooling water</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Flow of cooling water</td>
</tr>
<tr>
<td>Set-Points</td>
<td>50 °C</td>
</tr>
</tbody>
</table>

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).

![Control Loop of Storage Tanks (TK-203) and (TK-204).](image)
Table 7.6 Control Specification of Storage Tank (TK-203) and (TK-204)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Tank TK-203 and TK-204</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Strategy Selected</td>
<td>Backward Control (Level)</td>
</tr>
<tr>
<td>Controlled Variables</td>
<td>Level</td>
</tr>
<tr>
<td>Measured variables</td>
<td>Level</td>
</tr>
<tr>
<td>Manipulated Variables</td>
<td>Input flow rate</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Input flow rate</td>
</tr>
<tr>
<td>Set-Points</td>
<td>3 m</td>
</tr>
</tbody>
</table>

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)**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Tank TK-205 and TK-206</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Strategy Selected</td>
<td>Backward Control (Level)</td>
</tr>
<tr>
<td>Controlled Variables</td>
<td>Level</td>
</tr>
<tr>
<td>Measured variables</td>
<td>Level</td>
</tr>
<tr>
<td>Manipulated Variables</td>
<td>Input flow rate</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Input flow rate</td>
</tr>
<tr>
<td>Set-Points</td>
<td>3 m</td>
</tr>
</tbody>
</table>

### 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 °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).
Figure 7.9 Control Loop of Decomposition Units (DU-201) and (DU-202).

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

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Decomposition Unit DU-201 and DU-202</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Strategy Selected</td>
<td>Backward Control (Pressure)</td>
</tr>
<tr>
<td></td>
<td>Backward Control (Temperature)</td>
</tr>
<tr>
<td></td>
<td>Backward Control (Concentration)</td>
</tr>
<tr>
<td>Controlled Variables</td>
<td>Pressure, Temperature and Concentration</td>
</tr>
<tr>
<td>Measured variables</td>
<td>Pressure, Temperature and Oxygen</td>
</tr>
<tr>
<td></td>
<td>concentration at purge stream</td>
</tr>
<tr>
<td>Manipulated Variables</td>
<td>Pressure valve</td>
</tr>
<tr>
<td></td>
<td>Nitrogen flow rate</td>
</tr>
<tr>
<td>Disturbances</td>
<td>Compressing Pressure</td>
</tr>
<tr>
<td></td>
<td>Burner Temperature</td>
</tr>
<tr>
<td></td>
<td>Temperature = 475 °C</td>
</tr>
<tr>
<td></td>
<td>Pressure = 1 atm</td>
</tr>
<tr>
<td></td>
<td>Concentration of O₂ = 0 % at purge stream.</td>
</tr>
</tbody>
</table>

94
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).

![Control Loop of Flash Drum](image)

**Figure 7.10** Control Loop of Flash Drum (V-201) and (V-202).

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

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Flash drum (V-201 &amp; V-202)</th>
</tr>
</thead>
</table>
| 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>
<thead>
<tr>
<th>Material Name</th>
<th>Price ($/kg)</th>
<th>Flow rate (kg/h)</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrap Tire</td>
<td>$ 0.04</td>
<td>5000.00</td>
<td>$ 1,664,400</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>$ 4.00</td>
<td>10.00</td>
<td>$ 332,880</td>
</tr>
<tr>
<td><strong>Total ( C_{RM} )</strong></td>
<td></td>
<td></td>
<td><strong>$ 1,997,280</strong></td>
</tr>
</tbody>
</table>

8.1.2 Cost of Equipment

The cost of equipment is summarized in Table 8.2.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Type</th>
<th>Equipment Attribute</th>
<th>MOC</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-201</td>
<td>Compressor</td>
<td>1.32 KW</td>
<td>Carbon Steel</td>
<td>$ 595,000</td>
</tr>
<tr>
<td>C-202</td>
<td>Compressor</td>
<td>633 KW</td>
<td>Carbon Steel</td>
<td>$ 781,000</td>
</tr>
<tr>
<td>C-203</td>
<td>Compressor</td>
<td>42.5 KW</td>
<td>Stainless Steel</td>
<td>$ 1,250,000</td>
</tr>
<tr>
<td>C-204</td>
<td>Compressor</td>
<td>9.9 KW</td>
<td>Stainless Steel</td>
<td>$ 1,250,000</td>
</tr>
<tr>
<td>C-205</td>
<td>Compressor</td>
<td>73.9 KW</td>
<td>Carbon Steel</td>
<td>$ 595,000</td>
</tr>
<tr>
<td>E-201</td>
<td>Heat Exchanger</td>
<td>3.55 m²</td>
<td>Cupro- Nickel</td>
<td>$ 40,600</td>
</tr>
<tr>
<td>E-202</td>
<td>Heat Exchanger</td>
<td>5.24 m²</td>
<td>Cupro- Nickel</td>
<td>$ 40,600</td>
</tr>
<tr>
<td>E-203</td>
<td>Heat Exchanger</td>
<td>7.56 m²</td>
<td>Cupro- Nickel</td>
<td>$ 40,600</td>
</tr>
<tr>
<td>E-204</td>
<td>Heat Exchanger</td>
<td>4.33 m²</td>
<td>Cupro- Nickel</td>
<td>$ 40,600</td>
</tr>
<tr>
<td>F-201</td>
<td>Burner</td>
<td>10900 MJ/h</td>
<td>Stainless Steel</td>
<td>$ 2,260,000</td>
</tr>
<tr>
<td>R-201</td>
<td>Decomposition unit</td>
<td>13 m³</td>
<td>Stainless Steel</td>
<td>$ 108,000</td>
</tr>
<tr>
<td>R-202</td>
<td>Decomposition unit</td>
<td>13 m³</td>
<td>Stainless Steel</td>
<td>$ 108,000</td>
</tr>
<tr>
<td>Tk-201</td>
<td>Storage Tank</td>
<td>500 m³</td>
<td>Carbon Steel</td>
<td>$ 108,000</td>
</tr>
<tr>
<td>Tk-203</td>
<td>Storage Tank</td>
<td>120 m³</td>
<td>Carbon Steel</td>
<td>$ 71,100</td>
</tr>
<tr>
<td>Tk-205</td>
<td>Storage Tank</td>
<td>120 m³</td>
<td>Carbon Steel</td>
<td>$ 71,100</td>
</tr>
<tr>
<td>HP-201</td>
<td>Hopper</td>
<td>H= 3 m D= 1.4 m</td>
<td>Carbon Steel</td>
<td>$ 43,900</td>
</tr>
<tr>
<td>V-201</td>
<td>Flash Drum</td>
<td>H= 1.97 m D= 0.907 m</td>
<td>Stainless Steel</td>
<td>$ 40,200</td>
</tr>
<tr>
<td>V-202</td>
<td>Flash Drum</td>
<td>H= 1.65 m D= 0.272 m</td>
<td>Stainless Steel</td>
<td>$ 22,500</td>
</tr>
<tr>
<td>Z-100</td>
<td>Size Reduction Plant</td>
<td>-</td>
<td>-</td>
<td>$ 1,162,432</td>
</tr>
</tbody>
</table>

**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**
  
  $COM_d = 0.18 \times FCI + 2.73 \times C_{OL} + 1.23 \times (C_{UL} + C_{WT} + C_{RM})$
  
  $COM_d = $8,129,647 / year

- **With depreciation**
  
  $COM = 0.28 \times FCI + 2.73 \times C_{OL} + 1.23 \times (C_{UL} + C_{WT} + C_{RM})$
  
  $COM = $9,629,647 / year
8.3 Estimating Manufacturing cost

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

- Direct Manufacturing Cost
  Total Direct Manufacturing cost = $U + W + R + 1.33 OL + 0.03 COM + 0.069 CI
  Total Direct Manufacturing cost = $4,867,031.81 / year

- Fixed Manufacturing Cost
  Total Fixed Manufacturing Cost = 0.708 OL + 0.168 CI
  Total Fixed Manufacturing cost = $3,194,922.24 / year

- General Manufacturing Cost
  Total General Manufacturing Cost = 0.177 OL + 0.009 CI + 0.16 COM
  Total General Manufacturing Cost = $1,844,474.08 / year

8.4 Products Prices

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

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Price ($/kg)</th>
<th>Flow rate (kg/h)</th>
<th>Annual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crumb Rubber</td>
<td>$0.27</td>
<td>1230.00</td>
<td>$2,733,028</td>
</tr>
<tr>
<td>First Condenser Liquid</td>
<td>$0.82</td>
<td>870.00</td>
<td>$5,900,714</td>
</tr>
<tr>
<td>Second Condenser Liquid</td>
<td>$0.88</td>
<td>672.00</td>
<td>$4,910,672</td>
</tr>
<tr>
<td>Iron</td>
<td>$0.30</td>
<td>700.00</td>
<td>$1,747,620</td>
</tr>
<tr>
<td>Total Revenue</td>
<td></td>
<td></td>
<td>$15,292,034</td>
</tr>
</tbody>
</table>
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) × (2.5%) = $141,559.675 / year

The Net profit = Revenue − Expenses − Income Tax

= $15,292,034 − $9,629,647 − $141,559.675 = $5,520,827.325 / year

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

After-Tax Cash Flow (ACF) = Net profit + Depreciation
ACF = $5,520,827.325 + $1,500,000 = $7,020,827.325
ACF = $7,020,827.325

8.6 Rate of Return (ROR %)

ROR = (After-Tax Cash Flow / TCI) * 100
Where,
TCI: Total Capital Investment = FCI + Working Capital

TCI = $15,000,000 + 3,000,000 = $18,000,000

ROR = ($7,020,827.325 / $18,000,000) * 100 = 29%
ROR = 29%

8.7 Payback Period (PBP)

PBP = TCI / ACF
PBP = $18,000,000 / $7,020,827.325 = 2.56 years
PBP = 2.56 years
Figure 8.1 shows the cash flow diagram of the project.

![Cash Flow Diagram](image)

**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

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{RM}$</td>
<td>$1,997,280</td>
</tr>
<tr>
<td>Total Equipment Cost</td>
<td>$8,628,632</td>
</tr>
<tr>
<td>$C_{UL}$</td>
<td>$278,000</td>
</tr>
<tr>
<td>$C_{OL}$</td>
<td>$953,280</td>
</tr>
<tr>
<td>FCI</td>
<td>$15,000,000</td>
</tr>
<tr>
<td>Working Capital</td>
<td>$3,000,000</td>
</tr>
<tr>
<td>COM$_d$</td>
<td>$8,129,647</td>
</tr>
<tr>
<td>COM</td>
<td>$9,629,647</td>
</tr>
<tr>
<td>Revenue</td>
<td>$15,292,034</td>
</tr>
<tr>
<td>The Net profit</td>
<td>$5,520,827.325</td>
</tr>
<tr>
<td>ACF</td>
<td>$7,020,827.325</td>
</tr>
<tr>
<td>ROR</td>
<td>29%</td>
</tr>
<tr>
<td>PBP</td>
<td>2.56 years</td>
</tr>
</tbody>
</table>
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, e.g. 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

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

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 manuactories to be used in further processes. In general, there are no emissions and harmful from these hydrocarbons if the is no problems in transportation.
Table 9.14 Weight Fraction of Pyrolysis Liquid Products

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>0.231653</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.156943</td>
</tr>
<tr>
<td>Hexene</td>
<td>0.111975</td>
</tr>
<tr>
<td>Hexane</td>
<td>0.079759</td>
</tr>
<tr>
<td>Styrene</td>
<td>0.071806</td>
</tr>
<tr>
<td>Ethyl Benzene</td>
<td>0.181398</td>
</tr>
<tr>
<td>Cyclopentane</td>
<td>0.023607</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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: H₂, H₂S, CO, CO₂, CH₄, C₂H₄, C₃H₆ 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:

- H₂O
- CO₂
- SO₂

CO₂

Carbon dioxide (CO₂) is a colorless, odorless, non-flammable gas that is a product of cellular respiration and burning of fossil fuels. CO₂ 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 CO₂ 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 CO$_2$ can displace oxygen (O$_2$) and nitrogen (N$_2$), potentially causing health problems.

To reduce the CO$_2$ 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].

**SO$_2$**

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 SO$_2$ 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

<table>
<thead>
<tr>
<th>Component</th>
<th>Problem</th>
<th>Cause</th>
<th>Consequences</th>
<th>Limit of emission</th>
<th>Prevent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>Particulate matters. 10 micrometers in diameter.</td>
<td>Reduction in the particles after size reduction and pyrolysis.</td>
<td>Attack the respiratory system of human.</td>
<td>-</td>
<td>Be sure to collect in safe bags.</td>
</tr>
<tr>
<td>Liquid</td>
<td>Explosion</td>
<td>High pressure or temperature.</td>
<td>May explosion.</td>
<td>-</td>
<td>Be aware about the dangers of liquids while collect and transport.</td>
</tr>
<tr>
<td>Gas</td>
<td>Emissions</td>
<td>Leakage or purge</td>
<td>Air pollution</td>
<td>-</td>
<td>Reduce the emission by flaring or separation processes.</td>
</tr>
<tr>
<td>CO₂</td>
<td>Emission</td>
<td>A product of combustion.</td>
<td>High levels of CO₂ causing health problems.</td>
<td>5,000 ppm over an 8-hour workday.</td>
<td>By using aqueous solution of monoethanolamine (MEA) in an absorber or polymeric based membranes</td>
</tr>
<tr>
<td>SO₂</td>
<td>Emission</td>
<td>A product of combustion H₂S</td>
<td>Affects human health by breathing. Irritates the nose, throat, and airways to cause coughing and breathing problems.</td>
<td>2 ppm over an 8-hour workday.</td>
<td>By using an aqueous Fulvic acid solution or ionic liquids in an absorber.</td>
</tr>
</tbody>
</table>
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 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 manufactories 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 idea 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.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Riyadh</th>
<th>Jubail</th>
<th>Yanbu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw material</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Market availability</td>
<td>5</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Land Available and Cost</td>
<td>7</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Utilities</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Weather</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>42</td>
<td>33</td>
<td>33</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Description</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development Charges (paid only once)</td>
<td>50 SR/m²</td>
</tr>
<tr>
<td>Total customer invoicing per annum</td>
<td>1 SR/m²</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.15 SR/KWh</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.36 SR/L</td>
</tr>
<tr>
<td>Water</td>
<td>1.71 SR/m³</td>
</tr>
</tbody>
</table>

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

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.
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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):

\[ M_{in} = M_{out} \]

\[ M_{20} = M_{25} + M_{29} \]

\[ 0.595 M_{20} = 0.405 M_{20} \]

\[ M_{20} = 3027.5 \text{Kg/hr} \]

\[ M_{29} = 1801.36265 \text{Kg/hr} \]

\[ M_{25} = 1226.1375 \text{Kg/hr} \]

<table>
<thead>
<tr>
<th>Stream</th>
<th>Component</th>
<th>T (°C)</th>
<th>N (mol/hr)</th>
<th>H (J/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Crumb Rubber</td>
<td>25</td>
<td>442664.516</td>
<td>0</td>
</tr>
<tr>
<td>48</td>
<td>Hot gases</td>
<td>534.873045</td>
<td>49467.3915</td>
<td>16578.9025</td>
</tr>
<tr>
<td>29</td>
<td>Gas + Vapor oil</td>
<td>475</td>
<td>34825.6742</td>
<td>105093.704</td>
</tr>
<tr>
<td>46</td>
<td>Hot gases</td>
<td>1956.13</td>
<td>49467.3915</td>
<td>1952.304202</td>
</tr>
<tr>
<td>25</td>
<td>Char</td>
<td>475</td>
<td>102178.125</td>
<td>8719.929017</td>
</tr>
</tbody>
</table>

Component and mole fraction of stream number 20

<table>
<thead>
<tr>
<th>Component</th>
<th>C</th>
<th>H</th>
<th>N</th>
<th>S</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>mole fraction</td>
<td>0.457661153</td>
<td>0.491059588</td>
<td>0.0024426</td>
<td>0.002543354</td>
<td>0.046293</td>
</tr>
</tbody>
</table>
Component and mole fraction of stream number 25

<table>
<thead>
<tr>
<th>Component</th>
<th>C</th>
<th>H</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>mole fraction</td>
<td>0.999999874</td>
<td>1.1543E-07</td>
<td>1.0983E-08</td>
</tr>
</tbody>
</table>

Component and mole fraction of stream number 29

<table>
<thead>
<tr>
<th>Component</th>
<th>CO2</th>
<th>H2S</th>
<th>C3H6</th>
<th>H2</th>
<th>CH4</th>
<th>C2H4</th>
<th>CO</th>
<th>Toluene</th>
<th>Benzene</th>
<th>Hexene</th>
<th>Hexane</th>
<th>Styrene</th>
<th>Ethyl Benzene</th>
<th>Cyclopentane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mol fraction</td>
<td>0.0209</td>
<td>0.011</td>
<td>0.03</td>
<td>0.2198</td>
<td>0.16828</td>
<td>0.0321</td>
<td>0.0172</td>
<td>0.13024</td>
<td>0.1040</td>
<td>0.0689</td>
<td>0.0479</td>
<td>0.0357</td>
<td>0.0885</td>
<td>0.01744</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CP_{mix20} )</td>
<td>23.15408155</td>
<td>0.005197964</td>
<td>-5.96426E-06</td>
<td>3.23245E-09</td>
</tr>
<tr>
<td>( CP_{mix25} )</td>
<td>18.3195011</td>
<td>0.001524001</td>
<td>-1.50002E-07</td>
<td>5.00087E-12</td>
</tr>
<tr>
<td>( CP_{mix29} )</td>
<td>18.90471826</td>
<td>0.254477</td>
<td>-0.000147616</td>
<td>3.30646E-08</td>
</tr>
</tbody>
</table>

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

\[
Q = n_{29} \left( y_i \cdot \Delta H_f + \int_{297}^{(475+273)} Cp_{mix29}dT \right) + n_{25} \left( y_i \cdot \Delta H_f + \int_{297}^{(475+273)} Cp_{mix25}dT \right) - n_{20} \left( y_i \cdot \Delta H_f + \int_{297}^{297} Cp_{mix19}dT \right)
\]

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

\[
Q_{\text{of hot gases}} = n \int_{25}^{T_{48}} Cp_{mix48} - n \int_{297}^{1543.747} Cp_{mix46}
\]

\[
Q = 49467.3915 \int_{25}^{T_{48}} Cp_{mix48} - 49467.3915 \int_{297}^{1543.747} Cp_{mix46} =
\]

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\[
Q_{\text{of decomposition unit}} = 0 \\
Q_{\text{of hot gases}} = Q_{\text{product}}
\]

\[
9.55 \times 10^6 \frac{\text{kJ}}{\text{h}} = 49467.3915 \int_{25}^{T_{48}} C_{\text{pmix}_{48}} - 49467.3915 \int_{297}^{1543.747} C_{\text{pmix}_{46}}
\]

\[T_{48} = 534.87 ^\circ C\]

**Energy Balance for the cooler (H-201)**

![Diagram of the cooler](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>CO2</th>
<th>H2S</th>
<th>C3H6</th>
<th>H2</th>
<th>CH4</th>
<th>C2H4</th>
<th>CO</th>
<th>Toluene</th>
<th>Benzene</th>
<th>Hexene</th>
<th>Hexane</th>
<th>Styrene</th>
<th>Ethyl Benzene</th>
<th>Cyclopentane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mol fraction</td>
<td>0.0209</td>
<td>0.011</td>
<td>0.03</td>
<td>0.2198</td>
<td>0.16828</td>
<td>0.0321</td>
<td>0.0172</td>
<td>0.13024</td>
<td>0.1040</td>
<td>0.0689</td>
<td>0.0479</td>
<td>0.0357</td>
<td>0.0885</td>
<td>0.01744</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stream</th>
<th>Component</th>
<th>T (C)</th>
<th>N (mol/hr)</th>
<th>H (J/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Gas + Vapor oil</td>
<td>513.3</td>
<td>34825.67</td>
<td>105093.704</td>
</tr>
<tr>
<td>31</td>
<td>Gas + Vapor oil</td>
<td>270</td>
<td>34825.67</td>
<td>29119.4851</td>
</tr>
</tbody>
</table>

\[Q = n_{31} \Delta H_{31} - n_{30} \Delta H_{30} = 1106076 \text{ kJ}/\text{h}\]
Energy Balance for the cooler (H-202)

<table>
<thead>
<tr>
<th>Stream</th>
<th>Component</th>
<th>T (°C)</th>
<th>N (mol/hr)</th>
<th>H (J/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>Gas + Vapor oil</td>
<td>270</td>
<td>34825.67</td>
<td>29119.4851</td>
</tr>
<tr>
<td>32</td>
<td>Gas + Vapor oil</td>
<td>170</td>
<td>34825.67</td>
<td>303342</td>
</tr>
</tbody>
</table>

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

Energy Balance for the condenser (H-203)

<table>
<thead>
<tr>
<th>Stream</th>
<th>Component</th>
<th>T (°C)</th>
<th>N (mol/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>Gas + Vapor oil</td>
<td>170</td>
<td>34825.67</td>
</tr>
<tr>
<td>33</td>
<td>Gas + Vapor oil + liquid</td>
<td>120</td>
<td>34825.67</td>
</tr>
</tbody>
</table>
\[ Q = n_{33}(\Delta H_{33}(\text{gas}) + \Delta H_{33}(\text{liquid}) - n_{32}\Delta H_{32} = Q_{(\text{non-condensable mixture})} + Q_{(\text{condensable})} = (378918.3 + 97105.02) \]

\[ 476023.3 \text{ kJ/h} \]

**Material balance for the flash drum (V-201)**

<table>
<thead>
<tr>
<th>Stream</th>
<th>Component</th>
<th>T (°C)</th>
<th>M (Kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>Gas + Vapor oil + liquid</td>
<td>120</td>
<td>1801.3626</td>
</tr>
<tr>
<td>37</td>
<td>Gas + Vapor oil</td>
<td>120</td>
<td>929.7158</td>
</tr>
<tr>
<td>34</td>
<td>liquid</td>
<td>120</td>
<td>871.6462</td>
</tr>
</tbody>
</table>

**Energy Balance for the condenser (H-204)**

Hot effluents (120 °C)

Cooling water (40 °C)

Cooling water (25 °C)

Hot effluents (50 °C)
Material balance for the flash drum (V-202)

Stream | Component | T (°C) | N (mol/hr) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>37</td>
<td>Gas + Vapor oil</td>
<td>120</td>
<td>27094.9</td>
</tr>
<tr>
<td>38</td>
<td>Gas + liquid</td>
<td>50</td>
<td>27094.9</td>
</tr>
</tbody>
</table>

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

\[ Q_{(\text{non-condensable mixture})} + Q_{(\text{condensable})} = (332324 + 49535.66) = 381859.66 \text{ kJ/h} \]

Material balance for the flash drum (V-202)

Stream | Component   | T (°C) | M (Kg/hr) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>Gas + liquid</td>
<td>50</td>
<td>929.7158</td>
</tr>
<tr>
<td>42</td>
<td>gas</td>
<td>50</td>
<td>257.9154</td>
</tr>
<tr>
<td>39</td>
<td>liquid</td>
<td>50</td>
<td>671.8</td>
</tr>
</tbody>
</table>
Material Balance for the Furnace (F-201)

Combustion Equations:

\[ \text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O} \]
\[ 2\text{H}_2\text{S} + 3\text{O}_2 \rightarrow 2\text{SO}_2 + 2\text{H}_2\text{O} \]
\[ 2\text{CO} + \text{O}_2 \rightarrow 2\text{CO}_2 \]
\[ \text{C}_3\text{H}_6 + 4\text{O}_2 \rightarrow 3\text{CO}_2 + 2\text{H}_2\text{O} \]
\[ \text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \]
\[ \text{C}_2\text{H}_4 + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O} \]
\[ \text{CO}_2 \rightarrow \text{CO}_2 \]
The inlet flow gases at stream number (44)

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow rate (Kg/h)</th>
<th>Mass fraction</th>
<th>LHV (KJ/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>16.78</td>
<td>0.065</td>
<td>10112</td>
</tr>
<tr>
<td>CO₂</td>
<td>32.1</td>
<td>0.125</td>
<td>---</td>
</tr>
<tr>
<td>CH₄</td>
<td>94.02</td>
<td>0.365</td>
<td>50000</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>31.33</td>
<td>0.122</td>
<td>47195</td>
</tr>
<tr>
<td>H₂</td>
<td>15.43</td>
<td>0.06</td>
<td>120000</td>
</tr>
<tr>
<td>C₃H₆</td>
<td>54.8</td>
<td>0.212</td>
<td>45800</td>
</tr>
<tr>
<td>H₂S</td>
<td>13.3</td>
<td>0.052</td>
<td>15191</td>
</tr>
</tbody>
</table>

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 = \(4.23 \times 10^4\) KJ/Kg

The total heat generated by combustion = \((4.23 \times 10^4\) KJ/Kg) * (225.76 Kg/h)

\[= 9.55 \times 10^6\ KJ/h\]

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

The Outlet flow gases at stream number (46)

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow rate (Kg/h)</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>587</td>
<td>0.96</td>
</tr>
<tr>
<td>SO₂</td>
<td>25</td>
<td>0.04</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Component</th>
<th>$C_p$ (kJ/kg.K)</th>
<th>$u_i$ (mN-s/m²)</th>
<th>$\rho$ (kg/m³)</th>
<th>$K$ (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture</td>
<td>2.5258</td>
<td>$1.62 \times 10^{-02}$</td>
<td>0.9794</td>
<td>0.0698</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>4.1867</td>
<td>0.7865</td>
<td>994.5747</td>
<td>0.6163</td>
</tr>
</tbody>
</table>

Heat Load ($Q$)

$Q = m_{Cp_{Mix}} \Delta T = 1106076$ kJ/h = 307243.5 J/s

Finding Water flow required

$Q = m_{Cp_{Mix}} \Delta T = 1106076$ kJ/h = 307243.5 J/s = $m_{Cp_{water}} \Delta T$

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

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

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

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

- The heat exchanger will consist of one shell pass and two tube passes.
- The correction factor will be = 1
  $$\Delta T_m = F_t (\Delta T_{lm}) = (1) \times 346.63 = 346.63 \, ^\circ C$$

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

$$U = 250 \, W/m^2.C$$

**Required Area for Heat transfer**

$$Q = UA \Delta T_m \Rightarrow A = \frac{Q}{U \Delta T_m}$$

$$A = 3.545 \, m^2$$

- 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**

$$N_t = \frac{\text{Area}}{\pi \times do \times L}$$

$$N_t = 45.17 = 46 \, tubes$$

- A triangular pitch arrangement with $pt= 1.25d_o$ will be used:
Calculation of bundle diameter $D_b$

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

$K_1$, $n_1$ are constants.

$K_1 = 0.249$, $n_1 = 2.207$

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

$\Rightarrow D_b = 0.2628$ 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

$\Rightarrow D_s = 0.2628 + 0.054 = 0.3178$ m

Calculating the heat transfer coefficients for tube side ($h_i$)

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

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

Total cross sectional area for mixture $= \left( \frac{N_i}{NO.\, pass} \right) \times \frac{\pi}{4} d_i^2 = 7.818 \times 10^{-3}$ m$^2$
Mass velocity \((G_{\text{mixture}})\) = \(\frac{m(\text{mixture})}{\text{flow area}} = \frac{4.892}{7.818 \times 10^{-3}} = 64.005 \text{ kg/m}^2\cdot\text{s}\)

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

Average mixture Temperature = 391.55 °C.

To calculate \(h_i\):

\[
Re = 8.28 \times 10^4
\]

\[
Pr = 0.587303
\]

\[
Jh = 2.95 \times 10^{-3}
\]

\[
h_i = (Jh \times Re \times Pr^{0.33} \times k) / di
\]

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

**Calculate heat transfer coefficients for shell side (ho)**

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 : \(P_t = \text{tube pitch}\)

\(d_o = \text{tube outside diameter}\)

\(D_s = \text{shell inside diameter}\)

\(L_B = \text{Baffle spacing (usually one fifth of Shell diameter)}\)

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

\(P_t = 1.25 \text{ d}_o \text{ mm} = 31.25 \times 10^{-3} \text{ m}\)

\(L_B = \frac{D_s}{5} = \frac{0.3178}{5} = 0.0636 \text{ m}\)
\[ A_s = \left[ \frac{P_t - d_o}{P_t} \right] (D_s)(L_H) = \frac{31.25 - 25}{31.25} (0.3178) (0.0636) = 4.041 \times 10^{-3} \text{ m}^2 \]

mass velocity ( \( G_s \) ) and liner velocity ( \( v_s \) )

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

\( m_{shell} \) = mass flow rate of water = 17612.54 kg/h

\( \Rightarrow G_s = \frac{4.892}{4.041 \times 10^{-3}} = 1210.798 \text{ kg/m}^2\text{s} \)

\( \Rightarrow v_s = \frac{1210.798}{994.5747} = 1.217 \text{ m/s} \)

the equivalent (Hydraulic) diameter \( d_e \):

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

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

Re & Pr for shell side

Average water Temperature = 32.5 °C.

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

\[ \text{Pr} = \frac{C_p u}{K} = \frac{(4.1867)(0.7865)}{0.6163} = 5.343 \]

the shell side coefficient ( \( h_s \) or \( h_o \) )
\[ h_o = \frac{(Jh \times Re \times Pr^{0.33} \times K)}{de} \]

\[ Jh = 3.9 \times 10^{-3} \]

\[ h_o = \frac{(3.9 \times 10^{-3} \times 2.73 \times 10^4 \times 0.5.343^{0.33} \times 0.6163)}{17.75 \times 10^{-3}} \]

\[ \Rightarrow h_o = 728.55 \text{ W/m}^2.\text{°C} \]

**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)

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

\[ \Rightarrow U_o = 279.85 \text{ W/m}^2.\text{°C} \]
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 ΔPₜ

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

Where : \( \Delta P_t \) = tube side pressure drop (N/m²)

\( N_p \) = Number of tube passes

\( j_f \) = fraction factor ' depending on Re '

\( L \) = length of one tube = 1 m

\( v_i \) = flow velocity inside the tube

\( m \) = exponent value depending on type of flow

at laminar (Re<2100) \( \Rightarrow m = 0.25 \)

at Turblent (Re>10000) \( \Rightarrow m = 0.14 \)

now;

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

\[
\Delta P_t = 2 \left[ 8(2.9 \times 10^{-3}) \left( \frac{1}{21 \times 10^{-3}} \right) + 2.5 \left( \frac{0.9794 \times (65.35138)^2}{2} \right) \right]
\]
\[ \Delta P_t = 15078.084 \text{ Pa} = 15.078 \text{ kPa} \text{ (Acceptable)} \]

**The shell side \( \Delta P_s \)**

\[ \Delta P_s = 8J_f \left( \frac{D_s}{D_e} \right) \left( \frac{L}{L_B} \right) \left( \frac{\rho_v^2}{2} \right) \left( \frac{\mu}{\mu_w} \right)^{0.14} \]

Where : \( \Delta P_s \) = shell side pressure drop (N/m\(^2\))

\( j_f \) = 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

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

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

\[ \Rightarrow \Delta P_s = 71412.71 \text{ Pa} = 71.412 \text{ KPa (acceptable)} \]

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

<table>
<thead>
<tr>
<th>Component</th>
<th>$C_p$ (kJ/kg.K)</th>
<th>$u_i$ (mN-s/m$^2$)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$K$ (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture</td>
<td>2.0612</td>
<td>$1.26 \times 10^{-02}$</td>
<td>1.3127</td>
<td>0.0472</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>4.1867</td>
<td>0.7865</td>
<td>994.5747</td>
<td>0.6163</td>
</tr>
</tbody>
</table>

Heat Load (Q)

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

Finding Water flow required

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

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

Finding $\Delta T_{lm}$

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

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

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

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

\[ \Delta T_m = F_t (\Delta T_{lm}) = (1) \times 187.159 = 187.159 \, ^\circ C \]

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

\[ U = 100 \, W/m^2.C \]

**Required Area for Heat transfer**

\[ Q = UA \Delta T_m \Rightarrow A = \frac{Q}{U \Delta T_m} \]

\[ A = 5.235 \, m^2 \]

• 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**

\[ N_t = \frac{\text{Area}}{\pi \times d_o \times L} \]

\[ N_t = 66.69 = 67 \, \text{tubes} \]

• A triangular pitch arrangement with \( pt = 1.25d_o \) will be used:

**Calculation of bundle diameter \( D_b \)**

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

\( K_1, \, n_1 \) are constants.

\( K_1 = 0.249, \, n_1 = 2.207 \)
\[ D_b = 25 \times 10^{-3} \left( \frac{66.69}{0.249} \right)^{\frac{1}{2.207}} \]

\[ \Rightarrow D_b = 0.315 \text{ m} \]

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 \( \text{m} \)

\[ \Rightarrow D_s = 0.315 + 0.054 = 0.369 \text{ m} \]

Calculating the heat transfer coefficients for tube side (\( h_i \))

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

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

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

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

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

Average mixture Temperature = 222.5 °C.

To calculate \( h_i \):

\[ h_i = (Jh \times Re \times Pr^{0.33} \times k) / \text{di} \]
\[ h_i = 399.55 \text{ W/m}^2\text{.}^\circ\text{C} \]

**Calculate heat transfer coefficients for shell side (ho)**

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

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

Where: \( P_t \) = tube pitch

- \( d_o \) = tube outside diameter
- \( D_s \) = shell inside diameter
- \( L_B \) = Buffle spacing (usually one fifth of Shell diameter)

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

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

\[ L_B = \frac{D_s}{5} = \frac{0.369}{5} = 0.07376 \text{ m} \]

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

**mass velocity ( \( G_s \)) and liner velocity ( \( v_s \))**

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

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

\[ G_s = \frac{1.56}{5.44 \times 10^{-3}} = 286.796 \text{ kg/m}^2\text{.s} \]

\[ v_s = \frac{286.796}{994.5747} = 0.288 \text{ m/s} \]

**the equivalent (Hydraulic) diameter \( d_e \):**
\[ d_e = \frac{1.10}{d_o} \left[ P_l^2 - 0.917d_o^2 \right] \]

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

**Re & Pr for shell side**

Average water Temperature = 32.5 °C.

\[ \text{Re} = \frac{G_s d_e}{\mu_w} = \frac{(286.796)(0.01775)}{0.7865} = 6.47 \times 10^3 \text{ "Turbulent Flow"} \]

\[ \text{Pr} = \frac{C_p u}{K} = \frac{(4.1867)(0.7865)}{0.6163} = 5.343 \]

**the shell side coefficient (h_s or h_o)**

\[ h_o = \frac{(Jh \times \text{Re} \times \text{Pr}^{0.33} \times K)}{d_e} \]

Jh = 7.5 \times 10^{-3}

\[ h_o = (7.5 \times 10^{-3} \times 6.47 \times 10^3 \times 0.5343^{0.33} \times 0.6163) / 17.75 \times 10^{-3} \]

\[ \Rightarrow h_o = 224.411 \text{ W/m}^2\cdot\text{°C} \]

**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\cdot°C) for "Cupro-Nickel"
\[ h_{od} = \text{outside dirt " fouling " coefficient} = 6000 \text{ (W/m}^2\text{.}^\circ\text{C)} \]

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

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

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

\[ U_o = 126.76 \text{ W/m}^2\text{.}^\circ\text{C} \]

The value of 126.76 W/m\(^2\).{^\circ}C is above the estimated value of 100 W/m\(^2\).{^\circ}C.

Hence, the current design satisfactory. (ok)

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

**The tube side ΔP\(_t\)**

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

Where: \( \Delta P_t = \text{tube side pressure drop (N/m}_2\)\)

\( N_p = \text{Number of tube passes} \)

\( j_f = \text{fraction factor } ' \text{ depending on } \text{Re}' \)

\( L = \text{length of one tube } = 1 \text{ m} \)

\( v_i = \text{flow velocity inside the tube} \)

\( m = \text{exponent value depending on type of flow} \)

at laminar (Re<2100) \[ m = 0.25 \]

at Turblent (R>10000) \[ m = 0.14 \]

now;
\[ \Delta P_i = N_p \left[ 8 j_f \left( \frac{L}{d_i} \right) \left( \frac{\mu}{\mu_w} \right)^{-m} + 2.5 \left( \frac{\rho v_i^2}{2} \right) \right] \]

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

\[ \Delta P_i = 5159.74 \text{ Pa} = 5.16 \text{ kPa} \text{ (Acceptable)} \]

The shell side \( \Delta P_s \)

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

Where: \( \Delta P_s = \) shell side pressure drop (N/m\(^2\))

\( j_f = \) fraction 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

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

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

\[ \Delta P_s = 5124.755 \text{ Pa} = 5.125 \text{ kPa} \text{ (acceptable)} \]

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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

<table>
<thead>
<tr>
<th>Component</th>
<th>$C_p$ (kJ/kg.K)</th>
<th>$u_i$ (mN.s/m²)</th>
<th>$\rho$ (kg/m³)</th>
<th>$K$ (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensable mixture</td>
<td>2.1227</td>
<td>0.1986</td>
<td>$\rho_l$ 752</td>
<td>0.1031</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\rho_v$ 5.3978</td>
<td></td>
</tr>
<tr>
<td>Non-condensable</td>
<td>0.0517</td>
<td>0.0124</td>
<td>1.8658</td>
<td>2.0901</td>
</tr>
<tr>
<td>mixture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_2O$</td>
<td>4.1867</td>
<td>0.7865</td>
<td>994.5747</td>
<td>0.6163</td>
</tr>
</tbody>
</table>

Heat Load (Q)

$$Q = mC_{p_{Mix}} \Delta T = Q_{\text{(non-condensable mixture)}} + Q_{\text{(condensable mixture)}} = (378918.3 + 97105.02) = 476023.3 \text{ kJ/h} = 132228.6936 \text{ J/s}$$

Finding Water flow required

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

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

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

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

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

- The heat exchanger will consist of one shell pass and two tube passes.
- The correction factor will be $= 1$
  $\Delta T_m = F_t (\Delta T_{lm}) = (1) \times 346.63 = 116.62 \, ^\circ C$

- The following value of overall heat transfer coefficient $U$ can be assumed based on the cold and hot fluids:
  
  $U = 150 \, W/m^2.C$

**Required Area for Heat transfer**

$Q=UA \Delta Tm \rightarrow A = \frac{Q}{U \Delta Tm}$

$A = 7.56 \, m^2$

- 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**

$N_t = \frac{\text{Area}}{\pi \times do \times L}$

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

- A triangular pitch arrangement with $pt = 1.25d_o$ will be used:
Calculation of bundle diameter $D_b$

$$D_b = d_o \left[ \frac{N_t}{K_1} \right]^{1/m_1}$$

$K_1$, $n_1$ are constants.

$K_1 = 0.249$, $n_1 = 2.207$

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

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

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

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

Calculating the heat transfer coefficients for tube side ($h_i$)

- First : heat transfer coefficients for non-condensable mixture

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

Number of tube per pass = $\frac{N_t}{NO\_pass} = 97 / 1 = 96.28 \text{ tube/pass}$
Total cross sectional area for mixture = \( \left( \frac{N_i}{NO.\,pass} \right) \times \frac{\pi}{4} d_i^2 = 0.033 \text{ m}^2 \)

Mass velocity (\(G_{\text{non-condensable mixture}}\)) = \( \frac{m_{\text{non-condensable mixture}}}{\text{flow area}} = \frac{0.258255}{0.033} = 7.748 \text{ kg/m}^2\cdot\text{s} \)

Linear velocity (\(v_{\text{non-condensable mixture}}\)) = \( \frac{G_{\text{non-condensable mixture}}}{\rho(\text{mixture})} = \frac{7.748}{1.8658} = 4.152 \text{ m/s} \)

Average mixture Temperature = 150 °C.

To calculate \(h_i(\text{non-condensable mixture})\):

\[
Re = 1.31 \times 10^4
\]
\[
Pr = 0.50049
\]
\[
Jh = 3.60 \times 10^{-3}
\]

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

\(\Rightarrow h_i(\text{non-condensable mixture}) = 92.69 \text{ W/m}^2\cdot\text{°C}\)

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

The Prandtl number for the condensate film is given by:

\[
Pr_c = \frac{c_pU_l}{k_l}
\]

\[
Pr_c = \frac{2.1227 \times 0.1986}{0.1031} = 4.0889
\]

\[
r_v = \frac{W_c}{\pi d_i}
\]

Where: \(r_v = \text{vertical tube loading}\)

\(W_c = \text{total condensate flow}\)

\[
r_v = \frac{0.2421}{\pi \times 0.021} = 3.671 \text{ kg/m.s}
\]

The Reynolds number for the condensate film is given by:

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\[ Re_e = \frac{4u_t}{\nu} = 73955.34 \]

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

The heat transfer coefficients for condensable mixture inside tube:

\[
h_c = 0.7 \frac{k_l}{\rho_l(\rho_l-\rho_v)g} \left( \frac{u_t^2}{\rho_l(\rho_l-\rho_v)g} \right)^{\frac{1}{3}} = 3743.9 \text{ W/m}^2\cdot\text{C}
\]

**Boyko-kruzhilin method:**

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

Fluid velocity, total condensation:
\[
u_t = \frac{W_\ell}{A_s \rho_L} = 0.93 \text{ m/s}
\]

\[
Re_e = \frac{\rho_L u_t d_i}{\nu} = 73955.34
\]

The force convection in the tube:
\[
h_t' = 0.021 \left( \frac{k_l}{d_i} \right) \rho_e^{0.8} \rho_r^{0.43} = 1483.974 \text{ W/m}^2\cdot\text{C}
\]

The heat transfer coefficients by Boyko-kruzhilin method for condensable mixture inside tube:
\[
h_c = h_t' \left( \frac{\rho_L}{\rho_v} \right)^{\frac{1+\rho_L/\rho_v}{2}} = 9499.24 \text{ W/m}^2\cdot\text{C}
\]

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

\[
\Rightarrow h_i(\text{condensable mixture}) = 9499.24 \text{ W/m}^2\cdot\text{C}
\]

\[
\Rightarrow h_i = h_i(\text{non-condensable mixture}) + h_i(\text{condensable mixture}) = 9591.93 \text{ W/m}^2\cdot\text{C}
\]

Calculate heat transfer coefficients for shell side (ho)

Area for cross flow of the shell side \( A_s \), using Kern Method
Where: \( P_t \) = tube pitch
\( d_o \) = tube outside diameter
\( D_s \) = shell inside diameter
\( L_B \) = Buffle spacing (usually one fifth of Shell diameter)
\( d_o = 25 \times 10^{-3} \text{ m} \)
\( P_t = 1.25 \times d_o \text{ mm} = 31.25 \times 10^{-3} \text{ m} \)

\[ L_B = \frac{D_s}{5} = \frac{0.4258}{5} = 0.08516 \text{ m} \]

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

mass velocity (\( G_s \)) and liner velocity (\( v_s \))

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

\( m_{shell} \) = mass flow rate of water = 7579.92 kg/h

\[ G_s = \frac{2.105536}{0.007251} = 290.356 \text{ kg/m}^2\text{s} \]

\[ v_s = \frac{290.356}{994.5747} = 0.292 \text{ m/s} \]

the equivalent (Hydraulic) diameter \( d_e \):
\[ d_e = \frac{1.10}{d_o} \left[ P_i^2 - 0.917d_o^2 \right] \]

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

**Re & Pr for shell side**

Average water Temperature = 32.5 °C.

\[ \text{Re} = \frac{G \cdot s \cdot d_e}{\mu_v} = \frac{(290.356)(0.01775)}{0.7865} = 6.55 \times 10^3 \text{ ''Turbulent Flow''} \]

\[ \text{Pr} = \frac{C_p \cdot u}{K} = \frac{(4.1867)(0.7865)}{0.6163} = 5.343 \]

**the shell side coefficient (h_s or h_o)**

\[ h_o = \frac{(Jh \times \text{Re} \times \text{Pr}^{0.33} \times K)}{d_e} \]

\[ Jh = 5.6 \times 10^{-3} \]

\[ h_o = \frac{(5.6 \times 10^{-3} \times 6.55 \times 10^3 \times 5.343^{0.33} \times 0.6163)}{17.75 \times 10^{-3}} \]

\[ \Rightarrow h_o = 185.813 \text{ W/m}^2.\text{°C} \]

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

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

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

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

\[
\frac{1}{U_o} = 0.00596
\]

\[ U_o = 167.81 \text{ W/m}^2.\text{}^\circ\text{C} \]

The value of 167.81 W/m².ºC is above the estimated value of 150 W/m².ºC.

Hence, the current design satisfactory. (ok)

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

**The tube side ΔP_t**

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

\[ \Delta P_t = \text{tube side pressure drop (N/m²)} \]

\[ N_p = \text{Number of tube passes} \]

\[ j_r = \text{fraction factor ' depending on Re'} \]

\[ L = \text{length of one tube} = 1 \text{ m} \]

\[ v_i = \text{flow velocity inside the tube} \]

\[ m = \text{exponent value depending on type of flow} \]

at laminar (Re<2100) \[ m = 0.25 \]
at Turblent \((R>10000)\) \(\Rightarrow m = 0.14\)

now;

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

\[
\Delta P_s = 1 \left[ 8(3 \times 10^{-3}) \left( \frac{1}{21 \times 10^{-3}} \right) + 2.5 \left( \frac{752 \times (0.93)^2}{2} \right) \right]
\]

\(\Rightarrow \Delta P_s = 1184.98 \text{ Pa} = 1.185 \text{ kPa} \) (Acceptable)

**The shell side \(\Delta P_s\)**

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

Where: \(\Delta P_s\) = shell side pressure drop \((\text{N/m}^2)\)

\(j_f\) = fraction factor ' depending on \(Re\),

\(D_s\) = shell diameter = 0.3178 \(\text{m}\)

\(D_e\) = equivalent diameter for shell side = 0.01775 \(\text{m}\)

\(L\) = length of one tube = 1 \(\text{m}\)

\(Re= 6553.305638\)

\(v_s\) = flow velocity in shell = 0.291 \(\text{m/s}\)

\(L_B\) = Baffle spacing = 0.0851 \(\text{m}\)

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

\(\Rightarrow \Delta P_s = 4297.70 \text{ Pa} = 4.3 \text{ KPa} \) (acceptable)

4- heat exchanger “condenser “ \((E-204)\):

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**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 = $(125 + 50) / 2 = 87.5 \, ^\circ C$

$T_{av}$ for water = $(40+25) / 2 = 32.5 \, ^\circ C$

<table>
<thead>
<tr>
<th>Component</th>
<th>Cp</th>
<th>ui</th>
<th>ρ</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kJ/kg.K)</td>
<td>(mN-s/m2)</td>
<td>(kg/m3)</td>
<td>(W/m.K)</td>
</tr>
<tr>
<td><strong>Condensable mixture</strong></td>
<td>2.2144</td>
<td>0.2199</td>
<td>677.18</td>
<td>0.108</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ρ_l</td>
<td>ρ_v</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.108</td>
<td>5.1089</td>
</tr>
<tr>
<td><strong>Non-condensable mixture</strong></td>
<td>2.563</td>
<td>0.0137</td>
<td>0.8791</td>
<td>0.0766</td>
</tr>
<tr>
<td><strong>H₂O</strong></td>
<td>4.1867</td>
<td>0.7865</td>
<td>994.5747</td>
<td>0.6163</td>
</tr>
</tbody>
</table>

**Heat Load (Q)**

$$Q = mC_p\Delta T = Q_{(non\text{-}condensable \text{ mixture})} + Q_{(condensable \text{ mixture})} = (332324 + 49535.66) = 381859.66 \text{ kJ/h} = 106072.13 \text{ J/s}$$

**Finding Water flow required**

$$Q = mC_p\Delta T = 381859.66 \text{ kJ/h} = 106072.13 \text{ J/s} = mC_p\text{water} \Delta T$$

$$m(\text{water}) = 6080.52 \text{ kg/h} = 1.689 \text{ kg/s}$$

**Finding ΔT_{lm}**
\[ \Delta T_{out} = T_1 - t_2 = (50 - 25) = 25 \, ^\circ C \]

\[ \Delta T_{in} = T_2 - t_1 = (125 - 40) = 85 \, ^\circ C \]

\[ \Delta T_{lm} = \frac{\Delta T_{out} - \Delta T_{in}}{\ln \frac{\Delta T_{out}}{\Delta T_{in}}} = 49.03 \, ^\circ C \]

- The heat exchanger will consist of one shell pass and two tube passes.
- The correction factor will be = 1
  \[ \Delta T_m = F_t (\Delta T_{lm}) = (1) \times 346.63 = 49.03 \, ^\circ C \]
- The following value of overall heat transfer coefficient \( U \) can be assumed based on the cold and hot fluids:
  \[ U = 500 \, \text{W/m}^2\text{.C} \]  (reference)

**Required Area for Heat transfer**

\[ Q=UA \Delta T_m \Rightarrow A=\frac{Q}{U \Delta T_m} \]

\[ A = 4.33 \, \text{m}^2 \]

- 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 \( L=3 \, \text{m} \)

**Calculation of Number of tubes**

\[ N_t = \frac{\text{Area}}{\pi \times do \times L} \]

\[ N_t = 18.373 = 19 \, \text{tubes} \]

- 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.

$K_1 = 0.249$, $n_1 = 2.207$

$$D_b = 25 \times 10^{-3} \left[ \frac{18.373}{0.249} \right]^{\frac{1}{2.207}}$$

$\Rightarrow D_b = 0.18$ m

Calculating the shell diameter $D_s$

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

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

$\Rightarrow D_s = 0.18 + 0.054 = 0.23$ m

Calculating the heat transfer coefficients for tube side (hi)

- First : heat transfer coefficients for non-condensable mixture

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

Number of tube per pass = $\frac{N_t}{NO.\, pass} = 18.373 / 1 = 18.373$ tube/pass
Total cross sectional area for mixture = \((\frac{N_r}{NO.pass})\times\frac{\pi}{4}d_i^2 = 0.0064 \text{ m}^2\)

Mass velocity \((G_{\text{non-condensable mixture}}) = \frac{m_{\text{(non-codensable mixture)}}}{\text{flow area}} = \frac{0.071644}{0.0064} = 11.26 \text{ kg/m}^2\cdot\text{s}\)

Linear velocity \((v_{\text{non-condensable mixture}}) = \frac{G_{\text{non-condensable mixture}}}{\rho(\text{mixture})} = \frac{11.26}{0.8971} = 12.8 \text{ m/s}\)

Average mixture Temperature = 87.5 °C.

To calculate \(h_i(\text{non-condensable mixture})\):

\[
\text{Re} = 1.73\times10^4
\]
\[
\text{Pr} = 0.4584
\]
\[
Jh = 4.0\times10^{-3}
\]

\[h_i = (Jh \times \text{Re} \times \text{Pr}^{0.33} \times \text{k}) / d_i\n\]

\[h_i(\text{non-condensable mixture}) = 194.74 \text{ W/m}^2\cdot\text{°C}\]

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

  The Prandtl number for the condensate film is given by

  \[Pr_c = \frac{c_p U_l}{k_l}\]

  \[Pr_c = \frac{2.1227\times0.1986}{0.1031} = 4.509\]

  \[r_v = \frac{W_c}{\pi d_i}\]

  Where : \(r_v = \text{vertical tube loading}\)

  \[W_c = \text{total condensate flow}\]

  \[r_v = \frac{0.1866}{\pi \times 0.021} = 2.83 \text{ kg/m.s}\]
The Reynolds number for the condensate film is given by:

\[ Re_c = \frac{4r_v}{u_l} = 51478.2 \]

From figure 12.39. \( \frac{h_c}{k_l} \left( \frac{u_l^2}{\rho_l(\rho_l-\rho_v)g} \right)^{\frac{1}{3}} = 0.57 \)

The heat transfer coefficients for condensable mixture inside tube:

\[ h_c = 0.57k_l/\left( \frac{u_l^2}{\rho_l(\rho_l-\rho_v)g} \right)^{\frac{1}{3}} = 2782.35 \text{ W/m}^2\cdot{}^\circ\text{C} \]

Boyko-kruzhilin method:

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

Fluid velocity, total condensation:

\[ u_t = \frac{W_c}{\Delta h} = 0.796 \text{ m/s} \]

\[ Re = \frac{\rho_l u_t d_l}{u_l} = 51478.2 \]

The force convection in the tube:

\[ h'_t = 0.021 \left( \frac{k_l}{d_l} \right) Re^{0.8} p_t^{0.43} = 1213.3 \text{ W/m}^2\cdot{}^\circ\text{C} \]

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

\[ h_c = h'_t \left( 1 + \sqrt{\frac{\rho_l/\rho_v}{2}} \right) = 7591 \text{ W/m}^2\cdot{}^\circ\text{C} \]

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

\[ \Rightarrow h_i(\text{condensable mixture}) = 7591 \text{ W/m}^2\cdot{}^\circ\text{C} \]

\[ \Rightarrow h_i = h_i(\text{non-condensable mixture}) + h_i(\text{condensable mixture}) = 7785.73 \text{ W/m}^2\cdot{}^\circ\text{C} \]
Calculate heat transfer coefficients for shell side (ho)

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 = Buffle spacing (usually one fifth of Shell diameter)

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

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

$$L_B = \frac{D_s}{5} = \frac{0.23}{5} = 0.0459 \text{ m}$$

$$A_s = \left[ \frac{P_t - d_o}{P_t} \right] (D_s)(L_B) = \frac{31.25 - 25}{31.25} (0.23) (0.0459) = 0.002107 \text{ m}^2$$

mass velocity (G_s) and liner velocity (v_s)

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

$m_{shell} = \text{mass flow rate of water} = 6080.52 \text{ kg/h}$

$$\Rightarrow G_s = \frac{1.689}{0.002107} = 801.54 \text{ kg/m}^2.\text{s}$$

$$\Rightarrow v_s = \frac{801.54}{994.5747} = 0.806 \text{ m/s}$$
the equivalent (Hydraulic) diameter \( d_e \):

\[
d_e = \frac{1.10}{d_o} \left[ P^2 - 0.917d_o^2 \right]
\]

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

**Re & Pr for shell side**

Average water Temperature = 32.5 °C.

\[
Re = \frac{Gs \ d_e}{\mu_o} = \frac{(801.54)(0.01775)}{0.806} = 1.81 \times 10^4 \text{ "Turbulent Flow"}
\]

\[
Pr = \frac{C_p \ u}{K} = \frac{(4.1867)(0.7865)}{0.6163} = 5.343
\]

**the shell side coefficient ( \( h_s \) or \( h_o \))**

\[
h_o = \frac{(Jh \times Re \times Pr^{0.33} \times K)}{d_e}
\]

\[
Jh = 5.5 \times 10^{-3}
\]

\[
h_o = \frac{(5.5 \times 10^{-3} \times 1.81 \times 10^4 \times 5.343^{0.33} \times 0.6163)}{17.75 \times 10^{-3}}
\]

\[
\Rightarrow h_o = 746.42 \text{ W/m}^2\text{.°C}
\]

**Calculating the overall heat transfer coefficient ( \( U \))**

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

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\(\cdot\)°C) for "Cupro-Nickel"

\(h_{od} = \) outside dirt " fouling " coefficient = 6000 (W/m\(^2\)·°C)

\(h_{id} = \) inside dirt " fouling " coefficient = 5000 (W/m\(^2\)·°C)

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

\[
\frac{1}{u_o} = 0.00195
\]

\(\Rightarrow U_o = 513.922\)W/m\(^2\)·°C

The value of 513.922 W/m\(^2\)·°C is above the estimated value of 500 W/m\(^2\)·°C.

Hence, the current design satisfactory. (ok)

**Calculating the pressure drop ( \(\Delta P\) ) for side tube and shell tube:**

**The tube side \(\Delta P_t\)**

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

Where: \(\Delta P_t = \) tube side pressure drop (N/m\(_2\))

- \(N_p = \) Number of tube passes
- \(j_f = \) fraction 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;

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

\[ \Delta P_i = 1 \left[ 8\left(3.15 \times 10^{-3}\right) \left( \frac{1}{21 \times 10^{-3}} \right) + 2.5 \left( \frac{677 \times (0.769)^2}{2} \right) \right] \]

\[ \Rightarrow \Delta P_i = 1308.74 \text{ Pa} = 1.31 \text{ kPa} \text{ (Acceptable)} \]

The shell side \( \Delta P_s \)

\[ \Delta P_s = 8J_f \left( \frac{D_s}{D_e} \right) \left( \frac{L}{L_B} \right) \rho_s \left( \frac{\mu}{\mu_w} \right)^{-0.14} \]

Where: \( \Delta P_s = \) shell side pressure drop (N/m²)

\( j_f = \) fraction factor ' depending on \( \text{Re} = 0.09 \)

\( D_s = \) shell diameter = 0.3178 m

\( D_e = \) equivalent diameter for shell side = 0.01775 m

\( L = \) length of one tube = 1 m

\( \text{Re} = 18100 \)

\( v_s = \) flow velocity in shell = 0.8059 m/s

\( L_B = \) Baffle spacing = 0.0851 m

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

\[ \Rightarrow \Delta P_s = 65502.5 \text{ Pa} = 65.5 \text{ KPa} \text{ (acceptable)} \]
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 \( k_v = 0.0107 \text{ m/s} \) (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, \( \rho_v \): The density of the vapor phase = 1.8658 Kg/m\(^3\)

\( \rho_L \): The density of the liquid phase = 752 Kg/m\(^3\)

\[ v_v = 0.0107 \left( \frac{752 - 1.8658}{1.8658} \right)^{\frac{1}{2}} = 0.215 \text{ m/s} \]

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 \text{ m} \text{ (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.

The shell factor $\alpha_s = \frac{P}{2S - 1.2P}$

Where, $S$: the hoop stress.

The material of construction is stainless steel 316, so $S= 15200 \text{ psi}$

$\alpha_s = \frac{37.34}{2(0.8)(15200) - 1.2(37.34)} = 0.001758$

and the head factor $\alpha_h = \frac{1.104P}{2S - 0.2P} = \frac{1.104(37.34)}{2(0.7)(15200) - 0.2(37.34)} = 0.001696 \text{ (for a torispherical head)}$
The shell thickness = \( \alpha_s D + tc \)

The head thickness = \( \alpha_h D + tc \)

Where, \( tc \): the minimum corrosion allowance = 0.00318 m

\[
\text{The shell thickness} = \alpha_s D + tc = 0.001758 (0.907) + 0.00318 = 0.004774 \text{ m} = 4.77 \text{ mm}
\]

\[
\text{The head thickness} = \alpha_h D + tc = 0.001696 (0.907) + 0.00318 = 0.004717 \text{ m} = 4.77 \text{ mm}
\]

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 \( (v_v) \):

\[
v_v = k_v \left( \frac{\rho_L - \rho_v}{\rho_v} \right)^{1/2}
\]

Where, \( \rho_v \): The density of the vapor phase = 0.8791 Kg/m\(^3\)

\( \rho_L \): The density of the liquid phase = 677 Kg/m\(^3\)

\[
v_v = 0.0107 \left( \frac{677 - 0.8791}{0.8791} \right)^{1/2} = 0.29674 \text{ m/s}
\]

The cross sectional area \( (A) \):

\[
A = \frac{V_v}{v_v}
\]

Where, \( V_v \): The volumetric flow rate of the vapor.

\[
V_v = \frac{\text{mass flow rate of the vapor}}{\text{density of the vapor}} = \frac{257.92}{0.8791} = 293.391 \text{ m}^3/\text{hr} = 0.0815 \text{ m}^3/\text{s}
\]

\[
\Rightarrow A = \frac{0.0815}{0.29674} = 0.275 \text{ m}^2
\]
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.

\[
V_L = \frac{\text{mass flow rate of the liquid}}{\text{density of the liquid}} = \frac{671.8}{677} = 0.9923 \text{ m}^3/\text{hr} = 0.000276 \text{ m}^3/\text{s}
\]

\[
L_L = \frac{(0.000276 \times 300)}{0.275} = 0.3011 \text{ m}
\]

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.

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 \( S = 15200 \) psi

\[ \alpha_s = \frac{37.34}{2(0.8)(15200) - 1.2(37.34)} = 0.001758 \]

and the head factor \( \alpha_h = \frac{1.104 P}{2\varepsilon_h S - 0.2P} = \frac{1.104(37.34)}{2(0.7)(15200)-0.2(37.34)} = 0.001696 \) (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 = \( \alpha_s D + tc = 0.001758(0.907) + 0.00318 = 0.004774 \) m = 4.77 mm

The head thickness = \( \alpha_h D + tc = 0.001696(0.907) + 0.00318 = 0.004717 \) m = 4.77 mm
Sizing of Equipment

1- Decomposition unit (DU-201&202):
   - Density of crumb rubber = 389 Kg/m$^3$
   - Flow of crumb rubber per batch = 3027.5 Kg

The volume needed for the crumb rubber is:

\[
V = \frac{m}{\rho}
\]

\[
V = \frac{3027.5}{389} = 7.8 \text{ m}^3 = 8 \text{ m}^3
\]

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

Volume of one pipe = \[
V = \frac{\pi (0.03)^2 (3.1)}{4} = 0.0022 \text{ m}^3
\]
Volume of pipes = N * V of one = 8 * 0.0022 = 0.0175 m$^3$

The Total volume of Decomposition unit = 12.9 m$^3$ + 0.0175 m$^3$ = 12.92 m$^3$ = 13 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;

\[
W_{\text{rev} & \text{adiab}} = \frac{mzRT_1 \left[ \left( \frac{P_2}{P_1} \right)^a \right] - 1}{a}
\]

Where:

- $m$: Flow rate of inlet (mol/s)
- $z$: compressibility factor
- $R$: Gas constant (J/mol . K)
- $T_1$: Temperature inlet (K)
- $P_1$: Pressure inlet (bar)
- $P_2$: 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;

- $T_2$ : Temperature outlet (K)
- $T_1$ : Temperature inlet (K)
- $P_1$ : Pressure inlet (bar)
- $P_2$ : 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.

<table>
<thead>
<tr>
<th>Use</th>
<th>Discharge the char from reactor.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed component</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>Type of Compressor</td>
<td>Blower compressor</td>
</tr>
<tr>
<td>Inlet Pressure</td>
<td>1 bar</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>2 bar</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>25 $^\circ$C</td>
</tr>
<tr>
<td>Flow</td>
<td>0.7 mol/s</td>
</tr>
<tr>
<td>Compressibility factor, $z$</td>
<td>1</td>
</tr>
<tr>
<td>$C_p/C_v, k$</td>
<td>1.4</td>
</tr>
<tr>
<td>Gas constant, $R$</td>
<td>8.314 J/mol.K</td>
</tr>
<tr>
<td>$a$</td>
<td>0.29</td>
</tr>
</tbody>
</table>

$$W_{Theoretical} = \frac{mzRT_1 \left[ \left( \frac{P_2}{P_1} \right)^a - 1 \right]}{a}$$

$$W_{Theoretical} = 1.32 \text{ KW}$$

$$T_2 = T_1 \left( \frac{P_2}{P_1} \right)^a = 363.47 \text{ K} = 90.3 \text{ }^\circ\text{C}$$
Efficiency = $\eta = 0.8$

\[ W_{Actual} = \frac{W_{Theoretical}}{Efficiency} \]

\[ W_{Actual} = \frac{1.32 \text{ KW}}{0.8} \]

\[ W_{Actual} = 1.65 \text{ KW} \]

\[ \text{ C-202 } \]

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.

<table>
<thead>
<tr>
<th>Use</th>
<th>Discharge the char from reactor.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed component</td>
<td>Air</td>
</tr>
<tr>
<td>Type of Compressor</td>
<td>Centrifugal</td>
</tr>
<tr>
<td>Inlet Pressure</td>
<td>1 bar</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>15 bar</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>25 $^\circ$C</td>
</tr>
<tr>
<td>Flow</td>
<td>50 mol/s</td>
</tr>
<tr>
<td>Compressibility factor, $z$</td>
<td>1</td>
</tr>
<tr>
<td>$C_p/C_v, k$</td>
<td>1.4</td>
</tr>
<tr>
<td>Gas constant, $R$</td>
<td>8.314 J/mol.K</td>
</tr>
<tr>
<td>$a$</td>
<td>0.29</td>
</tr>
</tbody>
</table>

\[ W_{rev \ & \ adiab} = \frac{mzRT_1\left(\frac{P_2}{P_1}\right)^a - 1}{a} = 506.6 \text{ KW} \]

\[ T_2 = T_1 \left(\frac{P_2}{P_1}\right)^a = 363.47 \text{ K} = 90.3 \text{ }^\circ\text{C} \]

\[ T_2 = T_1 \left(\frac{P_2}{P_1}\right)^a = 363.47 \text{ K} = 90.3 \text{ }^\circ\text{C} \]
Efficiency \( \eta = 0.8 \)

\[
W_{Actual} = \frac{W_{Theoretical}}{Efficiency}
\]

\[
W_{Actual} = \frac{506.6 \text{ KW}}{0.8}
\]

\[
W_{Actual} = 633.24 \text{ KW}
\]

\[ \mathbb{C-203} \]

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.

<table>
<thead>
<tr>
<th>Use</th>
<th>Compress the gas to the cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed component</td>
<td>Gases</td>
</tr>
<tr>
<td>Type of Compressor</td>
<td>Blower compressor</td>
</tr>
<tr>
<td>Inlet Pressure</td>
<td>1 bar</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>2 bar</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>475 C(^o)</td>
</tr>
<tr>
<td>Flow</td>
<td>9.67 mol/s</td>
</tr>
<tr>
<td>Compressibility factor, (z)</td>
<td>0.99</td>
</tr>
<tr>
<td>(\frac{C_p}{C_v}, k)</td>
<td>1.06</td>
</tr>
<tr>
<td>Gas constant, (R)</td>
<td>8.314 J/mol.K</td>
</tr>
<tr>
<td>(a)</td>
<td>0.06</td>
</tr>
</tbody>
</table>

\[
W_{rev \& adiab} = \frac{mzRT_1 \left[ \left( \frac{P_2}{P_1} \right)^a \right] - 1}{a}
\]

\[
W_{Theoretical} = 42.5 \text{ KW}
\]

\[
T_2 = T_1 \left( \frac{P_2}{P_1} \right)^a = 779.09 \text{ K} = 505.9 \text{ C}^o
\]

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.

<table>
<thead>
<tr>
<th>Use</th>
<th>Compress the gas to the burner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed component</td>
<td>Gases</td>
</tr>
<tr>
<td>Type of Compressor</td>
<td>Blower compressor</td>
</tr>
<tr>
<td>Inlet Pressure</td>
<td>1 bar</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>2 bar</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>50 °C</td>
</tr>
<tr>
<td>Flow</td>
<td>4.91 mol/s</td>
</tr>
<tr>
<td>Compressibility factor, ( z )</td>
<td>0.99</td>
</tr>
<tr>
<td>( \frac{C_p}{C_v}, k )</td>
<td>1.3</td>
</tr>
<tr>
<td>Gas constant, ( R )</td>
<td>8.314 J/mol.K</td>
</tr>
<tr>
<td>( a )</td>
<td>0.23</td>
</tr>
</tbody>
</table>

\[ W\ rev\ &\ adiab = \frac{mzRT_1 \left[ \left( \frac{P_2}{P_1} \right)^a - 1 \right]}{a} \]

\[ W_{Theoretical} = 9.9 \text{ KW} \]

\[ T_2 = T_1 \left( \frac{P_2}{P_1} \right)^a = 379.9 \text{ K} = 106.75 °C \]

Efficiency = \( \eta = 0.8 \)

\[ W_{Actual} = \frac{W_{Theoretical}}{Efficiency} \]
\[ W_{Actual} = \frac{9.9\, KW}{0.8} \]

\[ W_{Actual} = 12.4\, KW \]

- **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.

<table>
<thead>
<tr>
<th>Use</th>
<th>Compress the air to the burner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed component</td>
<td>Gases</td>
</tr>
<tr>
<td>Type of Compressor</td>
<td>Blower compressor</td>
</tr>
<tr>
<td>Inlet Pressure</td>
<td>1 bar</td>
</tr>
<tr>
<td>Outlet Pressure</td>
<td>2 bar</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>25 C°</td>
</tr>
<tr>
<td>Flow</td>
<td>4.91 mol/s</td>
</tr>
<tr>
<td>Compressibility factor, z</td>
<td>0.99</td>
</tr>
<tr>
<td>( \frac{C_p}{C_v}, k )</td>
<td>1.4</td>
</tr>
<tr>
<td>Gas constant, R</td>
<td>8.314 J/mol.K</td>
</tr>
<tr>
<td>A</td>
<td>0.29</td>
</tr>
</tbody>
</table>

\[ W_{rev\&adiab} = \frac{mzRT_1 \left[ \left( \frac{P_2}{P_1} \right)^{\alpha} - 1 \right]}{\alpha} \]

\[ W_{Theoretical} = 73.9\, KW \]

\[ T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{\alpha} = 363.4\, K = 90.3\, C° \]

Efficiency = \( \eta = 0.8 \)

\[ W_{Actual} = \frac{W_{Theoretical}}{\text{Efficiency}} \]

\[ W_{Actual} = \frac{73.9\, KW}{0.8} \]
W_{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\, \text{C}^\circ
- Inlet Pressure 2 bar

**Inlet flow gases describe**

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow rate (Kg/h)</th>
<th>Mass fraction</th>
<th>LHV (KJ/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>16.78</td>
<td>0.065</td>
<td>10112</td>
</tr>
<tr>
<td>CO_2</td>
<td>32.1</td>
<td>0.125</td>
<td>---</td>
</tr>
<tr>
<td>CH_4</td>
<td>94.02</td>
<td>0.365</td>
<td>50000</td>
</tr>
<tr>
<td>C_2H_4</td>
<td>31.33</td>
<td>0.122</td>
<td>47195</td>
</tr>
<tr>
<td>H_2</td>
<td>15.43</td>
<td>0.06</td>
<td>120000</td>
</tr>
<tr>
<td>C_3H_6</td>
<td>54.8</td>
<td>0.212</td>
<td>45800</td>
</tr>
<tr>
<td>H_2S</td>
<td>13.3</td>
<td>0.052</td>
<td>15191</td>
</tr>
</tbody>
</table>

The heat capacity for inlet and outlet streams of the burner
The reactions are:

\[ 2H_2 + O_2 \rightarrow 2H_2O \]

\[ 2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \]

\[ 2CO + O_2 \rightarrow 2CO_2 \]

\[ C_3H_6 + \frac{9}{2}O_2 \rightarrow 3CO_2 + 3H_2O \]

\[ CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \]

\[ C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \]

The total heating value = \( 4.23 \times 10^4 \) KJ/Kg

The total heat generated by combustion = \((4.23 \times 10^4 \) KJ/Kg\) * (225.76 Kg/h)

\[ = 9.55 \times 10^6 \) KJ/h

Outlet flow gases describe

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow rate (Kg/h)</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>587</td>
<td>0.544</td>
</tr>
<tr>
<td>H₂O</td>
<td>466.9</td>
<td>0.432</td>
</tr>
<tr>
<td>SO₂</td>
<td>25</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Calculation of outlet temperature:

\[ Q = 0 = \Delta H = H_{46} - H_{44} - H_{45} \]

\[ H = n_i \cdot (y_i \cdot \Delta H_f + \int C_{p_{mix}}dT) \]
4- Sizing of storage tanks:

- **Gas storage**

<table>
<thead>
<tr>
<th>Used to</th>
<th>Storage the gases after the 2(^{nd}) condenser (E-204)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>257.9 Kg/h</td>
</tr>
<tr>
<td>Density</td>
<td>1.0887 Kg/m(^3)</td>
</tr>
<tr>
<td>Volumetric Flow rate</td>
<td>236.88 m(^3)/h</td>
</tr>
<tr>
<td>Maximum Storage Time</td>
<td>2 Hours</td>
</tr>
<tr>
<td>Volume required</td>
<td>500 m(^3)</td>
</tr>
<tr>
<td>Storage type</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Length</td>
<td>13 m</td>
</tr>
<tr>
<td>Height</td>
<td>7 m</td>
</tr>
</tbody>
</table>

- **Liquid storage**

  1- The storage after first flash drum

<table>
<thead>
<tr>
<th>Used to</th>
<th>Storage the liquid produces from 1(^{st}) flash drum (V-203)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>874.75 Kg/h</td>
</tr>
<tr>
<td>Density</td>
<td>772.73 Kg/m(^3)</td>
</tr>
<tr>
<td>Volumetric Flow rate</td>
<td>1.132 m(^3)/h</td>
</tr>
<tr>
<td>Maximum Storage Time</td>
<td>4 days</td>
</tr>
<tr>
<td>Volume required</td>
<td>120 m(^3)</td>
</tr>
<tr>
<td>Storage type</td>
<td>Vertical</td>
</tr>
<tr>
<td>Length</td>
<td>6 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>5m</td>
</tr>
</tbody>
</table>
1-The storage after second flash drum

<table>
<thead>
<tr>
<th>Used to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Volumetric Flow rate</td>
</tr>
<tr>
<td>Maximum Storage Time</td>
</tr>
<tr>
<td>Volume required</td>
</tr>
<tr>
<td>Storage type</td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Diameter</td>
</tr>
</tbody>
</table>

Storage the liquid produces from 2ⁿᵈ flash drum (V-202)
Appendix C

Heat Capacities
**APPENDIX C**

**HEAT CAPACITIES**

\[ \text{Cp} = A + BT + CT^2 + DT^3 = J/\text{gmol-K} \]

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B*10^2</th>
<th>C*10^4</th>
<th>D*10^8</th>
</tr>
</thead>
<tbody>
<tr>
<td>H_2S</td>
<td>33.3525</td>
<td>-0.7109</td>
<td>0.4022</td>
<td>-2.1178</td>
</tr>
<tr>
<td>C_3H_6</td>
<td>3.71</td>
<td>23.54</td>
<td>-1.16</td>
<td>2.205</td>
</tr>
<tr>
<td>H_2</td>
<td>27.14</td>
<td>0.9274</td>
<td>-0.1381</td>
<td>0.7645</td>
</tr>
<tr>
<td>C_2H_4</td>
<td>3.806</td>
<td>15.66</td>
<td>-0.8348</td>
<td>1.755</td>
</tr>
<tr>
<td>H_2O</td>
<td>32.24</td>
<td>0.1924</td>
<td>0.1055</td>
<td>-0.3596</td>
</tr>
<tr>
<td>N_2</td>
<td>31.15</td>
<td>-1.357</td>
<td>0.268</td>
<td>-1.168</td>
</tr>
<tr>
<td>Hexane</td>
<td>-4.413</td>
<td>58.2</td>
<td>-3.119</td>
<td>6.494</td>
</tr>
<tr>
<td>CH_4</td>
<td>19.25</td>
<td>5.213</td>
<td>0.1197</td>
<td>-1.132</td>
</tr>
<tr>
<td>CO</td>
<td>30.87</td>
<td>-1.285</td>
<td>0.2789</td>
<td>-1.272</td>
</tr>
<tr>
<td>Ethyl benzene</td>
<td>-43.1</td>
<td>70.72</td>
<td>-4.811</td>
<td>13.01</td>
</tr>
<tr>
<td>C_7H_8</td>
<td>-24.35</td>
<td>51.25</td>
<td>-2.765</td>
<td>4.911</td>
</tr>
<tr>
<td>C_2H_5O</td>
<td>-9.4394</td>
<td>23.2857</td>
<td>-1.4446</td>
<td>3.6226</td>
</tr>
<tr>
<td>Styrene</td>
<td>-28.25</td>
<td>61.59</td>
<td>-4.023</td>
<td>9.935</td>
</tr>
<tr>
<td>C_6H_6</td>
<td>-33.92</td>
<td>47.39</td>
<td>-3.017</td>
<td>7.13</td>
</tr>
<tr>
<td>C</td>
<td>18.3195</td>
<td>0.1524</td>
<td>-0.0015</td>
<td>0.0005</td>
</tr>
<tr>
<td>O_2</td>
<td>28.11</td>
<td>-0.0003</td>
<td>0.1746</td>
<td>-1.065</td>
</tr>
<tr>
<td>CO_2</td>
<td>19.8</td>
<td>7.344</td>
<td>-0.5602</td>
<td>1.715</td>
</tr>
</tbody>
</table>
Appendix D

*Figures Used in Calculations*
APPENDIX D

FIGURES USED IN CALCULATIONS

Constant K & n for bundle diameter:

<table>
<thead>
<tr>
<th>No. passes</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>0.319</td>
<td>0.249</td>
<td>0.175</td>
<td>0.0743</td>
<td>0.0365</td>
</tr>
<tr>
<td>$n_1$</td>
<td>2.142</td>
<td>2.207</td>
<td>2.285</td>
<td>2.499</td>
<td>2.675</td>
</tr>
</tbody>
</table>

Square pitch, $p_t = 1.25d_o$

<table>
<thead>
<tr>
<th>No. passes</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$</td>
<td>0.215</td>
<td>0.156</td>
<td>0.158</td>
<td>0.0402</td>
<td>0.0331</td>
</tr>
<tr>
<td>$n_1$</td>
<td>2.207</td>
<td>2.291</td>
<td>2.263</td>
<td>2.617</td>
<td>2.643</td>
</tr>
</tbody>
</table>

Minimum mechanical properties for 70-30 Cu-Ni(CW 354H) based on Euronorm Standards:

<table>
<thead>
<tr>
<th>Form</th>
<th>Condition</th>
<th>Thickness $t^*$</th>
<th>Tensile Strength</th>
<th>0.2% Proof Strength</th>
<th>Elongation</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mm</td>
<td>N/mm$^2$</td>
<td>N/mm$^2$</td>
<td>%</td>
<td>HV</td>
</tr>
<tr>
<td>Tube EN 12449: 1999</td>
<td>R370</td>
<td>10 max</td>
<td>370</td>
<td>120</td>
<td>35</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H085</td>
<td>10 max</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>85-120</td>
</tr>
<tr>
<td></td>
<td>R480</td>
<td>5 max</td>
<td>480</td>
<td>300</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H135</td>
<td>5 max</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>135</td>
</tr>
<tr>
<td>Sheet/plate EN 1652: 1997</td>
<td>R350</td>
<td>0.3-15</td>
<td>350-420</td>
<td>(120)</td>
<td>35 for $t$$&gt;$2.5mm</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H080</td>
<td>0.3-15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>80-120</td>
</tr>
<tr>
<td></td>
<td>R410</td>
<td>0.3-15</td>
<td>410</td>
<td>(300)</td>
<td>14 for $t$$&gt;$2.5mm</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H110</td>
<td>0.3-15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>110</td>
</tr>
<tr>
<td>Heavy Plate For pressure vessels EN 1653:1997</td>
<td>R320</td>
<td>2.5-125</td>
<td>320</td>
<td>120</td>
<td>30</td>
<td>(100)</td>
</tr>
<tr>
<td></td>
<td>R410</td>
<td>10-40</td>
<td>410</td>
<td>300</td>
<td>14</td>
<td>(140)</td>
</tr>
</tbody>
</table>
Shell-bundle clearance

- Pull-through floating head
- Spit-ring floating head
- Outside packed head
- Fixed and U-tube
Shell side heat transfer factors
Domed Heads

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)
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 PRESSURE, 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)
Section 3. Composition, Information on Ingredients

<table>
<thead>
<tr>
<th>Name</th>
<th>CAS number</th>
<th>% Volume</th>
<th>Exposure limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>124-38-9</td>
<td>100</td>
<td>ACGIH TLV (United States, 2/2010).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 54000 mg/m³ 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 30000 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 9000 mg/m³ 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 5000 ppm 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIOSH REL (United States, 6/2009).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 54000 mg/m³ 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 30000 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 9000 mg/m³ 10 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 5000 ppm 10 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OSHA PEL (United States, 6/2010).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 9000 mg/m³ 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 5000 ppm 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 54000 mg/m³ 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 30000 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 18000 mg/m³ 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 10000 ppm 8 hour(s).</td>
</tr>
</tbody>
</table>

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.
Carbon Dioxide

Carbon dioxide

ACGIH TLV (United States, 2/2010).
- STEL: 54000 mg/m² 15 minute(s).
- STEL: 30000 ppm 15 minute(s).
- TWA: 9000 mg/m² 8 hour(s).
- TWA: 5000 ppm 8 hour(s).

NIOSH REL (United States, 6/2009).
- STEL: 54000 mg/m² 15 minute(s).
- STEL: 30000 ppm 15 minute(s).
- TWA: 9000 mg/m² 10 hour(s).
- TWA: 5000 ppm 10 hour(s).

OSHA PEL (United States, 6/2010).
- TWA: 9000 mg/m² 8 hour(s).
- TWA: 5000 ppm 8 hour(s).

- STEL: 54000 mg/m² 15 minute(s).
- STEL: 30000 ppm 15 minute(s).
- TWA: 18000 mg/m² 8 hour(s).
- TWA: 10000 ppm 8 hour(s).

Consult local authorities for acceptable exposure limits.

Section 9. Physical and chemical properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight</td>
<td>44.01 g/mole</td>
</tr>
<tr>
<td>Molecular formula</td>
<td>C-O2</td>
</tr>
<tr>
<td>Melting/freezing point</td>
<td>Sublimation temperature: -79°C (-110.2 to °F)</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>30.9°C (87.6°F)</td>
</tr>
<tr>
<td>Vapor pressure</td>
<td>830 (psig)</td>
</tr>
<tr>
<td>Vapor density</td>
<td>1.53 (Air = 1) Liquid Density@BP: Solid density = 97.5 lb/ft³ (1562 kg/m³)</td>
</tr>
<tr>
<td>Specific Volume (ft³/lb)</td>
<td>8.7719</td>
</tr>
<tr>
<td>Gas Density (lb/ft³)</td>
<td>0.114</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Product/ingredient name</th>
<th>Result</th>
<th>Species</th>
<th>Dose</th>
<th>Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>LC50 Inhalation</td>
<td>Rat</td>
<td>470000 ppm</td>
<td>30 minutes</td>
</tr>
</tbody>
</table>

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.
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

<table>
<thead>
<tr>
<th>Regulatory Information</th>
<th>UN number</th>
<th>Proper shipping name</th>
<th>Class</th>
<th>Packing group</th>
<th>Label</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOT Classification</td>
<td>UN1013</td>
<td>CARBON DIOXIDE</td>
<td>2.2</td>
<td>Not applicable (gas).</td>
<td>Limited quantity</td>
<td>Yes.</td>
</tr>
<tr>
<td></td>
<td>UN2187</td>
<td>Carbon dioxide, refrigerated liquid</td>
<td></td>
<td></td>
<td></td>
<td>Packaging instruction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Passenger aircraft</td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Quantity limitation: 75 kg</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Cargo aircraft</td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Quantity limitation: 150 kg</td>
<td></td>
</tr>
<tr>
<td>TDG Classification</td>
<td>UN1013</td>
<td>CARBON DIOXIDE</td>
<td>2.2</td>
<td>Not applicable (gas).</td>
<td>Explosive Limit and Limited Quantity Index</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td>UN2187</td>
<td>Carbon dioxide, refrigerated liquid</td>
<td></td>
<td></td>
<td>Passenger Carrying Road or Rail Index</td>
<td>75</td>
</tr>
<tr>
<td>Mexico Classification</td>
<td>UN1013</td>
<td>CARBON DIOXIDE</td>
<td>2.2</td>
<td>Not applicable (gas).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>UN2187</td>
<td>Carbon dioxide, refrigerated liquid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."
**Carbon Dioxide**

**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 PRESSURE. 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
- Reactivity: 0
- Personal protection

National Fire Protection Association (U.S.A.)

- Health: 1
- Flammability
- Instability
- Special

Liquid:

- Flammability
- Instability
- Special

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.
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; Fermentation powder; Fermentice liquid; Sulfur oxide (SO2); Sulfurous anhydride; Sulfurous oxide; SO2; Sulphur dioxide; Fermentation liquid; Schwefeloxyst; Sianki [Sulfuric]
Sulfur oxide; UN 1079; Oxosulfane oxide 001047

MSDS #:
Date of Preparation/Revision: 3/20/2012.
In case of emergency: 1-866-734-3438

Section 2. Hazards identification

Physical state: Gas. [COLOURLESS 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:
Potential acute health effects:

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
Potential chronic health effects:

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

<table>
<thead>
<tr>
<th>Name</th>
<th>CAS number</th>
<th>% Volume</th>
<th>Exposure limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur Dioxide</td>
<td>7446-09-5</td>
<td>100</td>
<td>ACGIH TLV (United States, 1/2009).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 0.25 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 2 ppm 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 5 mg/m³ 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 5 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 10 mg/m³ 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIOSH REL (United States, 6/2009).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 2 ppm 10 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 5 mg/m³ 10 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 5 ppm 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STEL: 10 mg/m³ 15 minute(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OSHA PEL (United States, 11/2006).</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>TWA: 5 ppm 8 hour(s).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TWA: 10 mg/m³ 8 hour(s).</td>
</tr>
</tbody>
</table>

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.

Build 1.1

Page: 2/7
**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).
- 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: 10 mg/m³ 15 minute(s).
- 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: O2-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 (ft³/lb): 5.9172
- Gas Density (lb/ft³): 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

<table>
<thead>
<tr>
<th>Toxicity data</th>
<th>Result</th>
<th>Species</th>
<th>Dose</th>
<th>Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur dioxide</td>
<td>LC50 Inhalation Gas.</td>
<td>Mouse</td>
<td>3000 ppm</td>
<td>0.5 hours</td>
</tr>
<tr>
<td></td>
<td>LC50 Inhalation Gas.</td>
<td>Rat</td>
<td>2520 ppm</td>
<td>1 hours</td>
</tr>
<tr>
<td></td>
<td>LC50 Inhalation Gas.</td>
<td>Rat</td>
<td>2520 ppm</td>
<td>1 hours</td>
</tr>
</tbody>
</table>

- 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: No known significant effects or critical hazards.
- 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: Not available.
- Environmental fate: Not available.
- Environmental hazards: No known significant effects or critical hazards.
- 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

<table>
<thead>
<tr>
<th>Regulatory Information</th>
<th>UN number</th>
<th>Proper shipping name</th>
<th>Class</th>
<th>Packing group</th>
<th>Label</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOT Classification</td>
<td>UN1079</td>
<td>SULFUR DIOXIDE</td>
<td>2.3</td>
<td>Not applicable (gas).</td>
<td><img src="image1" alt="Image" /></td>
<td>Limited quantity Yes. Packaging instruction Passenger aircraft Quantity limitation: Forbidden. Cargo aircraft Quantity limitation: Forbidden. Special provisions 3, B14, T50, TP19</td>
</tr>
<tr>
<td>TDG Classification</td>
<td>UN1079</td>
<td>SULFUR DIOXIDE; OR SULPHUR DIOXIDE</td>
<td>2.3</td>
<td>Not applicable (gas).</td>
<td><img src="image2" alt="Image" /></td>
<td>Explosive Limit and Limited Quantity Index 0 ERAP Index 500 Passenger Carrying Ship Index Forbidden Passenger Carrying Road or Rail Index Forbidden</td>
</tr>
<tr>
<td>Mexico Classification</td>
<td>UN1079</td>
<td>SULFUR DIOXIDE</td>
<td>2.3</td>
<td>Not applicable (gas).</td>
<td><img src="image3" alt="Image" /></td>
<td>-</td>
</tr>
</tbody>
</table>

*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 302/304/311/313/312 extremely hazardous substances: sulphur dioxide
SARA 302/304 emergency planning and notification: sulphur dioxide
SARA 302/304/311/313/312 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.

Clean Air Act (CAA) 112 regulated flammable substances: No products were found.
Clean Air Act (CAA) 112 regulated toxic substances: sulphur dioxide

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 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 NPR: 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
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.