DESIGN AND FABRICATION OF A PILOT SCALE STRIPPING UNIT TO TREAT 5 BARRELS PER DAY OF ABU ZARIA MINIREFINERY SOUR WATER

BY

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DEPARTMENT OF CHEMICAL ENGINEERING,
FACULTY OF ENGINEERING,
AHMADU BELLO UNIVERSITY,
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April, 2021

DECLARATION

I declare that this dissertation titled “***DESIGN AND FABRICATION OF A PILOT SCALE STRIPPING UNIT TO TREAT 5 BARRELS PER DAY OF ABU ZARIA MINIREFINERY SOUR WATER***” was duly undertaken and compiled by me at the Department of Chemical Engineering, under close supervision of Prof. I. A Mohammmed-Dabo and Dr. M. A. Evuti. Literatures consulted have been duly acknowledged in the text and contained in the list of references.

Aminu, Uba Alhassan

..
Signature/Date

CERTIFICATION

This dissertation report titled "**DESIGN AND FABRICATION OF A PILOT SCALE SOUR WATER STRIPPING UNIT** meets the regulations governing the award of Master of Science in Chemical Engineering of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

Prof. I. A. Mohammed-Dabo __________________ ______________
(Chairman, Supervisory Committee) **Signature** **Date**

Prof. M. A. Evuti __________________ ______________
(Member, Supervisory Committee) **Signature** **Date**

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(Dean School of Postgraduate Studies) **Signature** **Date**

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DEDICATION

To my caring mother, myloving wife and my wonderful daughters; Umm-kursum, Zeenat, Umm-kursum, and Fatima-Zahra, respectively.

ABSTRACT

This research work, design and fabrication of a pilot scale sour water stripping unit, is an integral part of the ABU Mini-refinery development. The unit serves the functions of treating the effluent water from various units of the said refinery to environmentally acceptable threshold before disposal to the environment. The design was based ona capacity of 5 barrels per day. Material and Energy balances were performed on the developed process flow diagram before detailed equipment design was done using Mathcad and Hysys simulation. Fabricated equipment were Surge Drum (V-100), Reflux Drum (V-101), Feed Preheater (E-100), Stripper Column Overhead Condenser (E-101), Column Bottom Reboiler (E-102), Product Cooler (E-103), and Stripper Column (C-100). The Designed equipment were sequentially installed in accordance with the proposed Unit's Process Flow Diagram.For energy economy, the entire unit was lagged using ISO-900-01 Fiberglass.Instrumentation and Control systems were specified to measure and control Flow, Liquid level, Temperature & Pressure to ensure on-spec product.The unit was, finally, test ran and product samples were collected and analyzed in the laboratory. Results of the laboratory analyses show that the pH of the water was reduced from 6.8 to 7.5. This is within the acceptable standard pH range of 6.5 to 8.5. Volatile Organic Compounds were reduced from 1800 mgl^{-1} to 478.8 mgl^{-1}. This value is far above the standard value of <10 mgl^{-1}. The hydrogen sulfide was reduced from 16 mgl^{-1} to 12.26 mgl^{-1}. This value is far above the standard value of <0.2 mgl^{-1}. Also, Ammonia was also reduced from 11.8 mgl^{-1} to 6.2 mgl^{-1}. This value is also far above the standard value of <0.2 mgl^{-1}. For better result and efficiency, optimization and upgrading of the SWS unit is recommended.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATE

CHAPTER ONE

1.0 INTRODUCTION

1.1 **Back Ground:**

Stripping is the transfer of volatile components of a liquid into a gas stream (usually air or steam). It is an environmental engineering technology used for the purification of ground and waste waters containing volatile organic compounds (Henry, 1992).

Refineries that process crude containing sulfur liberate the sulfur in various unit operations as hydrogen sulfide. Water that contains sulfide is called sour water. Reuse or disposal of sour water requires removing the sulfides from the water in a process called stripping (Emerson, 2008).

The stripping process uses a gas stream to force both the hydrogen sulfide (H_2S), ammonia (NH_3), Volatile Organic Compounds (VOCs), and in some cases, sulfur dioxide (SO_2), out of solution and into the gas phase for further treatment. Although air stripping can be used, steam stripping (which liberates more H_2S due to higher temperatures) is typically required in refinery sour water treatment to meet specifications for the stripped water (Emerson, 2008).

Volatile compounds have relatively high vapor pressure and low aqueous solubility characterized by the compound's Henry's law coefficient, which is the ratio of the concentration in air that is in equilibrium with its concentration in water. Pollutants with relatively high Henry's Law coefficients can be economically stripped from water. These include BTEX (Benzene, Toluene, Ethylbenzene, and Xylene) compounds found in gasoline, and solvents including Trichloroethylene and Tetrachloroethylene. Ammonia can also be stripped from wastewaters and liquid digestates (often requiring pH adjustment prior to stripping). Since Henry's law coefficient increases with temperature, stripping is easier at warmer temperatures (Henry, 1992).

$$p_{\mathrm{a}}=H_{\mathrm{a}}\,x_{\mathrm{a}} \tag{1}$$

In the past, the major objectives of wastewater treatment were the removal of suspended solids (SS), biochemical oxygen demand (BOD), and coliform bacteria. It is only very recently that the removal of inorganic nutrients, such as nitrogen and phosphorus, has been brought into focus. This is because it has been realized that the discharge of these nutrients into surface waters can result in excessive growths of algae and other aquatic plants, a phenomenon commonly referred to as "eutrophication."

Municipal wastewater and many industrial wastes are among the principal contributors of these nutrients to surface waters. For example, the average concentrations of nitrogen and phosphorus in typical domestic wastewater are, respectively, about 35–45 mg/L as N and 10–15 mg/L as P. Yet, nutrient concentrations of as low as 0.3–0.5 mg/L of nitrogen and 0.01–0.05 mg/L of phosphorus have been reported to cause eutrophication. Therefore, to eliminate this problem, a high efficiency of nutrient removal in the waste treatment process must be achieved. Conventional waste treatment processes are effective in removing only about 40–50% of the nitrogen and 25–30% of the phosphorus. Therefore, new treatment technologies must supplement conventional methods in order to improve the nutrient removal efficiencies (Lamarre and Sherouse, 1994).

Within a waste treatment plant, organic nitrogen is easily converted into ammonia species through hydrolysis, which can take place in various treatment units. A portion of ammonia is then utilized by bacteria for cell synthesis, and the remaining ammonia usually leaks out in the final plant effluent as residual ammonia nitrogen. In some situations, active biological nitrification may take place in the aeration tank. In such a case, most of the excess ammonia will be converted to nitrates (Smith, 1972).

The presence of organic compounds that are potentially hazardous and toxic in water bodies is made increasingly evident by advances in analytical methods. This has resulted in the development of new technologies for the removal of these compounds from raw potable surface and groundwater supplies, as well as from process stream wastewater and effluent from groundwater remedial activities.

The removal of substances having reasonable equilibrium vapor pressures at ambient temperatures, including ammonia, carbon dioxide, hydrogen sulfide, and many VOCs (volatile organic compounds), by any of the processes known as air or gas stripping has proven to be efficient and cost effective. The Henry's law constant is a primary indicator of a compound's potential for removal by gas stripping (Lee *et at*, 1987).

It is an established fact that ABU Zaria Mini refinery, like any other conventional refinery, does produce waste (sour) water during operation. This waste water is being produced from its various process units like the Crude Distillation Unit (CDU), Desalter Unit, Fluid Catalytic Cracking (FCC) Unit, Naphtha Hydro-treating Unit (NHU), Catalytic Reforming Unit (CRU), etc. This waste water does contain toxic contaminants such as Dissolved Hydrogen Sulfide, Ammonia, Volatile Organic Compounds, etc. in environmentally unacceptable concentration, hence, need to be completely removed or lowered to abide by local Environmental laws before discharge.

AIM AND OBJECTIVES

The aim of this research work is to design and fabricate a pilot scale (5 BPD) Sour Water Stripping Unit for ABU Mini-refinery sour water treatment.

The aim was achieved via the following objectives:

- Carrying out feed (Sour Water) characterization.
- Carrying out detailed process/technology selection.
- Carrying out material and energy balances across the Stripper Unit.
- Carrying out detailed equipment design and material selection.
- Carrying out fabrication and installation of the process equipment.
- Carrying out test-running the SWS unit and generating operational data.

1.2 JUSTIFICATION

Gas stripper, also called sour water stripper (SWS) in petroleum refineries, is a process equipment usually installed in the manufacturing industries to treat their effluent sour water before release to the aquatic environment or before it is sent to the conventional sour water treatment (WWT) plants as they (WWT) do not have the capability of removing impurities such as VOCs, H_2S, NH_3, SO_2, etc.

The sour waterfrom various process units of many refineries (ABU Zaria mini refinery inclusive) contains these impurities in environmentally unacceptable concentrations.

This research project is to Design and Fabricate a SWS that can be used to remove or to lower the concentration of these impurities to an environmentally friendly threshold.

1.3 PROBLEM STATEMENT

- The non-existence of a local technology on Sour Water Stripper processes in Nigeria.
- In academia, the lack of SWS unit operational data fills the gap between theoretical knowledge and practical known how.
- Variation of pressure within columns leading to tray collapse.
- Absence of Sour Water Stripping unit in ABU Zaria Mini refinery.

1.4 SCOPE

This research project was limited to the Design and Fabrication of a mini-refinery sized Sour Water Stripper. In addition, it includes the analysis of the Stripper's operational performance by measuring and comparing the concentration of impurities in both its influent and effluent streams.

CHAPTER TWO

LITERATURE REVIEW

2.1 AIR STRIPPING

Air stripping is the transferring of volatile components of a liquid into an air (gas) stream. It is an environmental engineering technology used for the purification of ground waters and wastewaters containing volatile compounds (Ball and Edwards, 1992).

Volatile compounds have relatively high vapor pressure and low aqueous solubility characterized by the compound’s Henry's law coefficient, which is the ratio of the concentration in air that is in equilibrium with its concentration in water. Pollutants with relatively high Henry’s Law coefficients can be economically stripped from water. These include compounds like benzene, toluene, ethylbenzene, and xylene (BTEX) found in gasoline, and solvents including trichloroethylene and Tetrachloroethylene. Since Henry’s law coefficient increases with temperature, stripping is easier at warmer temperatures (Henry, 1992).

Air stripping is a technology in which volatile organic compounds (VOCs) are transferred from extracted water to air. Typically, air stripping takes place in a packed tower known as an air stripper (see Figure 2.1).

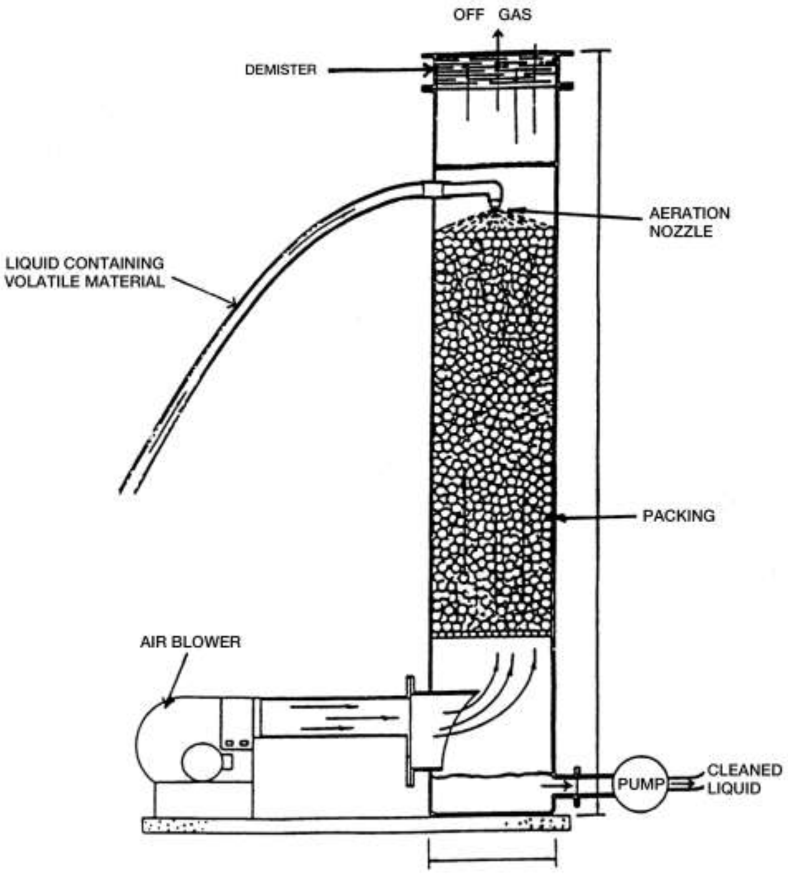


Figure 2.1: The Countercurrent Packed-Tower Type Air Stripper

The "air stripper" includes a spray nozzle at the top of the tower. It sprays groundwater that has been pumped to the surface over the packing in the column. As the water descends, air is forced up through the column, stripping off the volatile compounds. Packing or baffles within the tower increase the surface area of the contaminated water that is exposed to air, thus maximizing the amount of volatilization. A sump at the bottom of the tower collects decontaminated water. Auxiliary equipment may include an air heater to improve removal efficiency and air emission scrubbers (Little and Marinas, 1997).

Traditional air strippers vary in height, and the height is correlated to the chemical concentration of the contaminated water. A recent innovation in air strippers is the low-profile air stripper.

These units have a number of trays that are set almost horizontally. Water is cascaded over the trays to maximize air-water contact while minimizing vertical space. Because they are not so visible, they are increasingly being used for groundwater treatment.

2.1.1 The Stripping Theory:

Air stripping is the mass transfer of VOCs that are dissolved in water from the water phase to the air phase. The equilibrium relationship is linear and is defined by Henry's Law (Kavanaugh and Trussell, 1980; Shulka and Hicks, l984). For low concentrations of volatile compound *a*(see Equation 1)

At equilibrium, the partial pressure of a gas, p_a, above a liquid is directly proportional to the mole fraction of the gas, x_a, dissolved in the liquid. The proportionality constant, H_a, is known as the Henry's constant. The value of the constant generally increases or decreases with the liquid temperature (Plambeck, 1995). As a consequence, the solubility of gases generally decreases with increasing temperature (Plambeck, 1995).

Practical application of the technology for contaminant removal is generally limited to compounds with Henry's constant values greater than 100 atmospheres. Units, as defined by Henry's law, as stated, are standard atmospheres [atm] with the concentratio *n* of the solute given as the mole fraction of the solution.

Air strippers cannot remove chemicals that do not evaporate, but works best on chemicals that evaporate easily. The key variable in the design equations for air stripping systems is Henry's law constant ***H***, and the contaminant diffusivity in water. Table 2.1 below list common compounds and the easiness to strip by air based on Henry's law constant. The constant ***H*** will determine how appropriate air stripping can be as a remedial option (Nirmalakhandan*et al*, 1997).

Table 2.1: Contaminants Removal Based on Henry's Law Constant(Nirmalakhandan, 1997).

COMPOUND	Henry's Constant*	
Vinyl Chloride	50	Easiest to remove
Hydrogen Sulfide	9.784	↓
Tetrachloroethylene	1	
1,1-Dichloroethane	0.6	
Trichloroethylene	0.5	
Toluene	0.3	
Benzene	0.2	
1,1,1-Trichloroethane	0.2	
Chloroform	0.1	
Methylene Chloride	0.1	
Heptachlor	0.06	
Nitrobenzene	0.001	
Ammonia	0.0006	
Phenol	0.000005	Hardest to remove

* mg/L in air per mg/L at 25^{o}C

Air strippers are custom designed and fabricated for specific site requirements. Table 2.2provides a summary example of several air stripper systems (Nirmalakhandan*et al*, 1997).

Table 2.2: Summary Example of Air Stripper Systems

Contaminants	MTBE	TCE	Methane	Radon	H_2S	NH_3
Water Flow, gpm	150	250	200	1000	600	130
Concentration	1.0 mg/L	0.3 mg/L	15 mg/L	35 Bq/L	400 ppm	19 mmp
Temperature	70	70	60	70	54	90
Removal Efficiency %	98	98.5	99	99	90	90
Tower Diameter, Ft	4.0	3.5	3.0	6.0	6.0	9.0
Packing Height, Ft	18.0	16.0	8.5	10.5	10.0	20.5
Air Flow Rate, ACFM	4000	1000	600	4000	800	27000

2.1.2 Typical Air Stripping System

Air stripping is a full-scale technology in which volatile organics are partitioned from ground water by greatly increasing the surface area of the contaminated water exposed to air. Types of aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration (Stocking*et al*, 2001).

Air stripping involves the mass transfer of volatile contaminants from water to air. For ground water remediation, this process is typically conducted in a packed tower or an aeration tank (Linek *et al*, 1998). The typical packed tower air stripper includes a spray nozzle at the top of the tower to distribute contaminated water over the packing in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect decontaminated water. Auxiliary equipment that can be added to the basic air stripper includes an air heater to improve removal efficiencies; automated control systems with sump level switches and safety features, such as differential pressure monitors, high sump level switches, and explosion-proof components; and air emission control and treatment systems, such as activated carbon units, catalytic oxidizers, or thermal oxidizers. Packed tower air strippers are installed either as permanent installations on concrete pads or on a skid or a trailer (Srinivasan *et al*, 2002).

Aeration tanks strip volatile compounds by bubbling air into a tank through which contaminated water flows. A forced air blower and a distribution manifold are designed to ensure air-water contact without the need for any packing materials.

The baffles and multiple units ensure adequate residence time for stripping to occur. Aeration tanks are typically sold as continuously operated skid-mounted units. The advantages offered by aeration tanks are considerably lower profiles (less than 2 meters or 6 feet high) than packed towers (5 to 12 meters or 15 to 40 feet high) where height may be a problem, and the ability to modify performance or adapt to changing feed composition by adding or removing trays or chambers. The discharge air from aeration tanks can be treated using the same technology as for packed tower air discharge treatment (McKinnon and Dyksen, 1984).

Modifying packing configurations greatly increase removal efficiency. A recent innovation is the so-called low-profile air stripper that is offered by several commercial vendors. This unit packs a number of trays in a very small chamber to maximize air-water contact while minimizing space. Because of the significant vertical and horizontal space savings, these units are increasingly being used for ground water treatment.

Air strippers can be operated continuously or in a batch mode where the air stripper is intermittently fed from a collection tank. The batch mode ensures consistent air stripper performance and greater energy efficiency than continuously operated units because mixing in the storage tanks eliminates any inconsistencies in feed water composition.

The eventual duration of cleanup using an air stripping system may be tens of years and depends on the capture of the entire plume from the ground water (Ball and Edwards, 1992).

2.1.3 Applicability

Air stripping is used to separate VOCs from water. It is ineffective for inorganic contaminants. Henry's law constant is used to determine whether air stripping will be effective. Generally, organic compounds with constants greater than 0.01 atmospheres - m^3/mol are considered amenable to stripping. Some compounds that have been successfully separated from water using air stripping include BTEX, chloroethane, TCE, DCE, and PCE (Chang, et. al., (1992).

2.1.4 Limitations

The following factors may limit the applicability and effectiveness of air stripping process (Thom and Byers, 1993):

- The potential exists for inorganic (e.g., iron greater than 5 ppm, hardness greater than 800 ppm) or biological fouling of the equipment, requiring pretreatment or periodic column cleaning.
- Effective only for contaminated water with VOC or semi-volatile concentrations with a dimensionless Henry's constant greater than 0.01.

- Consideration should be given to the type and amount of packing used in the tower
- Process energy costs are high.
- Compounds with low volatility at ambient temperature may require preheating of the ground water.
- Off-gases may require treatment based on mass emission rate.

2.2 AIR STRIPPER TYPES

2.2.1 Packed Column Air Strippers

Air strippers provide contact between air and water that encourages volatile materials to move from the water to the air. A packed column air stripper consists of a cylindrical column that contains a water distribution system above engineered (structured or dumped) packing with an air distributor below (see Figure 2.2). Water containing VOCs is distributed at the top of the column and flows generally downward through the packing material (Treybal, 1980). At the same time, air, introduced at the bottom of the column, flows upward through the packing (countercurrent flow). The packing provides an extended surface area and impedes the flow of both fluids, extending the contact between them.

As water and air contact, VOCs move from the water to the air. The water leaves the bottom of the column depleted of VOCs. The VOCs transferred to the air exit the top of the column in the air stream. Off- gas (air) is released to the atmosphere or treated if necessary to meet emission limits. Detailed information on packed column air strippers is available in the literature (Kavanaugh and Trussell, 1980; Montgomery, 1985; Treybal, 1980).

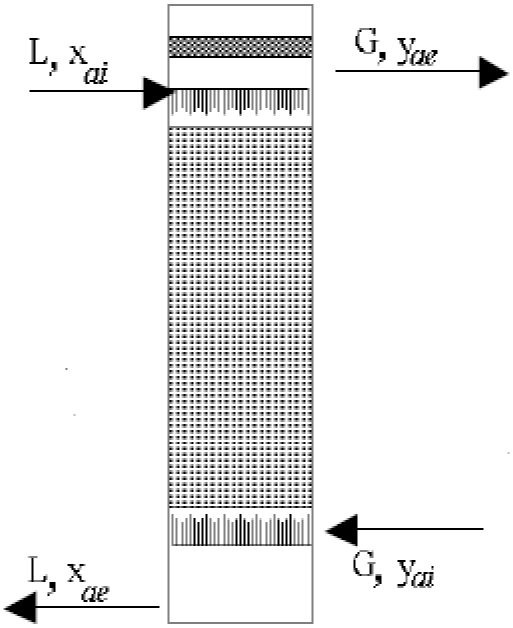


Figure 2.2: Typical Packed column air stripper.

Where:

L = molar flow of liquid (water)

G = molar flow of gas (air)

x_{ai} = mole fraction of compound *a* in influent liquid (water)

x_{ae} = mole fraction of compound *a* in effluent liquid (water)

y_{ai} = mole fraction of compound *a* in influent gas (air)

$y_{ai} = 0$

y_{ae} = mole fraction of compound *a* in effluent gas (air)

2.2.1.1 Mass Transfer Operations in Packed Towers

Stripping is the process of forcing gas through polluted groundwater or surface water to remove harmful chemicals. The air causes the chemicals to change from a liquid to a gas (evaporate).

The gas is then collected and cleaned. Air stripping is commonly used to treat ground-water as part of a pump and treat remedy (Hines and Maddox, 1995).

Process consists of counter-current flow of water and air through a packing material. The packing material provides a high surface area for VOC transfer from the liquid to the gaseous phase. A wide variety of packing types are presently in use; several of these are shown in Figure 2.3. Although Raschig rings and Berl saddles were the most popular packing for many years, these have been largely replaced by higher capacity and more efficient packing, such as Pall rings, Intalox and Super Intalox saddles, and Flexipak. The characteristics and effectiveness of the various types of Random packing can be seen on Table 2.3. The type of packing selected for a process depends on several factors. Desirable properties of the packing are (Straigle, 1994):

(i). Large void volume to decrease pressure drop,

(ii). Chemically inert to the fluids being processed.

(iii). Large surface area per unit volume of packing.

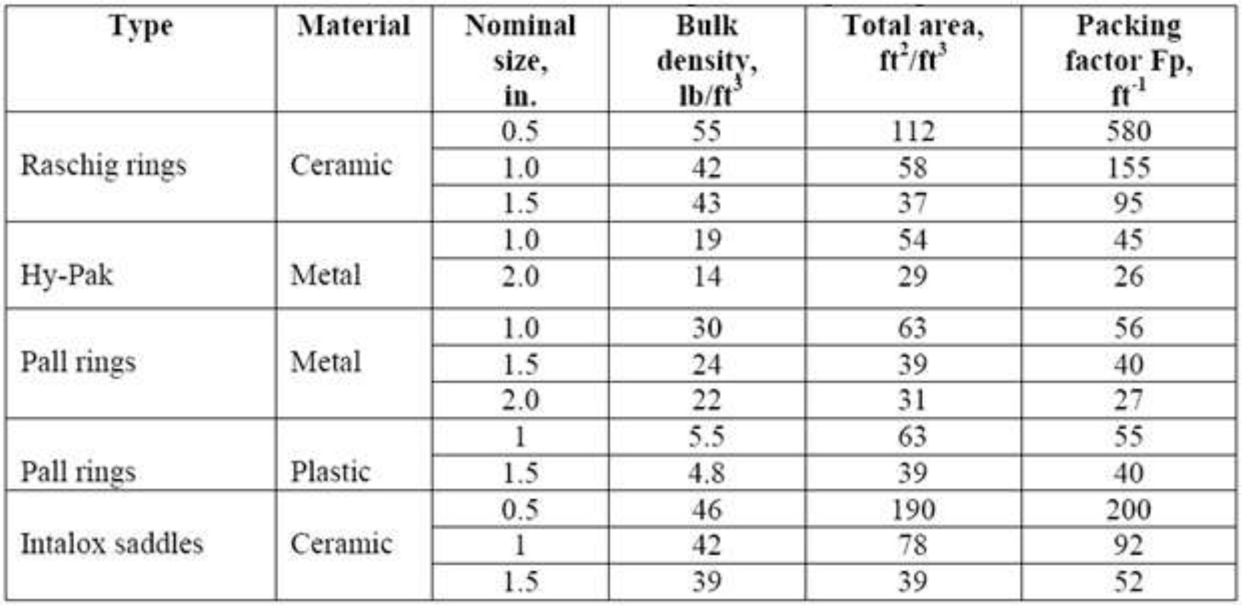
(iv). Light weight but strong.

(v). Good distribution of fluids.

(vi). Good wet ability.

Tower packing are usually available in a variety of materials, including ceramic, metal, plastic, and carbon. In addition to desirable properties of packing, one limitation on the packing is that the size should not be greater than one-eighthof the tower diameter. If the size of the packing for particular tower is too large, a decrease in operating performance will result because channeling along the column wall (Piche*et al*, 2001).

Table 2.3: Characteristics and Effectiveness of Types of Random Packing(Piche*et al*, 2001).



Type	Material	Nominal size, in.	Bulk density, lb/ft^3	Total area, ft^2/ft^3	Packing factor Fp, ft^{-1}
Raschig rings	Ceramic	0.5	55	112	580
		1.0	42	58	155
		1.5	43	37	95
Hy-Pak	Metal	1.0	19	54	45
		2.0	14	29	26
Pall rings	Metal	1.0	30	63	56
		1.5	24	39	40
		2.0	22	31	27
Pall rings	Plastic	1	5.5	63	55
		1.5	4.8	39	40
Intalox saddles	Ceramic	0.5	46	190	200
		1	42	78	92
		1.5	39	39	52

2.2.1.2 Types of Packing

Basically, there are two types of packing as used in the chemical, petroleum and petrochemical industries. These are; (1) Random Packing and (2) Structured Packing.

2.2.1.2.1 Random Packing:Random Packing is made-up of rings, saddles or spheres of different materials like metals, ceramic, plastics, wood etc (see Figure 2.3 A&B). They are placed randomly in columns to provide a high surface are of contact between liquid and gaseous streams.

Nominal packing size 50 mm			
Metal	Ceramic	Plastic	
CMR No. 2 $N = 32950$ $a = 150$ $\varepsilon = 0.95$	Pall ring $N = 6400$ $a = 120$ $\varepsilon = 0.78$	Pall ring $N = 5700$ $a = 110$ $\varepsilon = 0.92$	Hackette $N = 12400$ $a = 135$ $\varepsilon = 0.93$
Hiflow ring $N = 5000$ $a = 97.3$ $\varepsilon = 0.973$	Hiflow ring $N = 4950$ $a = 86.7$ $\varepsilon = 0.815$	Hiflow ring $N = 6400$ $a = 112$ $\varepsilon = 0.93$	DINPAC $N = 29000$ $a = 135$ $\varepsilon = 0.92$
VSP ring $N = 7800$ $a = 104$ $\varepsilon = 0.98$	INTALOX saddle $N = 9300$ $a = 120$ $\varepsilon = 0.77$	NOR-PAC ring $N = 7300$ $a = 90$ $\varepsilon = 0.952$	ENVIPAC $N = 5800$ $a = 96$ $\varepsilon = 0.961$
Units $N\ [1/m^3]$, $a\ [m^2/m^3]$, $\varepsilon\ [m^3/m^3]$			

Figure 2.3: (A) Samples of, (B) Types of Random Packing (Straigle, 1994).

2.2.1.2.2 Structured Packing: Structured packing is formed from thin corrugated metal plates or gauzes arranged in a way that forces fluid to take complicated paths through a column thereby creating a larges surface area of contact between different phases. The result is a very honeycomb structure with inclined flow channels giving a relatively high surface area but with low resistance to gas flow. The surface enhancement is chosen to maximize liquid spreading – this characteristic tends to show significant performance benefit in low pressure and low irrigation rate applications. Figure 2.4 A and B below shows different forms of structured parking(Straigle, 1994).

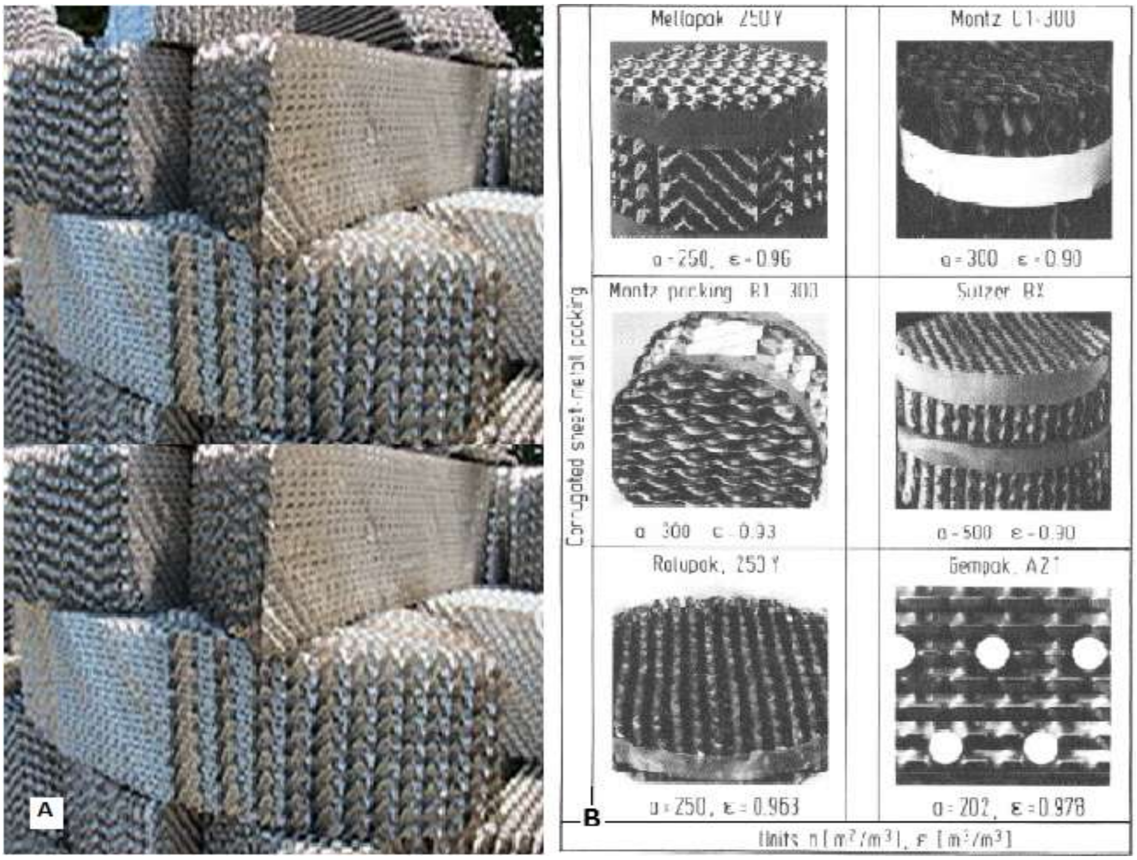


Figure 2.4: (A) Sample of, (B) Types of Structured Packing(Straigle, 1994).

The Packing surface ranges from 50 m^2/m^3 for lowest efficiency and highest capacity to 750 m^2/m^3 for highest efficiency and lowest capacity. A good compromise between efficiency and capacity is always recommended(Straigle, 1994).

2.2.2 Sieve Tray Air Stripper

Sieve tray air strippers operate in a similar way to packed column air strippers (Figure 2.5). The difference is that the liquid (water) flows across trays that are perforated with small holes, over a weir, and through a downcomer, to the next lower tray, tray by tray, until the treated water flows from the bottom of the stripper. Gas (air) is bubbled through the holes in the trays, stopping the liquid from dripping through them. The VOCs are transferred from the liquid to the gas phase as the air is bubbled through the water on the trays (Mead and Leibbert, 1998).

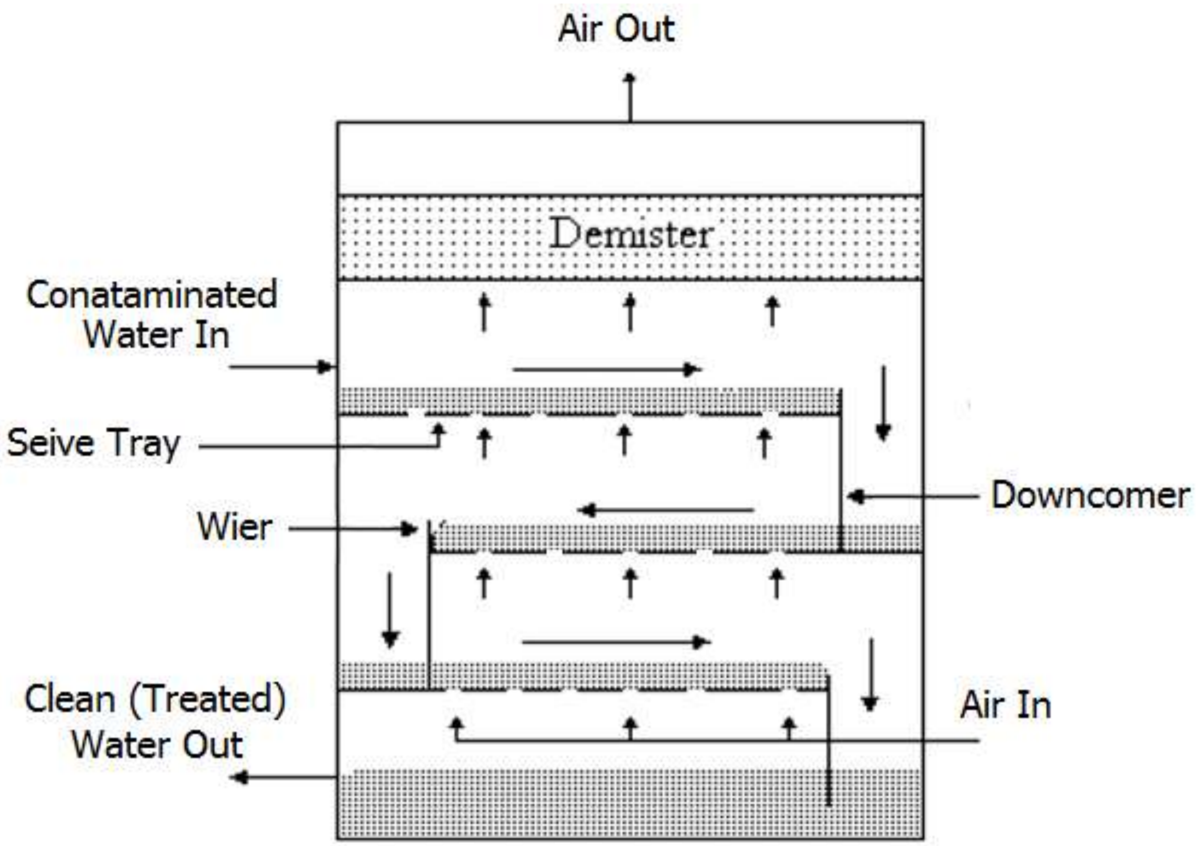


Figure 2.5: Low profile sieve tray air stripper(Mead and Leibbert, 1998).

2.2.3 Diffused Aeration Stripper:

A diffused aeration stripper is a vessel or liquid (water) reservoir with gas (air) diffusers near the bottom (Figure 2.6). Air enters through diffusers and rises through the liquid to exit at the top of the vessel. The VOCs move from the water to the air as the bubbles rise through the water. Transfer of the VOCs from the water to the air can be improved by increasing the vessel depth or by producing smaller bubbles. The air path through the liquid is straight and contact between the air and water is short. Therefore, diffused air is not efficient. Its main advantages are that it is simple and can handle water having high levels of suspended solids (Bilello and Singley, 1986).

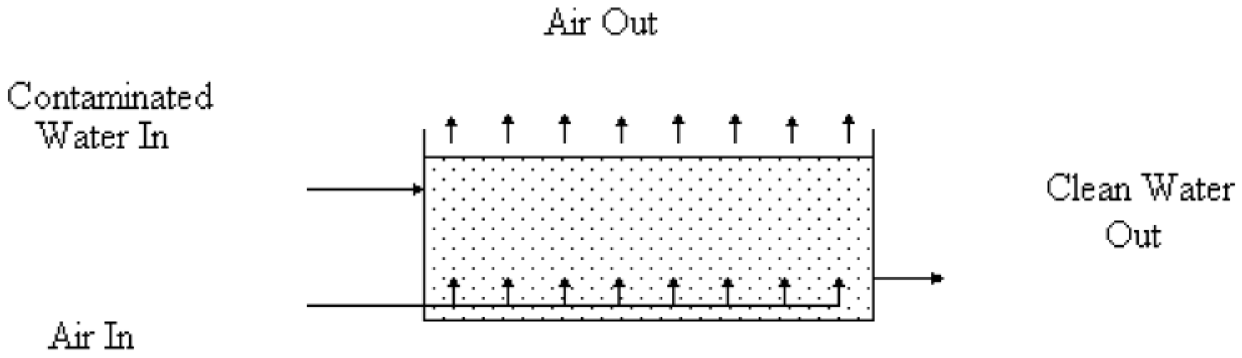


Figure 2.6: Diffused aeration air stripper.

2.3 STEAM STRIPPING

Stripping is a physical separation process where one or more components are removed from a liquid stream by vapor stream. In industrial applications, the liquid and vapor streams can have co-current or countercurrent flows. Stripping works on the basis of mass transfer. The idea is to make the conditions favorable for the component, A, in the liquid phase to transfer to the gas/vapor phase. This involves a gas–liquid interface that A must cross. The total amount of A that has moved across this boundary can be defined as the flux of A, N_A (Jaeger, 1996). Figure 2.7 shows the internal of Steam Stripping column with bubble cap trays.

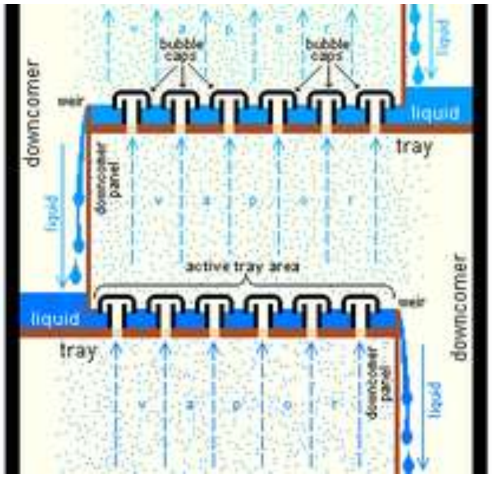


Figure 2.7: Bubble Cap Tray of a Stripping Column(Jaeger, 1996).

Stripping is mainly conducted in tray towers (plate columns) and packed columns, and less often in spray towers, bubble columns, and centrifugal contactors (Chuang and Nandakumar, 2000).

Tray towers consist of a vertical column with liquid flowing in the top and out the bottom. The vapour phase enters in the bottom of the column and exits out of the top. Inside of the column are trays or plates. These trays force the liquid to flow back and forth horizontally while the vapor bubbles up through holes in the trays. The purpose of these trays is to increase the amount of contact area between the liquid and vapor phases (Chuang and Nandakumar, 2000).

Packed columns are similar to tray columns in that the liquid and vapor flows enter and exit in the same manner. The difference is that in packed towers there are no trays. Instead, packing is used to increase the contact area between the liquid and vapor phases. There are many different types of packing used (see Figures 2.3 and 2.4).

The variables and design considerations for strippers are many. Among them are the entering conditions, the degree of recovery of the solute needed, the choice of the stripping agent and its flow, the operating conditions, the number of stages, the heat effects, and the type and size of the equipment.The degree of recovery is often determined by environmental regulations, such as for volatile organic compounds like chloroform (Culp and Culp, 1971).

Frequently, steam, air, inert gases, and hydrocarbon gases are used as stripping agents. This is based on solubility, stability, degree of corrosiveness, and availability. As stripping agents are gases, operation at nearly the highest temperature and lowest pressure that will maintain the components and not vaporize the liquid feed stream is desired. This allows for the minimization of flow. As with all other variables, minimizing cost while achieving efficient separation is the ultimate goal.

2.3.1 Typical Steam Stripping Set-Up

The configuration of a steam stripping unit can vary depending on the characteristics of the organic material to be removed, and on what is to be done with it in terms of disposal and recycle. As a minimum, a steam stripping unit will look like the unit depicted in Figure 2.8 (Jaeger,1996).

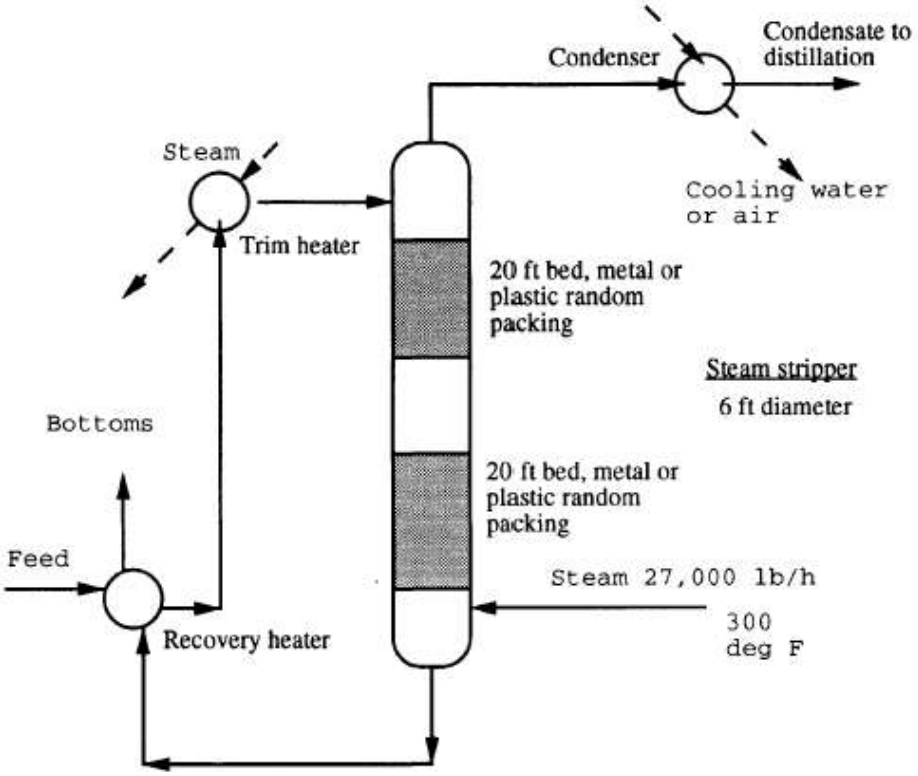


Figure 2.8: Simple Steam Stripper Without Solvent Recovery (Jaeger,1996)

It is important to note that heat recovery from the bottom product is necessary for economical operation. Operations at reduced pressure do not need recovery exchangers, but operate at lower temperatures and larger steam rates (Jaeger, 1996). The towers also tend to be a bit larger in vacuum operations.

Steam requirements for stripping vary with the operating pressure, the type of organic, and the degree of organic removal/recovery. Further, steam requirements for heat balance purposes need to be accounted for. A very important consideration in the design of a steam stripper is the fact that the column needs to be capable of handling enough steam flow to operate without the benefit of the recovery exchanger. This feature will be needed during start-up and when the exchanger is out of service for cleaning.

Some organic materials are not totally miscible in water and separate into a distinct organic phase when the concentration exceeds the solubility limit. Most aromatics and halogenated organics fall in this category. Steam stripping applications for these types of compounds can be very effective, since a good part of the concentration of the organic can be accomplished in a decanter as indicated in Figure 2.9.

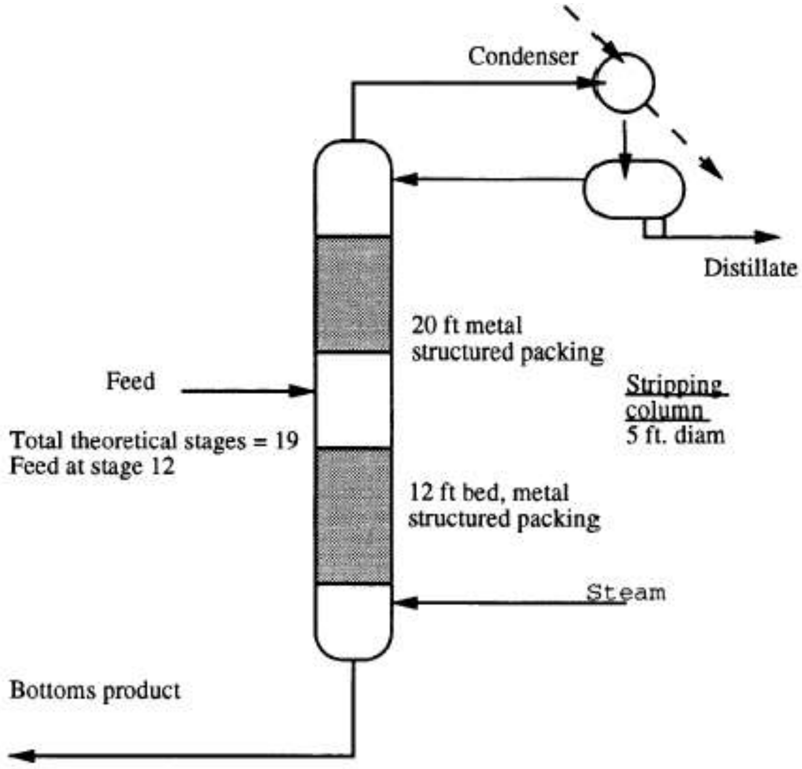


Figure 2.9: Steam Stripper using structured packing(Jaeger,1996).

In this case, the water layer is recycled to the stripping column for reprocessing. The design of the decanter poses some interesting questions since the water flow is generally significantly larger than the organic flow. Furthermore, in some cases (benzene, toluene, etc), the organic layer is the lighter of the two liquid phases (Jaeger,1996).

In applications involving halogenated organics, the organic liquid is heavier than water. Needless to say, good models to predict the phase behavior of the system in question are essential.

Figures 2.10 and 2.11 are refined versions of the flow sheet in Figure 9.

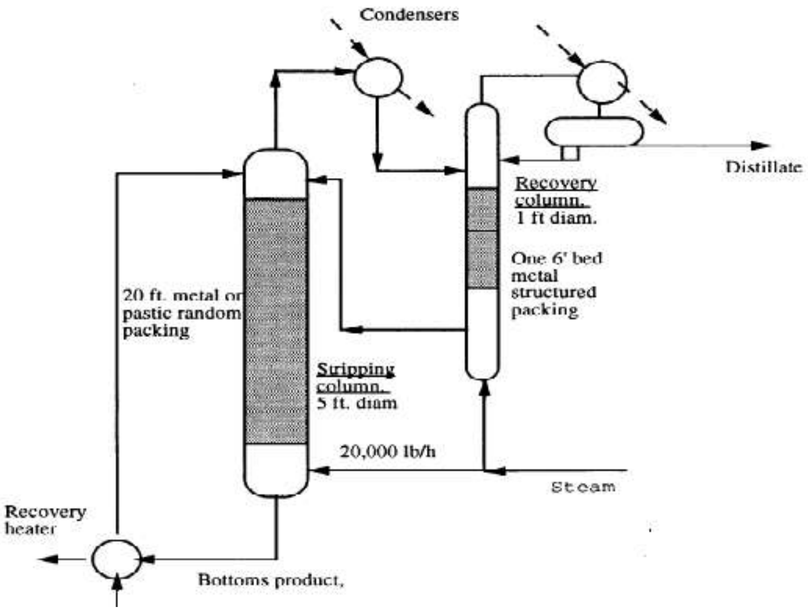


Figure 2.10: Steam Stripper with recovery column for moderately volatile miscible systems(Jaeger,1996).

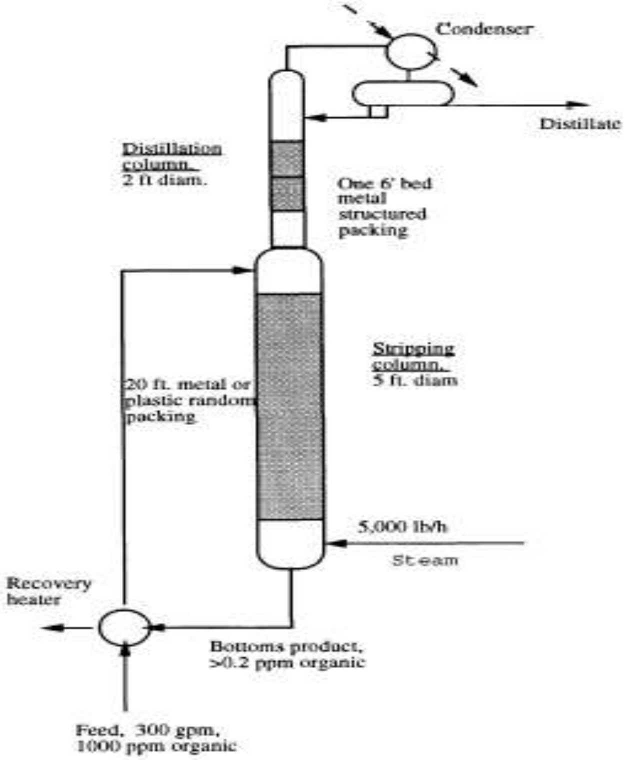


Figure 2.11: Steam Stripper with recovery column combination for highly volatile systems(Jaeger,1996).

These arrangements are needed when better organic recoveries are needed from more dilute streams. The selection between Figures 2.10 and 2.11 depend solely on the equipment sizing. Figure 10 is used when required steam flows are larger (less volatile compounds).

Figure 2.12 is applicable when the organic material to be removed exhibits very high solubility in water. In this case, a refluxed distillation column is needed to achieve high organic concentrations.

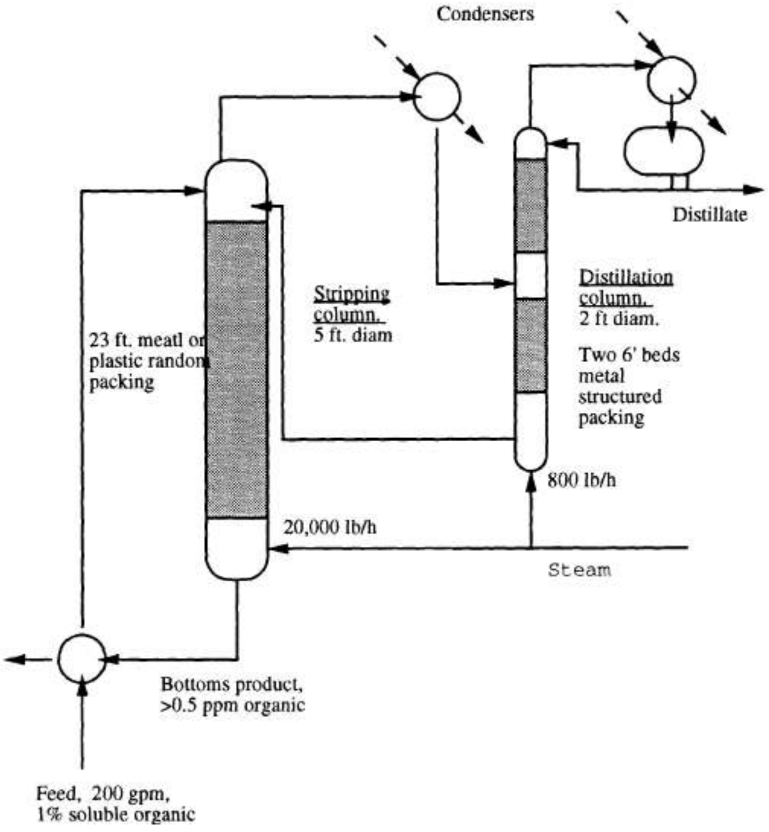


Figure 2.12: Steam Stripper and recovery column for miscible systems (Jaeger,1996).

Other variations on the same flow sheets shown above include the use of reboilers instead of direct steam injection and operation at reduced pressure to reduce operating temperature (Jaeger,1996).

2.3.2 Basic Stripping Process

Sour water stripping is a fairly simple process in which either external steam, steam generated by a reboiler is used to shift chemical reaction equilibria by heating the sour water. The steam is the "gaseous solvent" used to remove and carry the ammonia and H_2S out of the system. In other words, the application of heat generates internal stripping steam (equivalently, live steam injection can be used) and carries ammonia, H_2S, and CO_2 out of the water by (Ralph and Nathan, 2012):

1. Heating the sour water feed to boiling point.
2. Reversing chemical reactions.
3. Diluting the partial pressure of the gases stripped by furnishing excess steam.

This sounds a lot like an amine regenerator, and it is. Figure 2.13 shows a typical SWS column with heating by the injection of live steam. Because a sour water stripper does not form a fully closed loop like an amine regenerator does, maintaining a water balance is unnecessary. This means that live steam can be used as a stripping agent either alone or in conjunction with a conventional reboiler and the additional water added by the condensate simply added to the refinery's water inventory. Typical energy usage in the stripping process is in the range 1.0–1.5 lb of 50 psig equivalent saturated steam per gallon of sour water (Ralph and Nathan, 2012).

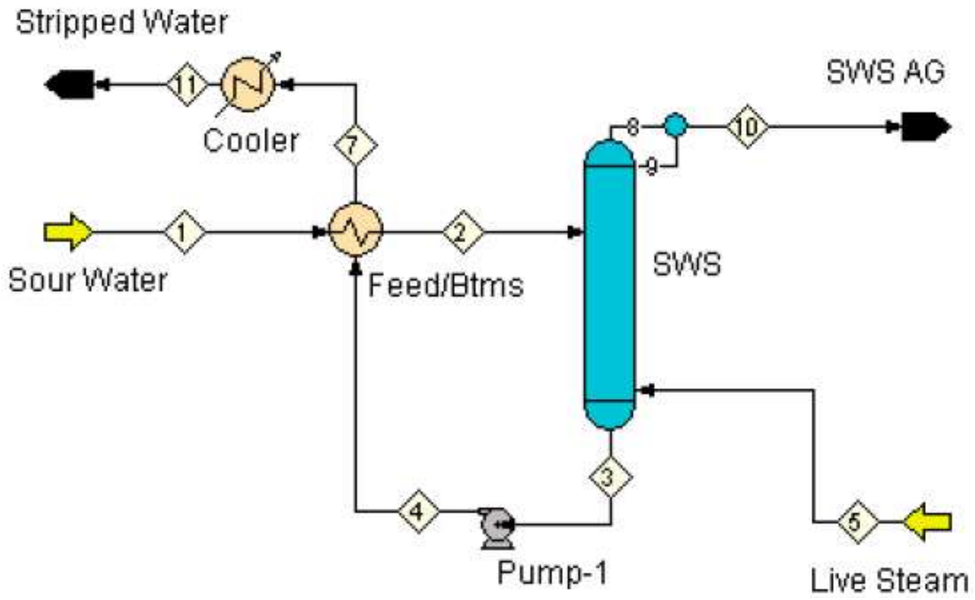


Figure 2.13: Sour Water Stripper with live Steam injection (Ralph and Nathan, 2012).

When an external reboiler is used, steam pressure is often higher than in an amine regenerator to minimize heat exchange surface. In an amine regenerator, amine degradation limits temperatures. In a sour water stripper, ammonia recycle in the stripped sour water is undesirable to begin with, so these concerns do not exist. However, there is a practical limit of 400-450°F where coking heavy hydrocarbons can lead to fouling and solids deposition in the reboiler, and corrosion is always a concern (Ralph and Nathan, 2012).

Higher NH_3 and H_2S concentrations require more stripping energy, but a higher concentration is also a more efficient way to store and transport the NH_3 and H_2S removed from upstream units. Because high H_2S solubility relies on the presence of ammonia, the molar concentration of H_2S very rarely exceeds that of ammonia, and then usually only in dilute systems. A typical molar ratio of H_2S to ammonia is 0.5-0.8 in the combined SWS feed water of a typical refinery. Ammonia levels in the water are often determined by upstream process conditions, and they can be highly specific to the process licensor and crude slate in operation. Obviously, higher concentrations of NH_3 and H_2S are preferred from a water consumption perspective. However, there is a practical limit of between one and several weight percent ammonium bisulfide equivalent in the sour water feed before metallurgy must be significantly upgraded.

Trays have historically been used in SWSs, but random packing is beginning to see use in units processing relatively clean water. Trays with directional, fixed valves have been reported to be more resistant to fouling because the horizontal velocity imparted as the gas leaves each valve tends to sweep clean the area near the valves (Hauser and Kirkey, 2003).

Stripped sour water specifications for NH_3 and H_2S can be highly dependent upon the locale where the unit is installed and the final discharge requirements. NH_3 is harder to strip than H_2S and typical targets for NH_3 are 30-80 ppmw in the stripped water versus undetectable to less than 0.1 ppmw for H_2S. Typical recent installations (Quinlan and Hati, 2010; Asquith and Moore, 2000) involve 35-45 actual trays with tray efficiencies quoted anywhere from 25 to 45%.

In some cases, other alkaline contaminants besides ammonia may be present in sour water. Amine can carry over into the regenerator purge or it can be present from injection into the crude unit overhead for corrosion control. Sodium, potassium, and magnesium may also be present from impurities in the makeup water (hardness) or by water-contacting various products containing these compounds within the upstream units. These species can chemically trap additional H_2S and prevent the H_2S from being stripped. In order to spring the H_2S, acid then must be added to the water. Other contaminants and their effect will be deferred to the next section on the chemistry of ammonia-acid gas systems (Barben, 2015).

2.4 Sources of Sour Water

All refineries that process crude which contains sulfur does librate sulfur inform of sulfides e.g. H_2S, SO_x, etc from various process unit of the refinery. Though, other contaminants as Ammonia, VOCs etc can also be present in significant amount, the water is called sour because it contains sour gas (H_2S) as a dominant compound. Table 2.4shows the various refinery process units and the amount of sour water they produce as feed to Sour Water Stripping Unit (Luke *et al*, 2004).

Table 2.4: Sources of Sour Water in Petroleum Refinery (Luke, 2004)

Process	Description	Flow Rate (gal/bbl)	Percentage of Total (%)
Distillation	H_2S, NH_3, Chlorides, Mercaptans, Phenol, and Solids.	26	40
Fluid Catalytic Cracking	H_2S, NH_3, Chlorides, Mercaptans, Phenol, and Solids.	15	26
Catalytic Reforming	H_2S, NH_3, Mercaptans, and Phenol.	6	10
Alkylation	Spent Caustic	2.6	4
Crude Desalting	Salts, Metals, H_2S, NH_3, and Phenol.	2.1	4
Visbreaking	H_2S, NH_3, Phenol, and Solids,	2	3
Hydrocracking	H_2S, NH_3, and Solids.	2	3
Coking	H_2S, NH_3, and Solids.	1	2
Others	All of the above contaminants.	< 4	4

2.5Typical Sour Water Contaminants

The dominant contaminant in sour water is hydrogen sulfide (H_2S). Wastewater from various units of oil refineries contains, on average, 350 ppm of hydrogen sulfide, while the second in amount ranking, ammonia, contains 150 ppm(Linek *et al*, 1998).

The contaminants for refinery streams may contain the acid components as hydrogen sulfide, hydrogen cyanide, phenol as well as the ammonia. Table 2.5 shows a typical concentration of contaminants for both the unprocessed sour water and the liquid effluent (stripped water) leaving the bottom of the sour water stripper in oil refinery applications (Linek *et al*, 1998).

Table 2.5: Typical sour water contaminants with feed and effluent concentration (Linek *et al*, 1998).

CONTAMINANTS	FEED	STRIPPED WATER
H_2S	300 – 12000 ppm	< 10 ppm (Often < 1 ppm)
NH_3	100 – 8000 ppm	< 100 ppm (Often < 30 ppm)
HCN	Various	Various
Phenol	Up to 200 ppm	Up to 200 ppm

2.6Threshold Limit Values For Sourwater Parameters

The Treshold Limit Value for chemical substances is defined as the allowable concentration of the subtances in the enviroment, typically for inhalation or skin exposure. Table 2.6 below provides the Treshold Limit Values for sour water parameters and the respective method of determination of each parameter (USEPA, 1986).

Treshold Limit Values are health-based values established by committees that review existing published and peer-reviewed literature in various scientific disciplines (e.g., industrial hygiene, toxicology, occupational medicine, and epidemiology). It is an estimate based on the known toxicity in humans or animals of a given chemical substance. Since these values are based solely on health factors, there is no consideration given to economic or technical feasibility (DOE, 1997).

Table 2.6: Threshold Limit Values for Sour Water parameters

Parameter	Amount in sour water*	Threshold limit**	Method of Determination
Temperature	Up to 95^0C	$<40^0$C	Thermometer
VOCs	Up to 1000 mgl^{-1}	<10 mgl^{-1}	Solvent Extraction
Ammonia	100 – 800 mgl^{-1}	<0.2 mgl^{-1}	Indophenols Reaction
Phenol	Up to 200 mgl^{-1}	<0.5 mgl^{-1}	Bathochromic Shift
H_2S	300 - 1200 mgl^{-1}	<0.2 mgl^{-1}	Titration
Suspended solid	Up to 500 mgl^{-1}	<30 mgl^{-1}	Turbidimeter
COD	400 - 1200 mgl^{-1}	< 120 mgl^{-1}	Potassium chromate Digestion

Source: *Luke, 2004 and **FEPA, 1999.

2.7 Typical Sour Water Stripping Unit

A sour water stripping unit may consist of the following engineering equipment strategically arranged to achieve the unit's purpose;

(1). Surge Drum.
(2). Heat Exchangers (Trim heaters, a cooler & a condenser).
(3). Steam Generator or a Reboiler.
(4). Stripping Column.
(5). Phase Separator.
(6). Centrifugal Pumps. (Jacobs, 2000)

2.7.1Types of Sour water stripping units:

Depending on the size of the petroleum industry, there are basically two types of SWS units as (i) Single tower unit and (ii) Double tower unit;

(i).***Single Tower unit:*** as the name implies, is when only a single stripping column or unit is installed for use in the refinery. The process flow diagram for a typical single tower unit can be seen on Figure 2.14 (Jacobs, 2000).

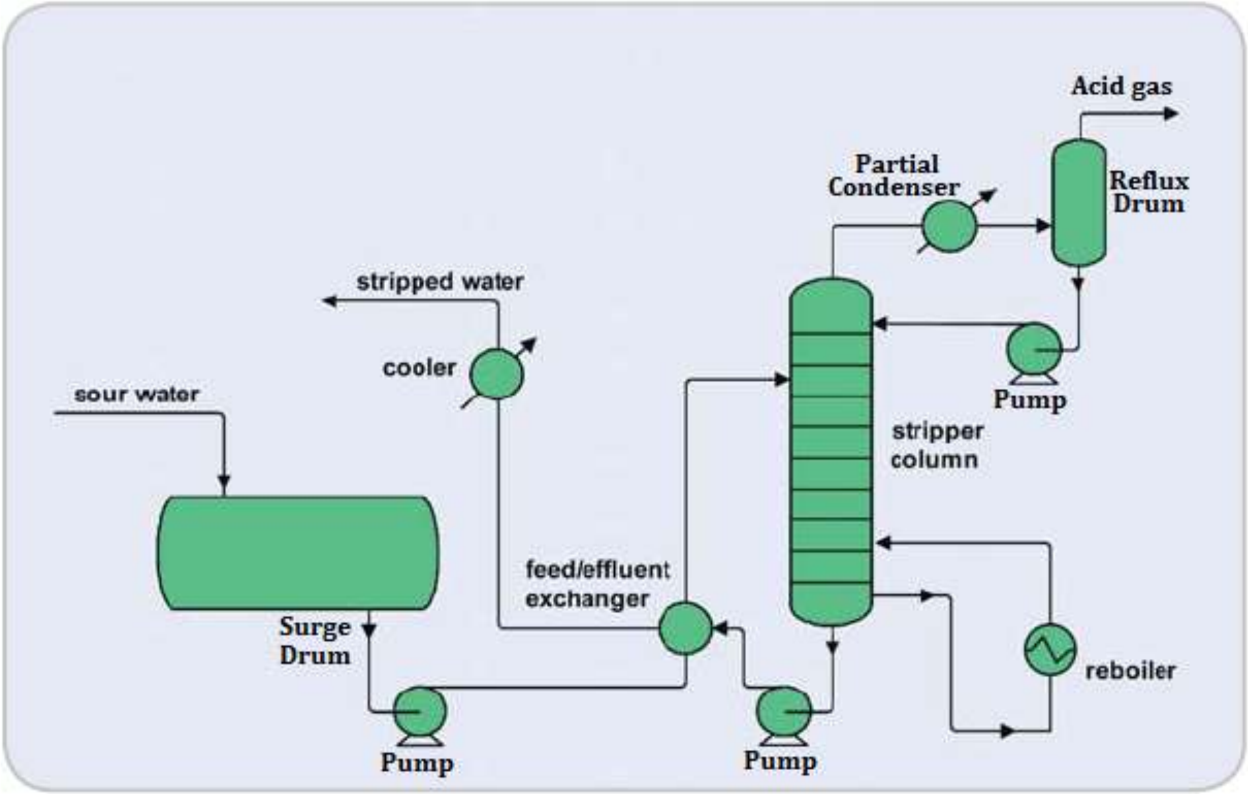


Figure 2.14: Process Flow Diagram for a Typical Single Tower Unit (Jacobs, 2000).

(ii). Double Tower unit: is when double stripping column or unit is installed for use in the refinery. The process flow diagram for a typical double tower unit can be seen on Figure 2.15 (Jacobs, 2000).

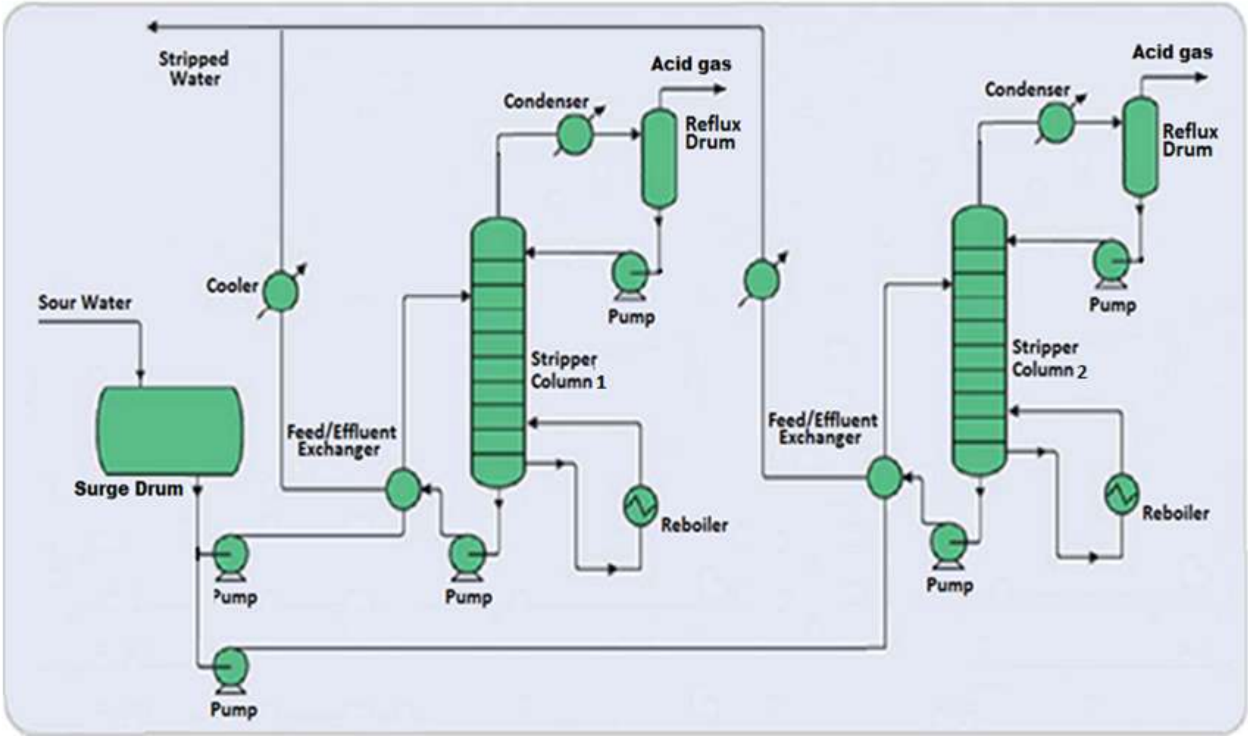


Figure 2.15: Process Flow Diagram for a Typical Double Tower Unit (Jacobs, 2000).

2.7.1.1 Modes of Operation

In large oil refineries, Double Tower unit sour water strippers are usually employed to achieve the stripping process (see Figure 2.15). Based on the volumetric availability of feed and/or for maintenance purposes, three modes of operation are used in the treatment of the sour water. They are;

(i). Normal Operation.
(ii). Single Tower Operation-1.
(iii). Single Tower Operation-2. (KRPC/NNPC, 2016)

2.7.1.1 Normal Operation

In this type of operation both the number one sour water stripper (No.1 SWS) and the number two sour water stripper (No.2 SWS) are used concurrently, Figure 2.16 (KRPC/NNPC, 2016).

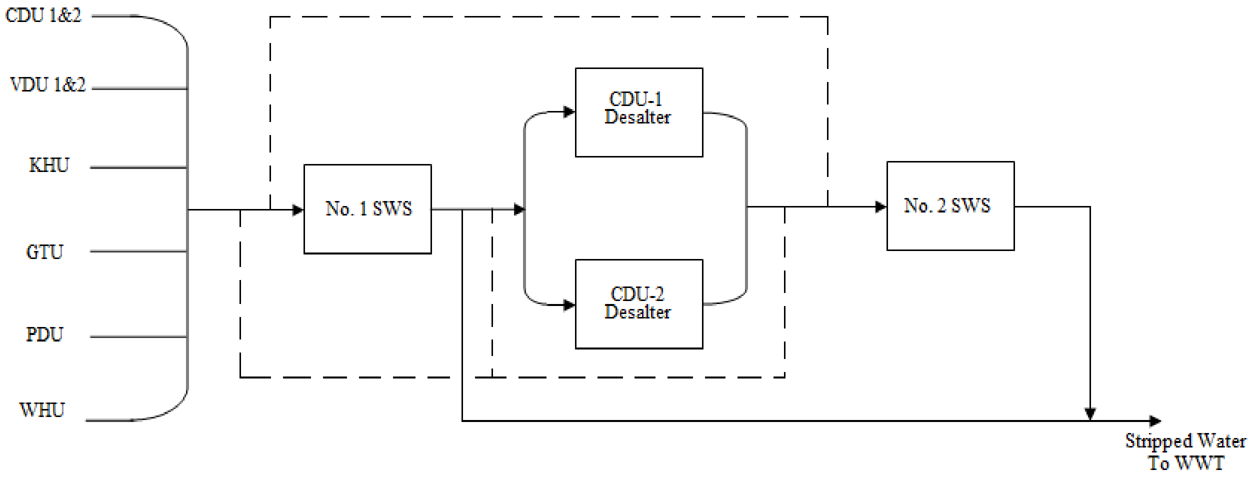


Figure 2.16: Normal Operation Block Diagram (KRPC/NNPC, 2016)

In the figure, normal straight lines indicate supply lines (pipes) that are in use during this particular operation while dotted lines indicates supply lines that are valve-shut (put off-line) as required for this operation.

This type of operation is applied when all units of the refinery are in full operation, hence, there is abundant supply of Sour water to be treated.

Sour water from all the sources except desalter effluent are merged and fed into the sour water stripper number one (No.1 SWS) for treatment. Some portion of the the treated water is sent to CDU-1&2 for use as desalter wash water. The desalter effluent water ia sent to Sour water stripper number two (No.2 SWS) for treatment. The remaining portion of the treated water from SWS-1 and the product of No.2 SWS are merged and sent for disposal or to waste water treatment (WWT) unit.

2.7.1.2 SingleTower Operation-1

This operation is applicable when No.2 SWS is taken out of service for either maintenance or due to a shortfall in the volume of the feed available for treatment, see Figure 2.17 (KRPC/NNPC, 2016).

As a requirement, portion of Sour water from available sources is sent to the desalter unit of CDU-1&2 for reuse. The remaining quantity is merged with the effluent of desalter unit of CDU-1&2 and fed to No.1SWS for treatment. The treated water from No.1SWS is sent for disposal or to waste water treatment (WWT) unit.

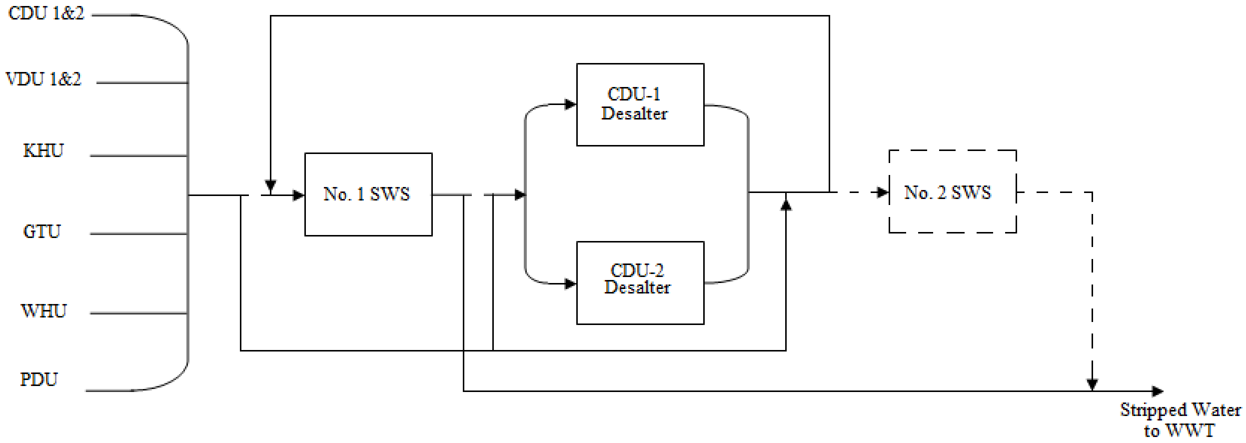


Figure 2.17: Single Tower Operation-1 Block Diagram (KRPC, 2016)

2.7.1.3Single Tower Operation-2

This operation is applicable when No.1 SWS is taken out of service for either maintenance or due to a shortfall in the volume of the feed available for treatment, see Figure 2.18.

As a requirement, portion of Sour water from available sources is sent to the desalter unit of CDU-1&2 for reuse. The remaining quantity is merged with the effluent of desalter unit of CDU-

1&2 and fed to No.2SWS for treatment. The treated water from No.1SWS is sent for disposal or to waste water treatment (WWT) unit.

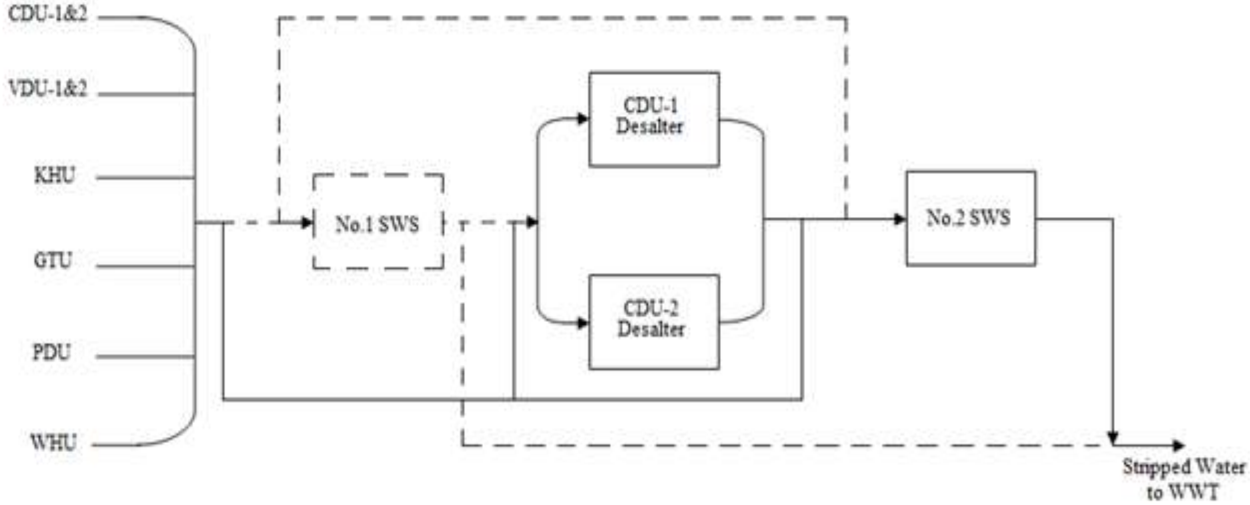


Figure 2.18: Single Tower Operation-2 Block Diagram (KRPC, 2016)

2.8 Stripping Column Design Procedure

(1). Identify a target contaminant or select the contaminant whose final water quality standard is the most difficult to achieve (usually the least volatile contaminant).

(2). Select removal efficiency needed.

(3). Select the lowest water temperature and compute Henry's law constant for the contaminant using Equation (2).

(4). Select steam to water (G/L) ratio – typical steam to water ratios for groundwater are between 10 and 100. Compute the stripping factor S with Equation (4). Most designs used a stripping factor in the range 3 - 5. However, **S** as high as 10 has been used.

(5). Compute NTU from Equation (3).

(6). Select a hydraulic loading rate and compute the cross-sectional area and the diameter of the tower. Hydraulic loading rates may vary between 5 and 50 gpm/ft2 (3.4 x 10-3 to 0.034 m3/m2•s). Hydraulic loading rates between 20 to 35 gpm/ft2 are usually used.

(7). Select the packing material and the mass transfer correlations to be used - for example, Onda's correlation.

(8). Compute the wetted surface area using Equation (10). The specific total packing area is usually obtained from the manufacturer, while the critical surface tension of the packing is assumed to be that of water. Several other pieces of information such as the density and viscosity of air and water, etc., can be obtained from standard textbooks or handbooks. Note that the equations use mass flux (kg/m^{2}s).

(9). If liquid and gas diffusivity of contaminant are not available, estimate the diffusivity of the contaminant in liquid and air phases with the Wilke and Chang equation and Hirschfelder, Bird, and Spotz equation, respectively.

(10). With information from items 7 and 8 above, calculate the liquid and air phase mass transfer coefficients (kL and kG) from Equations (11) and (12).

(11). The overall mass transfer KL is then computed using Equation (9). Compute HTU from Equation (5). Assume a = aw.

(12). The height of the tower required is then computed from Equation 6. A safety factor can be added to the height of packing, if required.

(13). Head losses through the packing itself can be estimated from manufacturers' literature or from Eckert's curve (see attached). The pressure drop across the demister packing support plate, duct work, and tower inlet and outlet is given by Equation 7. The pressure drop and gas flow rates can be calculated by applying the mathematical correlations and plots that were presented by Hines, et al and Trybal, et al.

(14). The value of **kp** in Equation (15) is approximately 0.093 ins H_2O-sec^2/ft^2) or 0.004 Ns^2/m^4 in SI units for a full-scale tower. The total horsepower requirement can be estimated from Equation 8 where an assumed fan and motor efficiency of 50 and 70 percent, respectively, can be used to yield an overall efficiency of 35 percent.

(15). The above procedure can be repeated, as required, for different air and liquid loading rates, packing materials, etc., to obtain the optimum design. (Mohamed et al, 2012)

2.9 Design Considerations/Parameter

The removal efficiency of organic contaminants by Stripping column towers is a function of many parameters as Liquid loading rate, Gas-to-Water ratio, Type & size of Parking, Temperature, Pressure drop etc. Manufacturers typically provide cylindrical towers with a limited selection of diameters. Economic considerations determine the trade-off between tower volume and air/water ratio as a function of standard air pressure drop and a given packing media.

Because the tower volume directly affects capital costs, design optimization involves minimizing tower volume at a pressure drop that minimizes energy requirements. In any given application, the optimal liquid loading rate, packing height, and air/water ratio will be functions of site-specific characteristics of influent water quality, required VOC removal efficiencies, operational considerations, and economics as well as aesthetic concerns. In addition, Table 2.7shows the effects of increasing various parameters on the removal efficiency and cost (assuming fixed tower volume, height, and packing) and the design of the packed tower (assuming fixed removal efficiency).

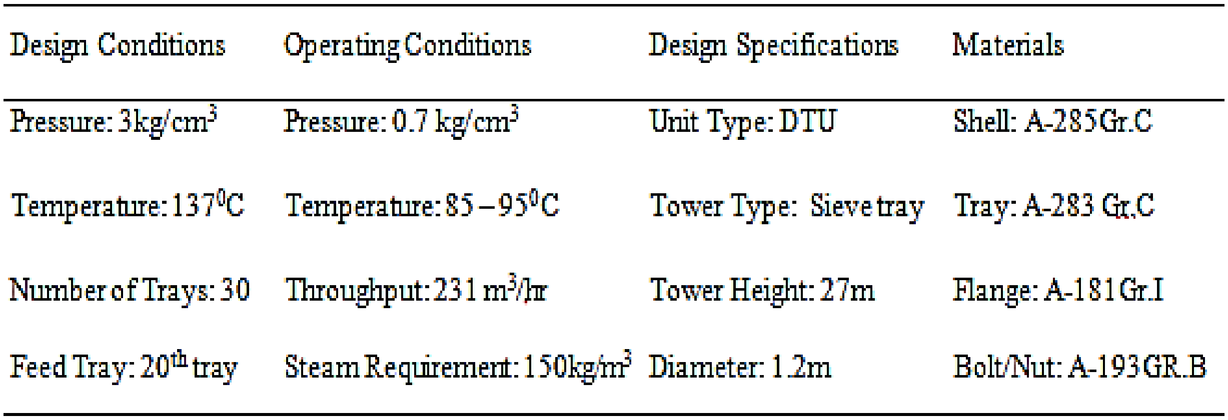
For example, in a groundwater treatment application, for a given tower design (fixed packing type, diameter, and height), increasing the water pumping rate to meet water demands will increase liquid loading. This causes a decrease in the air/water ratio, resulting in a decrease in removal efficiency and an increase in operating costs due to the greater volume of air required to meet the target removal efficiency. Similarly, while raising the influent water temperature will decrease the required tower volume for a given removal efficiency, it will alsoincrease operating costs substantially. In the case of tower design, the higher the design loading rate, the greater the tower height needed to achieve design removal efficiencies(Mohamed et al, 2012).

Table 2.7: Effect of Design Parameters on Efficiency (Stocking, 2001).

Parameter	Effect of increase in parameter on operation and cost, assuming no change in tower design	Effect of increase in parameter on tower design assuming no change in removal efficiency
Liquid Loading Rate	↓ Removal Efficiency ↑ Cost	↑ Tower Height
Air-to-water Ratio	↑ Removal Efficiency ↑ Cost	↓ Packing Volume
Water Temperature	↑ Removal Efficiency ↑ Cost ↑ Henry’s Constant	↓ Packing Volume
Packing Type and Size	↓ Removal Efficiency	↑ Packing Volume ↓ Pressure Drop
Pressure Drop/Depth	↑ Removal Efficiency ↑ Pump/Blower Cost	↑ Air-to-water Ratio

2.10 KRPC Sour Water Stripping Unit Parameters

Table 2.8: KRPC SWS Unit Parameters (KRPC, 201)



Design Conditions	Operating Conditions	Design Specifications	Materials
Pressure: 3kg/cm^3	Pressure: 0.7 kg/cm^3	Unit Type: DTU	Shell: A-285Gr.C
Temperature: 137^{0}C	Temperature: 85 – 95^{0}C	Tower Type: Sieve tray	Tray: A-283 Gr.C
Number of Trays: 30	Throughput: 231 m^3/hr	Tower Height: 27m	Flange: A-181Gr.I
Feed Tray: 20th tray	Steam Requirement: 150kg/m^3	Diameter: 1.2m	Bolt/Nut: A-193GR.B

2.11 Stripper Column Design and Column Selection:

2.11.1 Packed Column Air Strippers**:** Air strippers provide contact between air and water that encourages volatile materials to move from the water to the air. A packed column air stripper consists of a cylindrical column that contains a water distribution system above engineered (structured or dumped) packing with an air distributor below (see Figure 3.1).

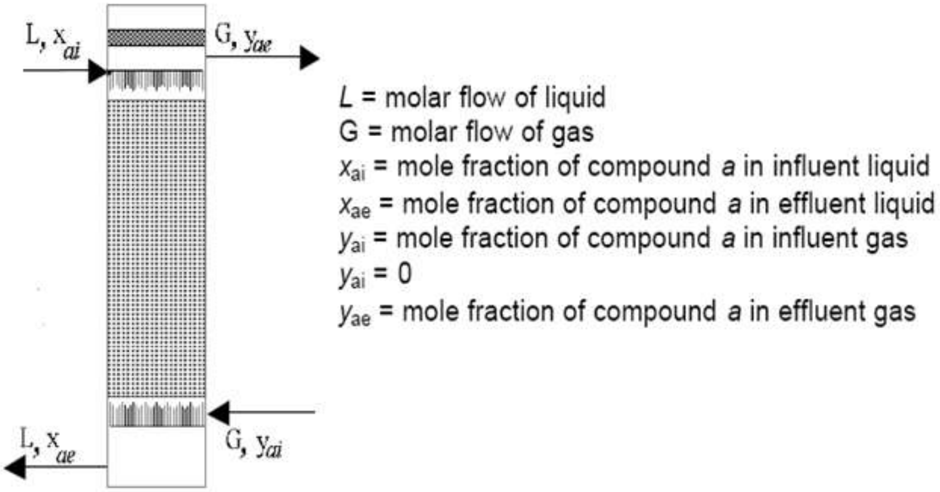


Figure 2.19: Packed Column Gas Stripper.

Water containing VOCs is distributed at the top of the column and flows generally downward through the packing material (Treybal, 1980). At the same time, air, introduced at the bottom of the column, flows upward through the packing (countercurrent flow). The packing provides an extended surface area and impedes the flow of both fluids, extending the contact between them.

As water and air contact, VOCs move from the water to the air. The water leaves the bottom of the column depleted of VOCs. The VOCs transferred to the air exit the top of the column in the air stream. Off- gas (air) is released to the atmosphere or treated if necessary to meet emission limits. Detailed information on packed column air strippers is available in the literature (Kavanaugh and Trussell, 1980; Montgomery, 1985; Treybal, 1980).

2.11.2 Sieve Tray Stripper**:** Sieve tray gas strippers operate in a similar way to packed column air strippers (Figure 3.2).

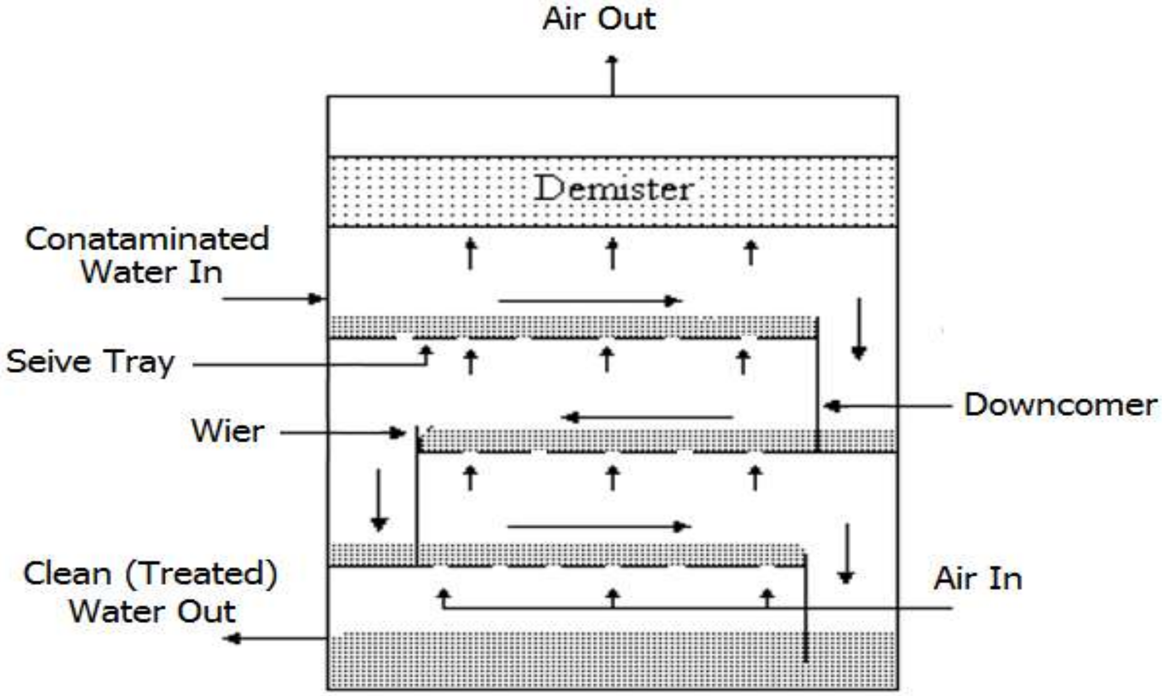


Figure 2.20: Sieve Tray Gas Stripper(Treybal, 1980).

The difference is that the liquid (water) flows across trays that are perforated with small holes, over a weir, and through a down-comer, to the next lower tray, tray by tray, until the treated water flows from the bottom of the stripper. Gas (air) is bubbled through the holes in the trays, stopping the liquid from dripping through them. The VOCs are transferred from the liquid to the gas phase as the air is bubbled through the water on the trays. (Treybal, 1980).

***2.11.3 Diffused Aeration Stripper*:** A diffused aeration stripper is a vessel or liquid (water) reservoir with gas (air) diffusers near the bottom (Figure 3.3).

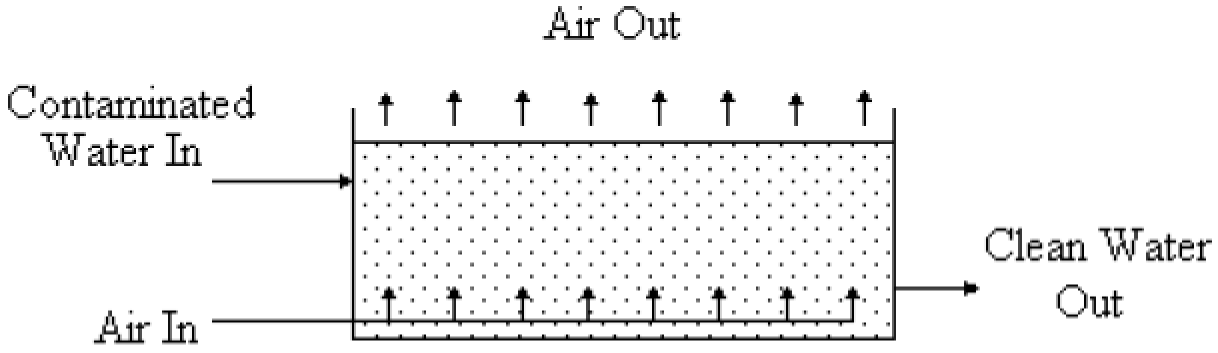


Figure 2.21: Diffused aeration air stripper (Treybal, 1980).

Air enters through diffusers and rises through the liquid to exit at the top of the vessel. The VOCs move from the water to the air as the bubbles rise through the water. Transfer of the VOCs from the water to the air can be improved by increasing the vessel depth or by producing smaller bubbles. The air path through the liquid is straight and contact between the air and water is short. Therefore, diffused air is not efficient. Its main advantages are that it is simple and that it can handle water having high levels of suspended solids (Kavanaugh and Trussell, 1980; Patterson, 1985).

Volatile organic compounds such as benzene, ethyl benzene, toluene, xylene (BETX), Sulfides such as H_2S, SO_x and chlorinated solvents such as trichloroethylene (TCE) and even Ammonia are often removed from groundwater by air stripping. Packed-column air strippers and low-profile sieve tray air strippers are often used for this. Other types of air strippers such as diffused air strippers or cooling towers are sometimes used, but for most applications they are not as efficient.

The following are characteristics of packed-column air strippers (Mead and Liebbart, 1998):

- Efficiency increases as the packing height increases
- Pressure drop is lower
- Preferred for liquids that tend to foam
- Difficult to clean when fouled
- Often use less air-reduced air pollution costs
- Operate over a wider range of air flow rates

The following are characteristics of sieve tray air strippers (Mead and Liebbart, 1998):

- Efficiency increases as the number of trays increases
- Fouling is easier to remove
- Operate over a fairly narrow range of air flow rates
- Operate over a fairly wide range of water flow rates
- Compact
- Aesthetically pleasing
- Fabricated by manufacturer
- Designs include trays that can be stacked

Packed column and plate columns are generally used in industrial stripping operations. Although packed column are used more often in air pollution control, both have their special area of usefulness. Their relative advantages and disadvantages are presented in Table 2.9 (Mead and Liebbart, 1998).

Table 2.9: Comparison Between Packed and Tray Column (Mead & Leibbert, 1998)

Parameter	**Packed Column**	**Tray Column**
Pressure Drop	More Favored	Less Favored
Flooding	Less Favored	More Favored
Channelling	Less Favored	More Favored
High Forming Liquid	More Favored	Less Favored
Liquid hold-up	Less Favored	More Favored
Corrosive atmosphere	More Favored	Less Favored
Sediment Deposition	Less Favored	More Favored
Temperature Variation	Less Favored	More Favored
Total weight	Less Favored	More Favored
Small column	More Favored	Less Favored
Large column	Less Favored	More Favored

Parameter	**Packed Column**	**Tray Column**
Pressure Drop	More Favored	Less Favored
Flooding	Less Favored	More Favored
Channelling	Less Favored	More Favored
High Forming Liquid	More Favored	Less Favored
Liquid hold-up	Less Favored	More Favored
Corrosive atmosphere	More Favored	Less Favored
Sediment Deposition	Less Favored	More Favored
Temperature Variation	Less Favored	More Favored
Total weight	Less Favored	More Favored
Small column	More Favored	Less Favored
Large column	Less Favored	More Favored

Due to the economic advantages and efficiency of Sieve Tray column over packed column, the Sieve Tray column will be adopted in this research work.

2.12 Process Description

The process flow diagram of the Sour Water Stripping Unit modeled in this work is displayed in Figure2.5. The feed stock to the unit is Sour waters from various units of the refinery e.g. CDU-1&2, VDU-1&2, KHU, SRU etc. These streams are merged and fed into sour water surge drum where the entrained hydrocarbons are removed by skimming. Then, the sour water is heated by feed/effluent exchanger before been fed into the stripping column at a calculated height for packed column or at tray number 20 for tray column. Feed distribution at the top of the column can be achieved using any of the five feed distribution methods shown on Figure 2.21.

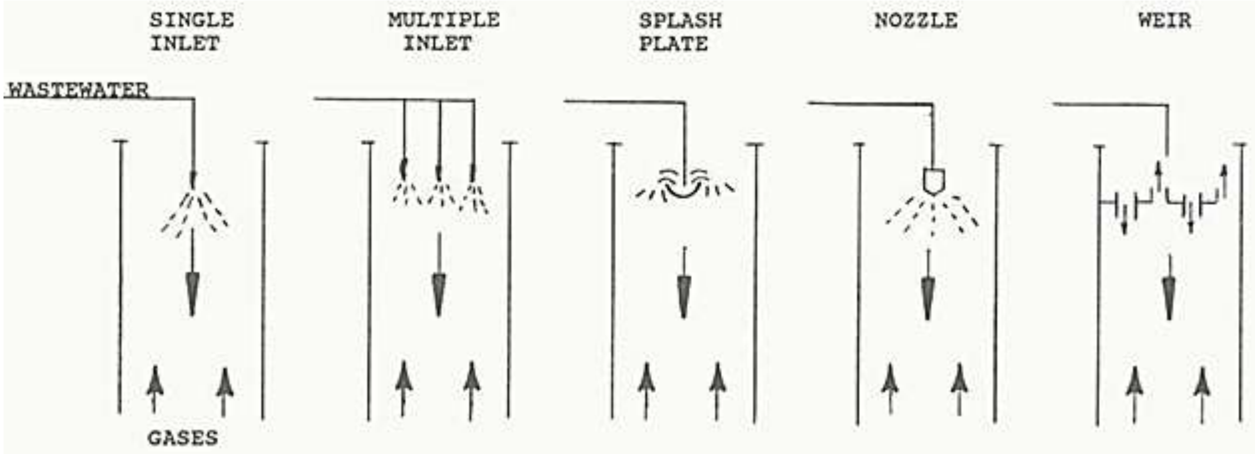


Figure 2.22: Liquid destribution systems (Hagani, 2008)

The sour water fed to the stripper is subsequently heated and stripped counter-currently by vapor (steam) stream generated by a bottom reboiler or stream of utility steam. The column is operated at a temperature little above the boiling point of all the VOCs to be stripped but lower than the boiling point of water to avoid water been stripped together with the volatile components. A favorable operating temperature is chosen between the ranges of 85 to 95^{O}C.

The column's overhead vapour is cooled in an overhead condenser, in which most steam is condensed and part is returned as reflux. The condensate which is water and traces of oil (light Hydrocarbons) are sent to a drum where the floating oil is skimmed off. The cooled uncondensed overhead gases (acid gases) are either burnt (in flare or fired heaters of CDU and VDU) or are sent to SRU depending on their volume.

The bottom product (Stripped Water) is drawn-off by treated water pump through the feed/effluent exchanger and trim cooler. Part of the bottom product is sent to CDU-1&2 where it is used as desalter wash water, while the remaining is disposed off or sent to conventional waste water treatment plant.

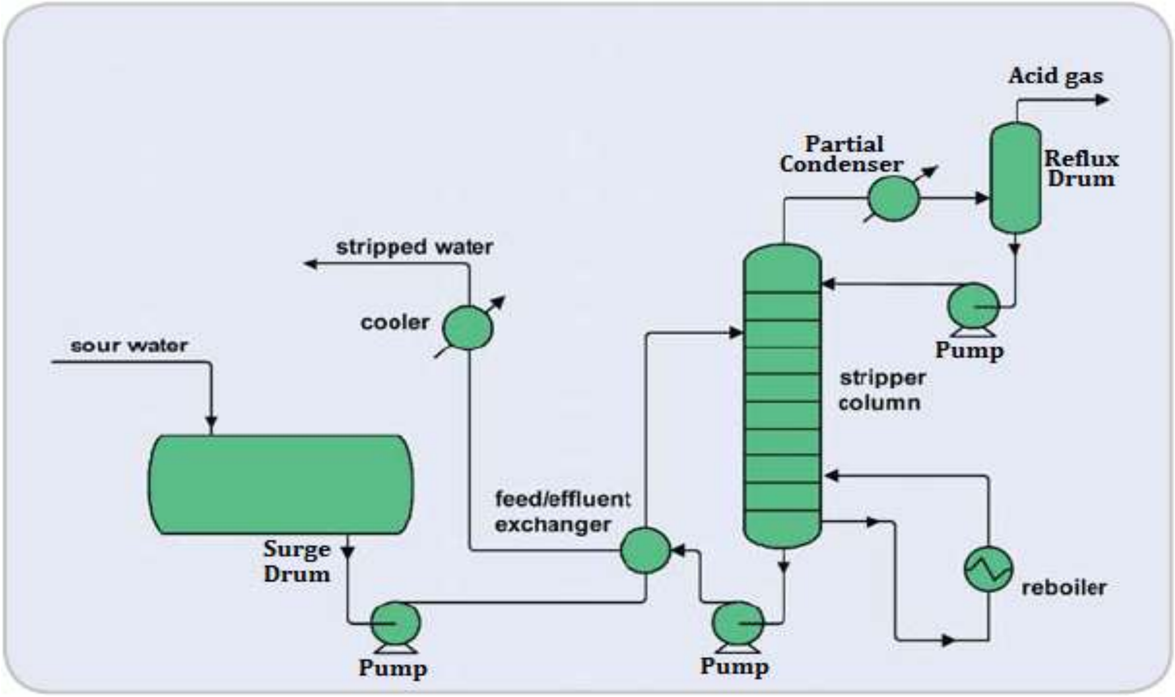


Figure 2.23: Process flow scheme of the Sour Water Stripping Unit (Jacobs, 2000).

2.13Sieve Tray Stripper

2.3.1 Input Data

Once sieve trays are selected for a given application, the input data that are required in the design calculations include density, viscosity, surface tension, diffusivity and flow rate of the liquid stream, as well as density, diffusivity and flow rate of the vapour stream. This information can be obtained by performing tray-to-tray calculations; several commercial computer packages are available for this purpose e.g. PRO II, ASPEN PLUS, HYSIM (Chuang and Nandakumar, 2000). As the physical properties and the vapour and liquid flow rates vary throughout a given column, it is difficult to provide a single design for the entire column.

Instead, the column is divided into a number of sections. Within each section, trays are designed with the same layout. Normally the section is a set of trays bounded by two column penetrations (feed and/or drawoff). Tray design calculations should be performed to ensure that trays at the top and bottom of the section meet the design requirements.

2.13.2Preliminary Specifications

2.13.2.1 Tray Spacing

Tray spacing is set by maintenance requirements, and also by support structure design in large-diameter columns. Sufficient crawl space must be provided for tray cleaning and repair. From these considerations, the minimum tray spacing is about 12 in (30 cm) for column diameter less than 5 ft, and (150cm) and 18 in (45 cm) for a column diameter greater than 10 ft (300 cm). In general, it is best to keep tray spacing to a minimum, which is often the most economical.

2.13.2.2 Downcomer Area

The downcomer area at the top is sized such that the velocity of the ascending vapour bubbles exceeds the down-flow velocity of the liquid. The size is related to the stability of the froth in the downcomer and determined by the residence time required for achieving the separation of the two-phase mixture. For non-foaming systems, such as lower alcohols, a residence time of 3 s is sufficient, whereas for extremely high foaming systems such as caustic regenerators, 9 s is required (Chuang and Nandakumar, 2000).

To prevent the liquid coming off the bubbling area from splashing against the column wall, the minimum downcomer width is 5 in (12.7 cm). Also, the minimum side chord length should be 60%of the column diameter. This is required to maintain good liquid distribution on the tray (Chuang and Nandakumar, 2000).

Since the separation of the vapour-liquid mixture is complete at the bottom of the downcomer, a sloped downcomer can be used to maximize the active tray area. In this case, the downcomer area at the bottom should be about 60% of that at the top (Chuang and Nandakumar, 2000).

It should be noted that the downcomer area occupies only a small fraction of the cross-sectional area. Thus, a small overdesign does not result in a significant economic penalty (Chuang and Nandakumar, 2000).

2.13.2.3 Column Diameter

The column diameter can be calculated once the tray spacing and downcomer area have been specified. The Fair correlation, based on the Souders and Brown criterion, is recommended by most designers. The vapour Sooding velocity can be calculated from equation (1).

$$U_{N,f} = C_{SB}\left(\frac{\rho_L - \rho_V}{\rho_V}\right)^{0.5}\left(\frac{\sigma_L}{20}\right)^{0.2} \qquad (2)$$

C_{SB} is the Souders-Brown coefficient,

ρ_L and σ_L (dyne cm^{-1}) are liquid density and surface tension, respectively, and ρ_V is the vapour density in the same units as σ_L. $U_{N,f}$ is based on the net area, A_N(ft^2), which is the active area plus one downcomer area. The unit for $U_{N,f}$ is ft s^{-1}. The most popular empirical formula for calculating C_{SB} is given in equation (2).

$C_{SB}(ft\ s^{-1}) = 0.04232 + 0.1674T_s + (0.0063 - 0.2686T_S)F_{IV} + (0.1448T_S -$

$0.008F2IV2$(3)

In this equation $F_{IV} = (L/V)(\rho_V / \rho_L)^{0.5}$, T_S is tray spacing in feet, and L and V are mass flow rates of the liquid and vapour. The C_{SB} is valid for trays with a fractional hole area greater than 10%. For areas of 8%and 6%, *C*SB should be multiplied by 0.9 and 0.8, respectively (Chuang and Nandakumar, 2000).

Knowing $U_{N,f}$ and the total vapour flow rate, the column diameter can be calculated by assuming that the column will be operated at a lower vapour velocity, say 80% of the flood point (Chuang and Nandakumar, 2000).

2.13.2.4 Number of Flow Passes

The number of flow passes is set to allow the tray to operate at a weir loading that does not result in excessive weir crest. The weir loading can be calculated once the column diameter and the downcomer area are determined. The optimum weir loading is 4-6 US gallons per minute and the maximum loading is about 20 (Chuang and Nandakumar, 2000). Downcomer choking, which causes liquid build-up on the tray, may occur if the maximum value is exceeded. Increasing the number of flow passes provides a solution to this problem. However, shorter liquid flow path and possible maldistribution of liquid and vapour streams in multipass trays may result in lower tray efficiency.

As a rule of thumb, the liquid and vapour handling capacity are a direct function of weir loading and column area, respectively. Since weir length and column area are proportional to column diameter and diameter squared, respectively, the use of multi-pass trays is often necessary for large-diameter columns (Chuang and Nandakumar, 2000).

2.14 Sieve Tray

Sieve trays can be classified as:

1. Cross-flow trays with downcomers (see Plate 3.1A);
2. Countercurrent trays without downcomers (also known as dual-flow trays) (see plate 3.1B).

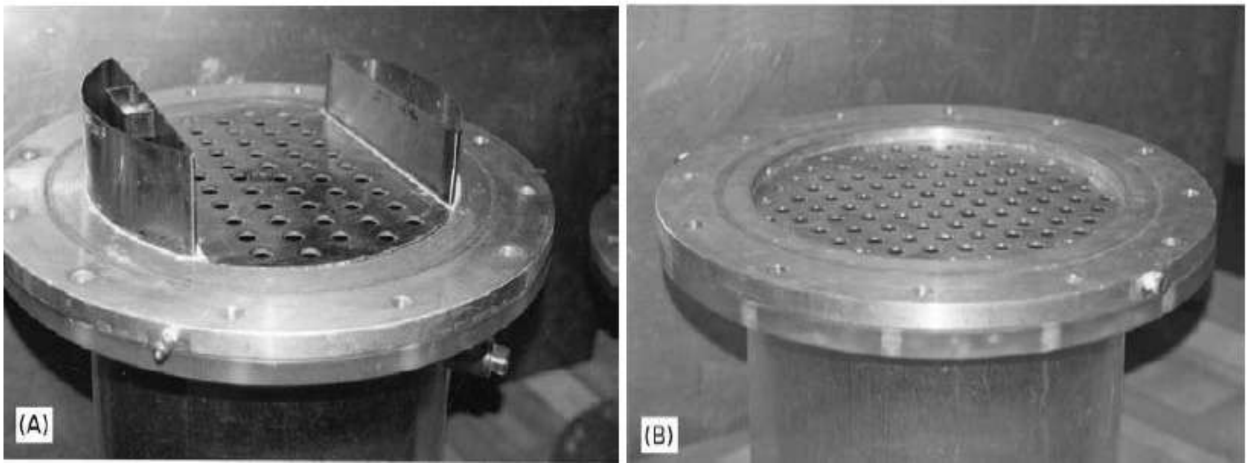


Plate 2.1: (A) Sieve ray with downcomer, (B) Dual-flow tray(Chuang and Nandakumar, 2000).

The dual flow tray allows the gas and liquid to pass through the same tray openings. This results in a limited operating range because the dispersion height is very sensitive to the gas/liquid flow rates. In general, dual-flow trays are employed only in cases where high capacity or high resistance to fouling are required.

The cross-flow tray utilizes a weir on the downcomer to control the spray height on the tray, and thus provides a stable gas-liquid dispersion over a wide range of gas/liquid flows.

A tray is the combination of a tray deck, where froth is generated to provide vapour-liquid contact, and a downcomer, where the vapour-liquid mixture is separated. The bulk of the vapour rises from the aerated liquid through the vapour disengagement space to the tray above. However, the passage of the liquid from the top to the bottom of the column occurs mainly via downcomers.

There are three types of cross-flow trays: (1) Sieve, (2) Valve and (3) Bubble cap.

Among them, sieve trays offer highest capacity and efficiency, low pressure drop, ease of cleaning, and low capital cost, but smaller turndown ratio. Although the design procedure is similar for all three types of trays, only sieve tray performance data are readily available in the public domain. The valve and bubble cap designs are often protected by patents, and thus the performance data are supplied by the vendors.

The cost of a tray column is determined by two factors, namely;

1. Column diameter, which determines the throughput;
2. Column height, which delivers the number of equilibrium stages.

The minimum cost is generally achieved when the column volume is minimized. The final selection of the tray design is based on the combined cost of the column shell, internals and installation. It should be noted that the fraction of the cross-sectional area available for vapour-liquid disengagement decreases when the downcomer area is increased. Thus, optimum design of the tray involves a balance between the tray area and the downcomer area (i.e. the capacity for the tray deck should match the capacity of the downcomer). The correlations for sizing trays are implicit in column diameter, tray spacing and tray geometry, thus requiring trial-and-error calculations to arrive at the final selection (Chuang and Nandakumar, 2000).

2.14.1 Tray Geometry

Tray geometry should be chosen so that hydraulic and efficiency calculations can be performed to arrive at the optimum design. The following parameters must be specified for tray design calculations.

2.14.1.1 Tray Thickness

The choice of material for the fabrication of trays is dependent mainly on the corrosion properties of the process fluids. In general, tray thickness is about gauge 10 (0.134 in; 3.40 mm) for carbon steel and gauge 12 (0.109 in; 2.77 mm) for stainless steel(Chuang and Nandakumar, 2000). For economic reasons the holes are punched, which dictates that the thickness must be less than the hole diameter (Chuang and Nandakumar, 2000).

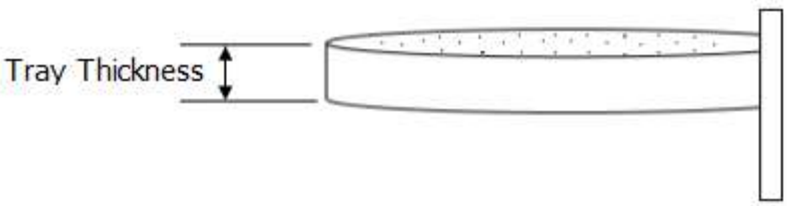


Figure 2.24: Sieve Tray Thickness

2.14.1.2 Hole Diameter

Small holes with a diameter in the range of 3/16 to ¼ in (4.76-6.35 mm) give better hydraulic and mass transfer performance than the large ones in the range of 12 to 34 in (12.7-19.0

mm)(Chuang and Nandakumar, 2000). However, large-hole trays are cheaper and show more resistance to fouling. Choose the hole size according to design requirements.

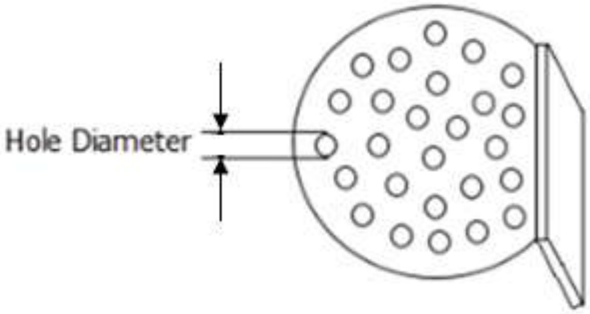


Figure 2.25: Sieve Tray Hole Diameter

2.14.1.3 Hole Area

The hole area is normally in the range of 5-16% of the bubbling area. Lower hole area allows the tray to operate at higher efficiency and turndown ratio, but at the expense of higher pressure drop. Since the operating pressure of the column dictates the maximum allowable pressure drop, the hole area is selected according to the type of service. Recommended hole area values are 5-10% for pressure and 10-16% for vacuum operations (Chuang and Nandakumar, 2000).

Hole areas below 5% are not used because the distance between holes becomes too tiny and liquid channeling may occur. However, the distance can also be adjusted by changing the hole diameter. In general, the hole pitch should not be larger than 2.5 in (6.35 cm)(Chuang and Nandakumar, 2000). On the other hand, if the hole areas are greater than 16%, significant weeping and entrainment may coexist and the design equations may not apply under these conditions (Chuang and Nandakumar, 2000).

2.14.1.4 Tray Weir

Outlet weirs are used to control the froth height on the tray. For most trays, the outlet weir height is about 1-4 in (2.5}10 cm) and the downcomer clearance, where the liquid is discharged from the bottom of the downcomer onto the tray below, should be 0.5 in (1.25 cm) smaller than the outlet weir height to ensure a positive downcomer seal.

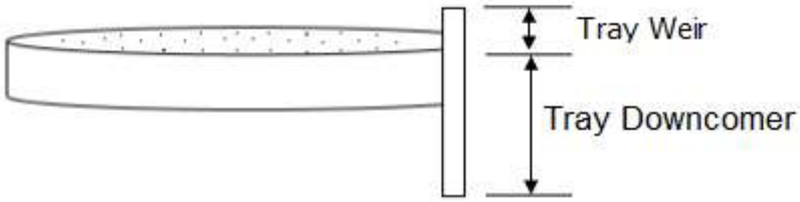


Figure 2.26: Tray Weir and Downcomer

From the above discussion, it may be concluded that the objective of tray design is to obtain the optimum combination of the following parameters:

1. Column diameter
2. Tray spacing
3. Top and bottom downcomer area
4. Hole diameter and hole area
5. Outlet weir height and downcomer clearance.

2.15 Design Criteria

The trays should be designed for maximum throughput. However, owing to inaccuracies in the design equations and fluctuation of process conditions (e.g. flow rates, temperature and pressure), safety factors are needed to ensure stable column operation at all time.

2.15.1 Jet Flood Safety Factor

The jet flood safety factor (JFSF) is defined as the ratio of vapour velocity required to entrain the entire liquid flow ($U_{\max}$) to the operating velocity (U_{op}). It is a useful measure of entrainment and hydraulic stability. The typical JFSF value is 1.2 (Chuang and Nandakumar, 2000).

2.15.2 Turndown Ratio

For various reasons, the column may be operated at a reduced throughput. Weeping is encountered if the vapour velocity can no longer support the liquid on the tray (Chuang and Nandakumar, 2000). Although Sow dynamics permit stable operation as long as dumping is avoided, tray efficiency suffers because weeping reduces the vapour-liquid contact. Turndown ratio is the width of the operational range of a devise or equipment. It is defined as the ratio of the maximum capacity to minimum capacity (Chuang and Nandakumar, 2000). For instance, an equipment with a maximum output of 10 units and a minimum output of 2 unit has a turndown ratio of 5. The turndown ratio is the ratio of the design vapour Sow rate to the Sow rate that permits some weeping without seriously affecting the tray efficiency.

Recommended weepages at turndown conditions for vacuum and pressure operations are 3%and 7%, respectively (Chuang and Nandakumar, 2000).

2.15.3 Downcomer Area and Backup Safety Factor

The liquid handling capacity of a tray is determined by downcomer design and tray spacing. The Downcomer Area Safety Factor (DCASF) determines the approach of the top downcomer areato the minimum area required for vapour-liquid disengagement. The Downcomer Backup Safety Factor (DCBUSF) determines the approach of the downcomer froth height to the downcomer depth (=tray spacing + outlet weir height). Safety factor in the range of 1.5-2.0 for both DCASF and DCBUSF are recommended (Chuang and Nandakumar, 2000).

2.15.4 Pressure Drop

The pressure drop across an operating tray should be specified if it affects the number of equilibrium stage requirements for the separation. This is often the case for vacuum applications. Stable operation of column trays can be obtained at a pressure drop of 1-3 in (2.5-7.6 cm) of liquid per tray for vacuum and 2-5 in (5.1-012.7 cm) for pressure operations (Chuang and Nandakumar, 2000).

CHAPTER THREE

3.0 METHODOLOGY

3.1 Introduction

This chapter presents the details of activities performed during the design and fabrication of the pilot scale Sour Water Stripping unit. The design was undertaken in stages as presented in Figure 3.1.

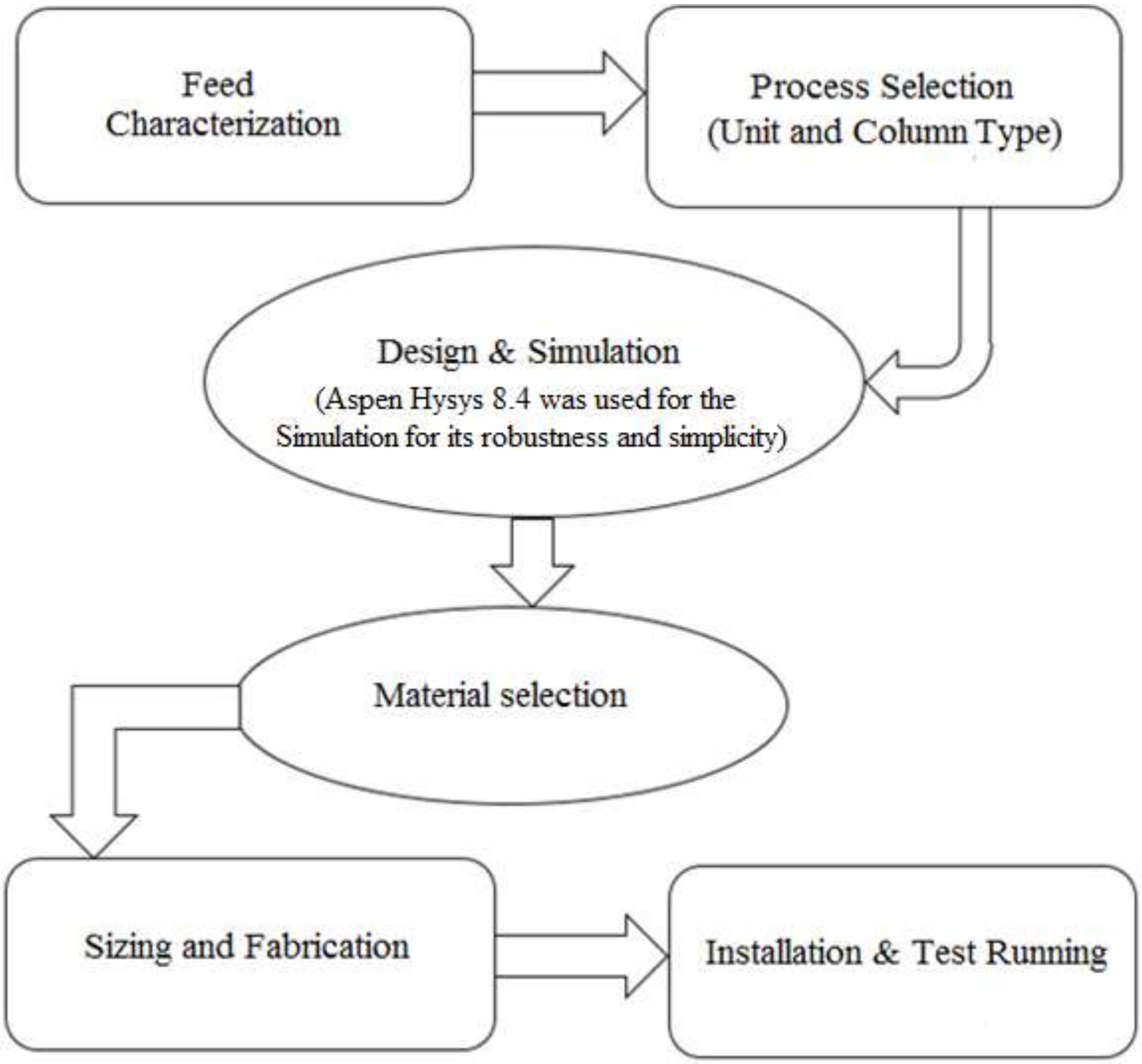


Figure 3.1: Project Methodology Chart

3.2 Design Basis and Feedstock Characterization

The feed (Sour Water) and its properties were first analyzed before establishing a design basis. The design basis and feedstock composition for the SWS Unit are shown in Tables 3.1 and 3.2 respectively.

Table 3.1: SWS Unit Design Basis

SWS Unit Capacity	5 barrels/day (33 l/hr)
Feed Type	Sour Water
Main Source	Crude Distillation Unit
Potential Hydrogen	Acidic

Table 3.2: SWS Unit Feedstock Composition (see lab result on Appendix-VI**)**

Component	Amount in Sour Water	Threshold Limit*
pH	6.8	6.5 – 7
Temperature	24.7 ^{o}C	<40 ^{o}C
VOCs	1800 mgl^{-1}	<10 mgl^{-1}
Ammonia	11.8 mgl^{-1}	<0.2 mgl^{-1}
H_2S	16 mgl^{-1}	<0.2 mgl^{-1}
Total	32.769	99.999

*FEPA, 1999.

3.3 Process Selection and PFD Development

Two process technologies for sour water stripping are available – the Single Tower Unit (STU), and the Double Tower Unit (DTU). The process unit selected is this work is the Single Tower

Unit type and the type of column is the sieve tray type. This selection was done due to suitable justifications/advantages below:

- Small amount of Sour water produced by mini-refineries.
- Lower cost of Design, Fabrication and Installation.
- Ease of Operation and Maintenance.
- Lesser control equipment and manpower requirement.
- Ease of optimization and upgrading.

3.4 Process Description

The Process Flow Diagram follows a general sequence of feed pre-heating, stripping and separation. Number of these equipment can be increased depending on the extent of stripping/separation and purity requirements. Figure 3.2 presents the developed PFD for Sour Water Stripping Unit Pilot Plant. Where; V-100 is the feed surge drum, P-100 is the feed charge pump E-100 is the Exchanger, C-100 is the stripping column, E-101 is the overhead condenser,V-101 is thereflux drum, E-102 is the column bottom reboiler, E-103 is the product cooler, P-101 is the bottom reboiler pump and P-102 is the reflux pump.

The feed, Sour Water, was pumped using feed charge pump (P-100) from Surge Drum (V-100) into the stripping column (C-100) after exchanging heat with the product via Feed Preheater (E-100). The feed enters the stripping column (C-100) onto the number eight (N-8) tray of the column.

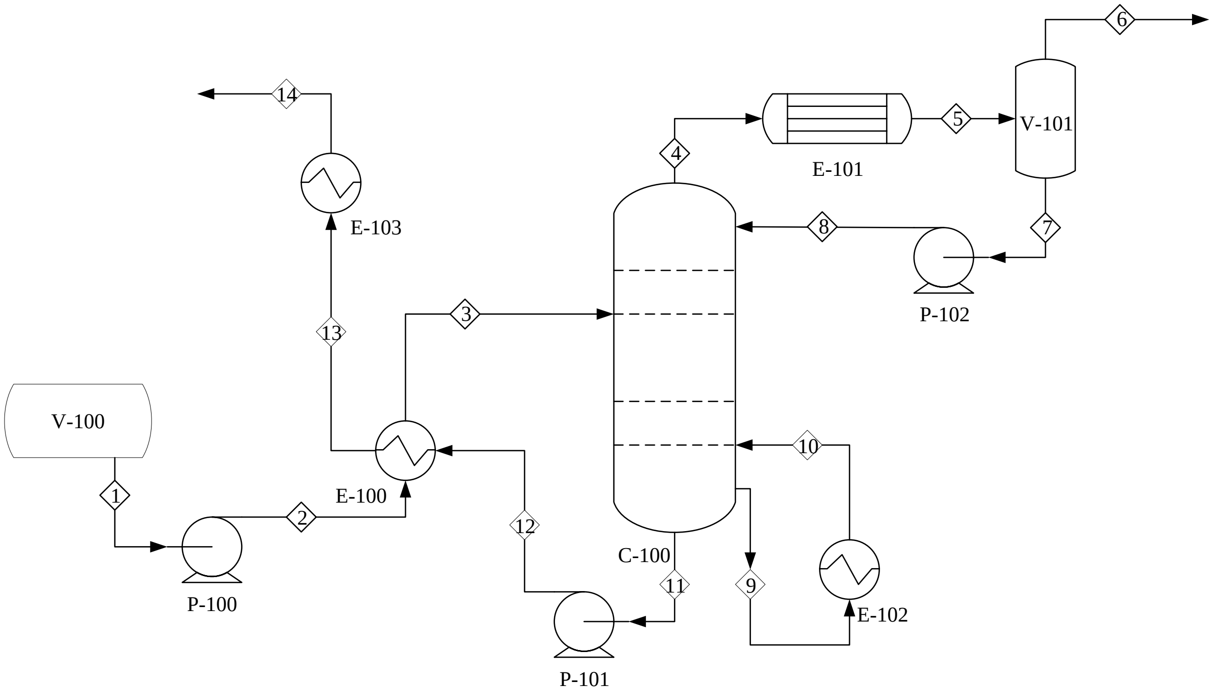


Figure 3.1:PFD for SWS Unit Pilot Plant

It is subsequently heated and stripped countercurrently by vapour generated by the bottom reboiler (E-102). The overhead vapour is cooled by water at a controlled temperature of 97^{o}C (CV-104) using the overhead condenser (E-101), in which most steam is condensed and drops onto the top tray as reflux.

The bottom product is drawnoff by treated water pump (P-101) under column level controller (CV-105) through feed preheater (E-100) where it loses some of its heat. It is again made to pass through product cooler (E-103) where the temperature is cooled to or below the acceptable threshold of 40^{0}C before a sample is sent to laboratory to ensure product quality and subsequently withdrawn as final product.

3.5 Material and Energy Balance

3.5.1 Material Balance

This stage was executed usingMathcad. The balance of materials/components passing through all the individual equipment that made up the mini-refinery SWS Unit was performed. This was actualized through implementation of law of conservation of mass over participating components (McCabe *et al.,* 2001). The general law of mass conservation was represented by material balance equation as shown by equation 3.1.

Materials in + Generation = Materials out + Accumulation + Consumption/Disappearance(3.1)

Figure 3.2 presents the SWS Unit PFD indicating streams used for the material and energy balances. All assumptions made on each equipment were clearly stated while inlet and outlet streams were clearly depicted.

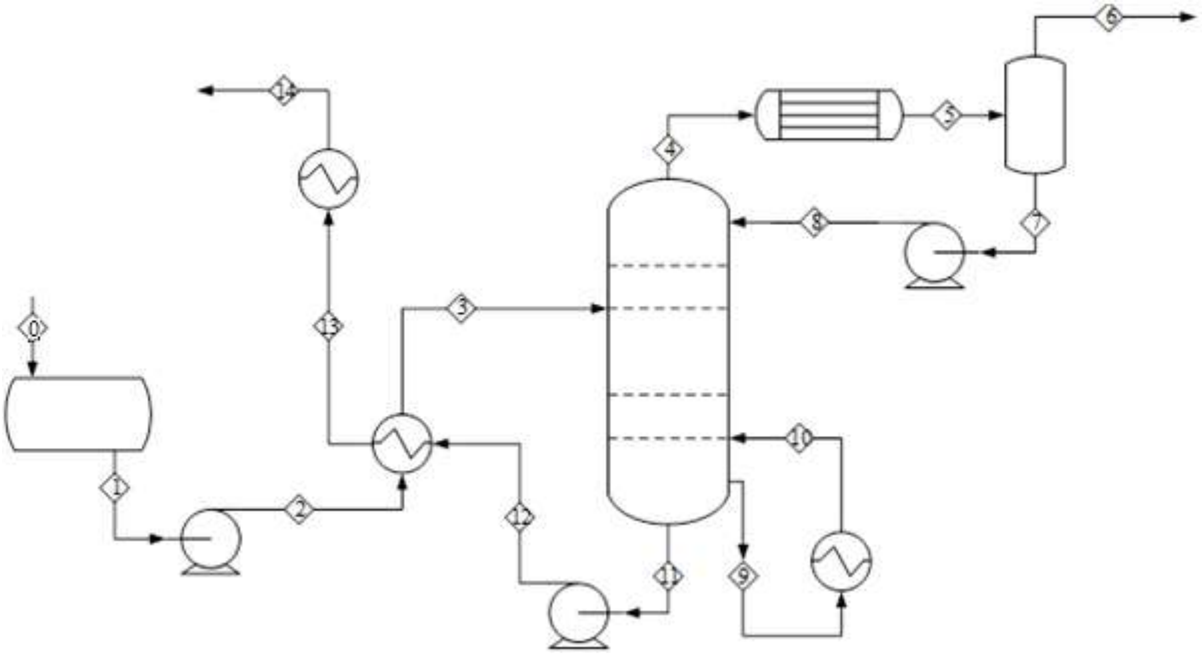


Figure 3.2: Process Flow Diagram indicating the SWS Unit streams 0 -14

3.5.2 *Unit 1: Surge Drum (V-100)*

Basis: 5 BPSD design capacity is considered for this design:

$$V_{sw} := 5\frac{\text{barrel}}{\text{day}} = 794.936\frac{\text{liter}}{\text{day}}$$

Mass flow rate equivalent of the design capacity in kg/hr is

$$\text{Feed} := V_{sw} \cdot \rho_{sw} = 32.748\frac{\text{kg}}{\text{hr}}$$

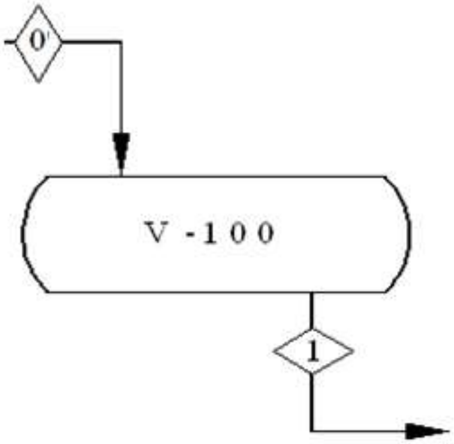


Figure 3.3: Material Balance across Surge Drum (V-100)

Assumption: Material Input = Material Output (Stream 0 = Stream 1)

3.5.3 *Unit 2: Charge Pump (P-100)*

Assumptions: Material Input = Material Output (Stream 1 = Stream 2)

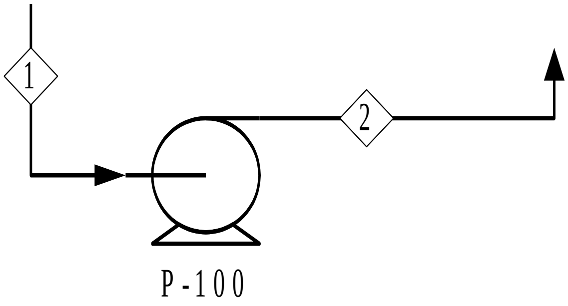


Figure 3.4: Material Balance across Charge Pump (P-100)

3.5.4 Unit 3: Material Balance across Feed Pre-Heater (E-100)

Assumption: Steady state operation prevails through the process, Input = Output

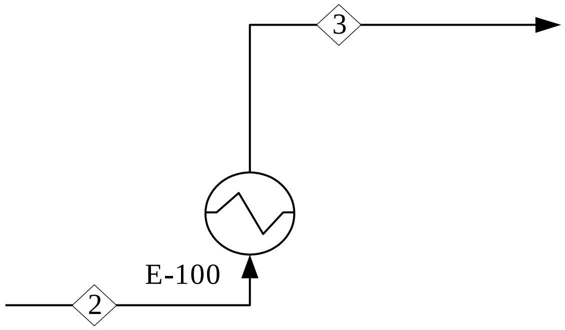


Figure 3.6: Material Balance across Feed Pre-Heater (E-100)

3.5.5 Unit 4: Material Balance across Stripping Column (C-100)

Assumptions:

1. Heavy Key component is water
2. Light Key component is H_2S
3. 97% water recovery at the bottom of the column

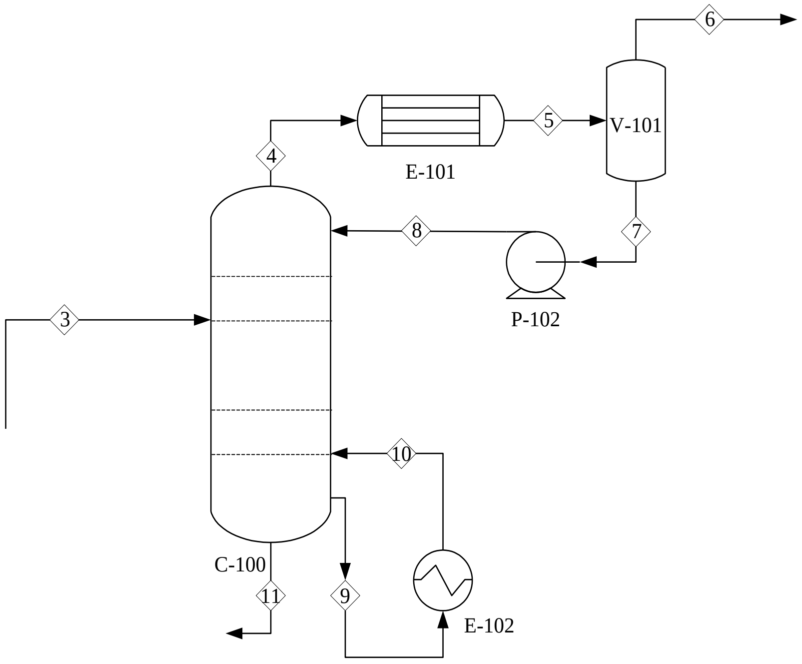


Figure 3.5: Material Balance across Stripping Column (C-100)

Minimum Reflux Ratio was calculated to be 1.333 (see Appendix-1)

At steady state, Stream-3 = Stream-6 + Stream-11

$$N_{11} := \sum_{s} n_{s,11} = 30.6189283 \frac{kg}{hr}$$

3.5.6 Unit 5: Material Balance across Column Overhead Condenser (E-101)

Assumption: Material Input = Material Output (Stream 4 = Stream 5)

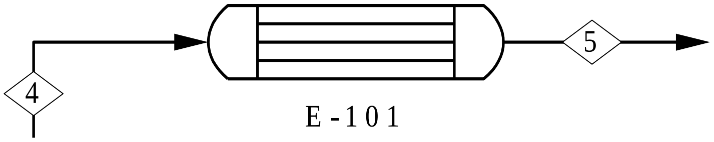


Figure 3.8: Material Balance across Overhead Condenser (E-101)

Since Input = Output for a boundary around the condenser (E-101), reflux drum (V-101) and reflux pump (P-102), therefore, Stream-4 = Stream-5 = Stream-6 + Stream-8

But, from the Aspen Hysys simulation, the flowrate of the stream entering the condenser (Stream-4) is 6.3871 kg/hr, therefore, Mass flowrate of component in stream 4 is;

3.5.7 Unit 6: Material Balance across Reflux Drum

Assumption: Material Input = Material Output (Stream 5 = Stream 6 + Stream 7)

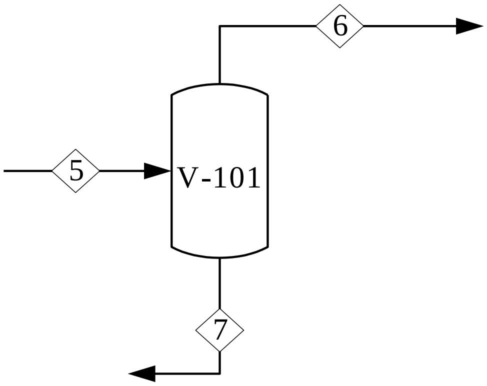


Figure 3.9: Material Balance across the Reflux Drum (V-101)

Stream 7: Mass flowrate of component in stream 7

$$N_7 := \sum_{s} n_{s,7} = 0.23631230 \cdot \frac{kg}{hr}$$

Stream 5: Stream 6 + Stream 7

$$N_5 := \sum_{s} n_{s,5} = 2.545430 \cdot \frac{kg}{hr}$$

3.5.8 Unit 7: Material Balance across Reflux Pump

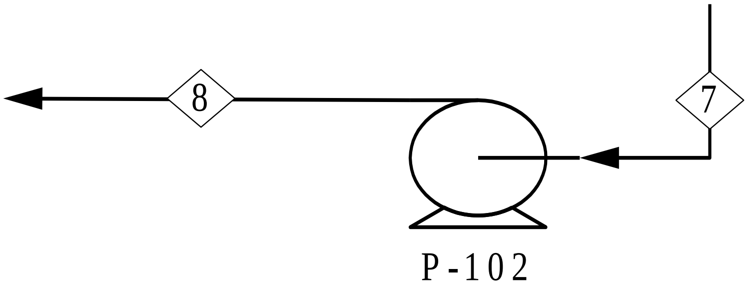


Figure 3.10: Material Balance across Reflux Pump (P-102)

Assumption: Steady state operation prevails throughout, Input (Stream 7) = Output (Stream 8)

Total mass flow rate of component in stream 8

$$N_8 := \sum_s n_{s,8} = 0.23631230 \cdot \frac{kg}{hr}$$

3.5.9 Unit 8: Material Balance across Bottom Reboiler (E-102)

Assumption: Steady state operation prevails, hence, Input = Output (Stream 9 = Stream 10)

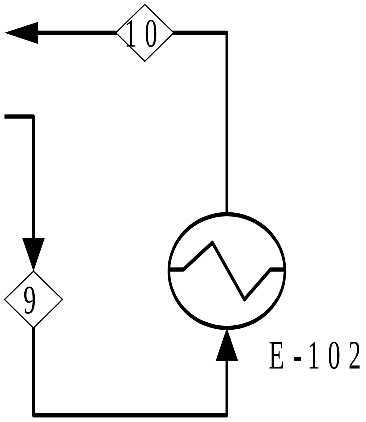


Figure 3.11: Material Balance across Bottom Reboiler (E-102).

Mass flowrate of component in stream 9

Total mass flow rate of component in stream 9

$$N_9 := \sum_s n_{s,9} = 6.38773648\frac{kg}{hr}$$

Stream 10: Steady state operation prevail through the process, Input = Output

Total mass flow rate of component in stream 10

$$N_{10} := \sum_s n_{s,10} = 6.38773648\frac{kg}{hr}$$

3.5.10 Unit 9: Material Balance across Product Pump (P-101)

Assumption: Steady state operation prevails, hence, Input = Output (Stream 11 = Stream 12)

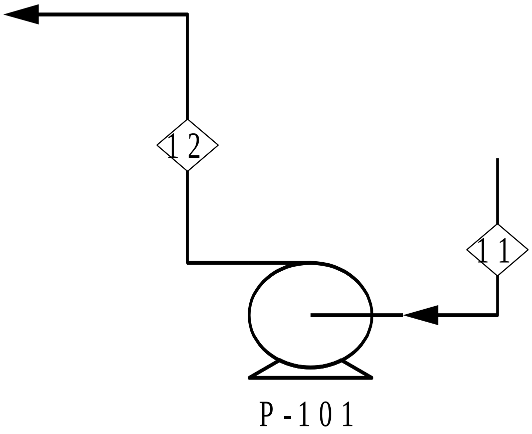


Figure 3.12: Material Balance across Product Pump (P-101)

Stream 12: Mass flow rate of component in stream 12

$$N_{12} := \sum_s n_{s,12} = 30.6189283\frac{kg}{hr}$$

3.5.11 Unit 10: Material Balance across Heat Exchanger Tube side

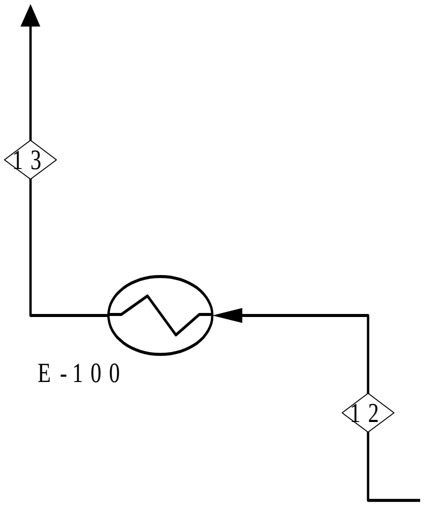


Figure 3.13: Energy Balance across Feed Pre-Heater (E-100)

Steady state operation prevails through the process, Input (Stream 12) = Output (Stream 13)

Mass flow rate of component in stream 13

$$N_{13} := \sum_{s} n_{s,13} = 30.6189283 \frac{kg}{hr}$$

3.5.12 Unit 11:Material Balance across Product Cooler (E-103)

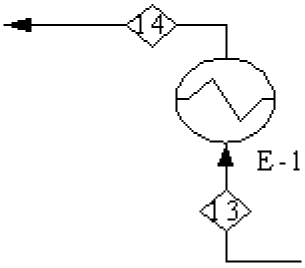


Figure 3.14: Material Balance across Product Cooler (E-103)

Steady state operation prevails through the process, Input (Stream 13) = Output (Stream 14)

3.5.2 Energy Balance

Assumptions:

The following assumptions were made in course of the energy balance calculation across the entire SWS unit;

1. Steady state operation prevails throughout the operation
2. The effect of pressure on enthalpy is considered negligible
3. Energy losses in pipeline is also considered negligible
4. All heat loss in the cause of the energy balance calculation is considered negligible
5. Reference temperature is considered to be 0 ^{o}C

3.5.2.1 Energy Balance across Sour Water Surge Drum

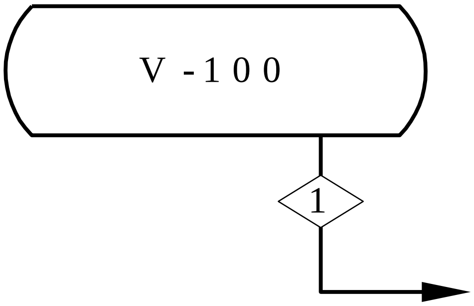


Figure 3.15: Energy Balance across Sour Water Surge Drum (V-100)

Energy Input: This is the sum of the enthalpies of all input stream into the unit

$$H_{Input} := \sum_{s} H_{s,1} = 1991.861303 \frac{kJ}{hr}$$

Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{Output} := \sum_{s} H_{s,1} = 1991.861303 \frac{kJ}{hr}$$

Surge Drum Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{surge} := H_{Output} - H_{Input} = 0 \cdot \frac{kJ}{hr}$$

3.5.2.2 Energy Balance across Sour Water Pump

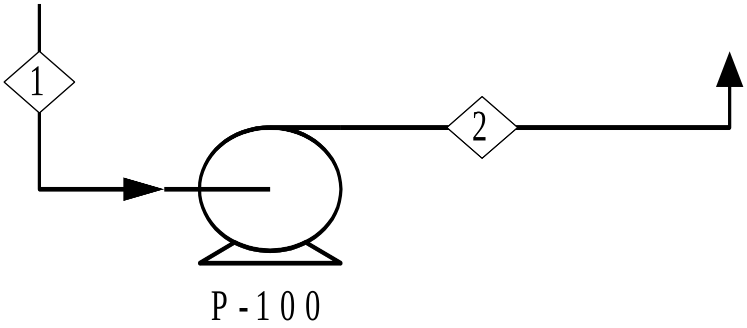


Figure 3.16: Energy Balance across Sour water Pump (P-100)

Energy Input (Stream 1)

This is the sum of the enthalpy of all input stream into the unit

$$H_{Input} = 1991.861303 \frac{kJ}{hr}$$

Outlet Stream (Stream 2)

The enthalpy of components in stream 2 at $T_2 = 35^oC$ (308.15K) is:

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{Output} := \sum_{s} H_{s,2} = 1991.861303 \cdot \frac{kJ}{hr}$$

Heat Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{P100} := H_{Output} - H_{Input} = 0 \cdot \frac{kJ}{hr}$$

3.5.2.3 Energy Balance across Feed Preheater Tube side

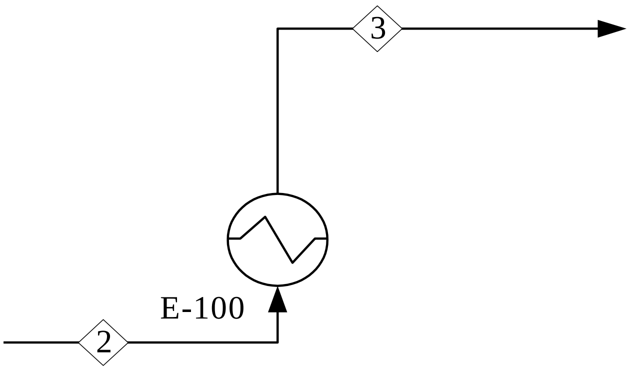


Figure 3.17: Energy Balance across Feed Preheater (E-100)

Energy Input (Stream 2)

This is the sum of the enthalpy of all input stream into the unit

$$H_{Input} = 1991.861303 \frac{kJ}{hr}$$

Outlet Stream (Stream 3)

The Enthalpy of components in stream 3 at $T_3 = 80^oC$ (353.15K) is:

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{Output} := \sum_{s} H_{s,3} = 4732.001144 \cdot \frac{kJ}{hr}$$

Shell side Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{EX\_tube} := H_{Output} - H_{Input} = 2740.13984 \frac{kJ}{hr}$$

3.5.2.4Energy Balance across Stripping Column

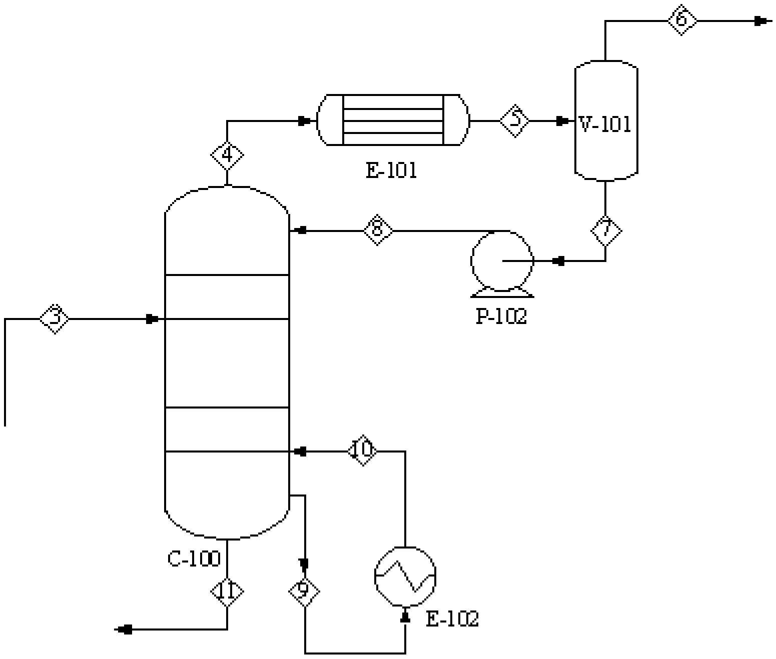


Figure 3.18: Energy Balance across Stripping Column (C-100)

Energy Input (Stream 3)

This is the sum of the enthalpy of all input stream into the unit

$$H_{Output} := \sum_{s} H_{s,3} = 4732.001144 \cdot \frac{kJ}{hr}$$

Outlet Stream (Stream 6)

The Enthalpy of components in stream 6 at T6 = 50^{o}C (323.15K) is:

$$H_6 := \sum_{s} H_{s,6} = 228.57 \frac{kJ}{hr}$$

Outlet Stream (Stream 11)

Enthalpy of components in stream 11 is:

$$T_{11} := 135°C = 408.15K$$

$$H_{11} := \sum_{s} H_{s,11} = 7583.292 \cdot \frac{kJ}{hr}$$

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{Output} := H_6 + H_{11} = 7811.86195 \cdot \frac{kJ}{hr}$$

Column Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{Col} := H_{Output} - H_{Input} = 3079.86081 \cdot \frac{kJ}{hr}$$

3.5.2.5 Energy Balance across Column Overhead Condenser

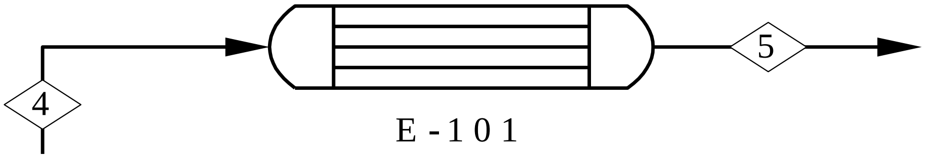


Figure 3.19: Energy Balance across Column Overhead Condenser (E-101)

Inlet Stream (Stream 4)

The Enthalpy of components in stream 4 at $T_4 = 123^{o}C$ (396.15K) is:

Total Energy Input (Stream 4)

This is the sum of the enthalpy of all input stream into the unit

$$H_{Output} := \sum_{s} H_{s,4} = 1463.776749 \cdot \frac{kJ}{hr}$$

Outlet Stream (Stream 5)

Enthalpy of components in stream 5 at T5 = $50^{o}C$ (323.15K) is:

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{Output} := \sum_{s} H_{s,5} = 613.034545 \cdot \frac{kJ}{hr}$$

Condenser Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{Cond} := H_{Output} - H_{Input} = -850.7422 \frac{kJ}{hr}$$

3.5.2.6 Energy Balance across Reflux Drum

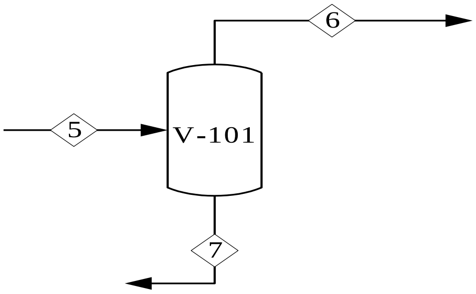


Figure 3.20: Energy Balance across Reflux Drum (V-101)

Total Energy Input (Stream)

This is the sum of the enthalpy of all input stream into the unit

$$H_{Input.} := \sum_{s} H_{s,5} = 613.034545 \frac{kJ}{hr}$$

Outlet Stream (Stream 6)

The Enthalpy of components in stream 6 at T_6 = 323.15K is:

$$H_6 := \sum_{s} H_{s,6} = 228.57 \cdot \frac{kJ}{hr}$$

Outlet Stream (Stream 7)

Enthalpy of components in stream 7 at T_7 = 323.15K is:

$$H_7 := \sum_s H_{s,7} = 373.279 \frac{kJ}{hr}$$

Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{Output.} := H_6 + H_7 = 601.849343 \frac{kJ}{hr}$$

Reflux Drum Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{Reflux} := H_{Output.} - H_{Input.} = -11.1852 \frac{kJ}{hr}$$

3.5.2.7 Energy Balance across Reflux Pump

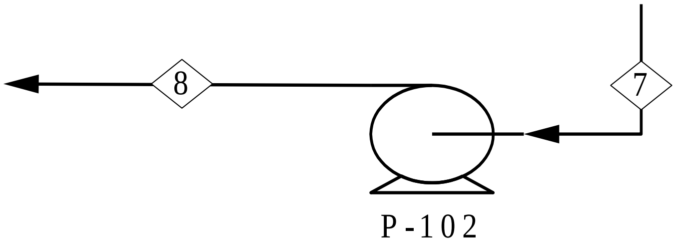


Figure 3.21: Energy Balance across Reflux Pump (P-102)

Energy Input (Stream 7)

This is the sum of the enthalpy of all input stream into the unit

$$H_{Input} := \sum_s H_{s,7} = 373.2793 \cdot \frac{kJ}{hr}$$

Outlet Stream (Stream 8)

Enthalpy of components in stream 8 at T_8 = 323.15 K is:

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{Output} := \sum_{s} H_{s,8} = 373.279331 \cdot \frac{kJ}{hr}$$

Reflux Pump Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{P102} := H_{Output} - H_{Input.} = 0 \cdot \frac{kJ}{hr}$$

3.5.2.8 Energy Balance across Column Bottom Reboiler

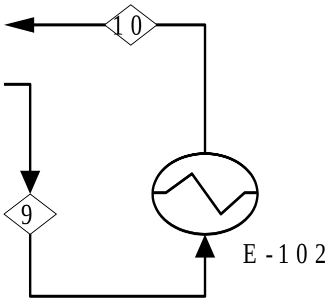


Figure 3.22: Energy Balance across Column Bottom Reboiler (E-102)

Inlet Stream (Stream 9)

Enthalpy of components in stream 9 at T_9 = 80°C (353.15K) is:

Total Energy Input (Stream 9)

This is the sum of the enthalpy of all input stream into the unit

$$H_9 := \sum_{s} H_{s,9} = 918.453891 \frac{kJ}{hr}$$

Outlet Stream (Stream 10)

Enthalpy of components in stream 10 at T10 = 135oC (408.15K) is:

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{10} := \sum_{s} H_{s,10} = 1584.531209 \frac{kJ}{hr}$$

Condenser Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{Reb} := H_{10} - H_{9} = 666.07732 \frac{kJ}{hr}$$

3.5.2.9 Energy Balance across Bottom Product Pump

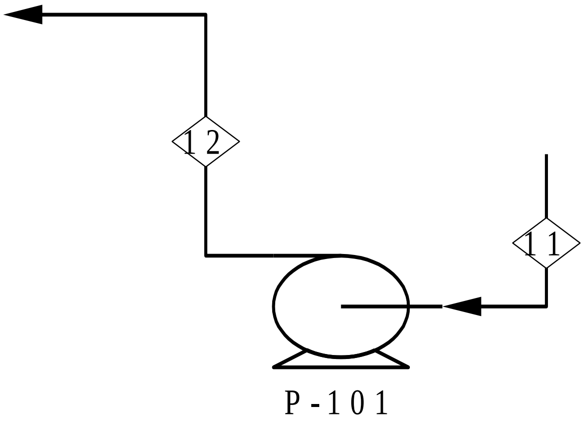


Figure 3.23: Energy Balance across Bottom Product Pump (P-101)

Energy Input (Stream 11)

This is the sum of the enthalpy of all input stream into the unit

$$H_{Input} := \sum_{s} H_{s,11} = 7583.291938 \cdot \frac{kJ}{hr}$$

Outlet Stream (Stream 12)

Enthalpy of components in stream 12 at T_{12} = 408.15K is:

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{output} := \sum_{s} H_{s,12} = 7583.291938 \cdot \frac{kJ}{hr}$$

Product Pump Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{P101} := H_{Output} - H_{Input} = 0 \cdot \frac{kJ}{hr}$$

3.5.2.10 Energy Balance across Feed Preheater Shell side (E-100)

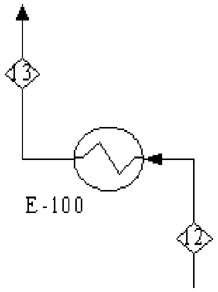


Figure 3.24: Energy Balance across Feed Preheater Shell Side (E-100)

Energy Input (Stream 12)

This is the sum of the enthalpy of all input stream into the unit

$$H_{Input} := \sum_{s} H_{s,12} = 7583.291938 \cdot \frac{kJ}{hr}$$

Outlet Stream (Stream 13)

The Enthalpy of components in stream 13 at $T_{13} = 88^{o}C$ (361.15k) is:

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{output} := \sum_{s} H_{s,13} = 4855.958086 \cdot \frac{kJ}{hr}$$

Exchanger Tube side Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{EX\_shell} := H_{Output} - H_{Input} = -2727.33385\frac{kJ}{hr}$$

$$Q_{EX\_shell} = -2727.334\frac{kJ}{hr}$$

$$Q_{EX\_shell} + Q_{EX\_tube} = 12.806\frac{kJ}{hr}$$

3.5.2.11 Energy Balance across Product Cooler

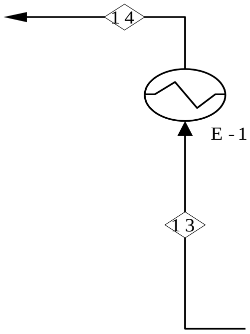


Figure 3.25: Energy Balance across Product Cooler (E-103)

Outlet Stream (Stream 14)

Enthalpy of components in stream 14 at T_{14} = 35^{o}C (308.15K) is:

Total Enthalpy Output

This is the sum of the enthalpy of all input stream out of the unit

$$H_{output} := \sum_{s} H_{s,14} = 1816.190491\cdot\frac{kJ}{hr}$$

Product Cooler Duty

This is the difference between the total energy output and the total energy input to the unit

$$Q_{cooler} := H_{Output} - H_{Input} = -3039.7676\frac{kJ}{hr}$$

3.6 Equipment Design

Equipment required for the Mini-refinery Sour Water Stripping Unit were designed using suitable established empirical correlations available in literatures (See Appendix III and IV) and Hysys was used to simulate the process. Subsequently, each equipment specifications were computed and presented. Seven equipment were required for the process. They include Surge Drum (V-100), Feed Charge Pump (P-100), Feed Pre-heater (E-100), Stripping Column (C-100), Bottom Reboiler (E-101), Overhead Condenser (E-102), Product Cooler (E-103), and Reflux Drum (V-101).

3.7 Development of Controls, Start-up and Shut Down Procedure

In order to ensure safety and success of the pilot SWS Unit operation, appropriate control points were specified to monitor and control temperature, pressure and flow along the process flow paths. With the aid of the controls, start-up and shut-down procedures were developed.

3.8 Materials Selection

The selected materials of construction were based on the design and operational considerations made for the fabrication of the mini-refinery SWS Unit is Stainless Steel (SS316 Austenite). The selection was due to the presence of corrosive substances (sulphur compounds) in the process stream and the ability of the stainless steel to withstand high temperature and pressure anticipated during operation. The chosen Stainless Steel SS316 has the following suitable properties (Stanley, 1990).

- Excellent Welding properties
- High Thermal Conductivity
- Suitable for handling organic and inorganic substances

- Maximum Allowable Stress
- Good Corrosion Resistance
- High workability Temperature range.

However, Mild Steel (which has lower corrosion resistance) was utilized for the fabrication of the designed equipment, as the recommended Stainless Steel was too costly to be used at this early stage of technology development. More so, use of corrosion inhibitors such as Butylated Hydroxitoluene (BHT), Ethylenediamine, etc is recommended during operation (Stanley, 1990).

3.9 Working Drawings/Models Development

The computed values derived from the equipment design were used to generate working drawings and models which served as templates and guides for the fabrication work. Each equipment's working drawing was drawn to specification using Solidworks before modelling using computerized modelling software (CREO Parametric tool) which generated elevated views, internals and detailed working dimensions.

3.10 Fabrication

The fabrication work was performed by certified fabrication company under close supervision of both the supervisors and the student. The working drawings generated were used as working templates at this stage. However, minor adjustments were made to the working drawings and the equipment design considering the material availability in the market.

3.11 Installation, Lagging and Cladding

The fabricated equipment were sequentially installed according to the Process Flow Diagram. Feed Surge drum (V-100) was the first to be installed. Outlet of V-100 was connected to the inlet of the feed pre-heater (E-100) for fluid flow from V-100 into E-100. The outlet of E-100 was joined with the inlet of Stripping column (C-100). The overhead of C-100 was connected to the inlet of overhead condenser (E101), while part of its bottom was channeled to the inlet of the Bottom Reboiler (E-102) and part to was linked to the inlet of the Product Cooler (E-103) via the Shell of E-100. The outlet of E-101 was connected to the inlet of the Reflux Drum (V-101) from which, overhead outlet was joined with the Flare line, while bottom outlet is sent back to C-100 as reflux.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents results and discussion of the designed pilot SWS Unit. It contains summaries of material and energy balances, detailed equipment design and working drawings. In the same vein, details of controls as well as fabrication is also presented. The chapter also presents the start-up and short-down procedures and results of data generated in the course of operating the plant.

4.2 Material Balance

The Sour Water Stripping process was designed to operate under steady state mode. Subsequently, with reference to the Pilot SWS Unit PFD (Figure 3.3), Material balance summaries (manually computed using MathCad) across each equipment are presented in Tables 4.1 - 4.10. MathCad detailed calculations and Hysys simulation are contained in Appendix I and VI respectively.

4.1.1 Surge Drum

Surge drums are usually used to provide suitable liquid hold up time within a process. The total volume of a surge drum is calculated using a residence time, also called surge time, which is obtained from experience, according to the type and degree of the process control required (Silla, 2003). Table 4.1 presents summary of Material balance across Surge drum. The balance has assumed total material recovery. However, for real-life application, the surge drum content is not expected to be completely depleted at any time(t) during plant operation because continued flow of feed is necessary for semi batch and continues processes.

Because it is assumed that there is no material accumulation and also no chemical reaction or physical separation taking place in the drum, the total amount of material that goes in (Streame-1’) will be equal to the total amount of material that comes out (Streame-1), hence, Streame-1’ and Streame-1 will have the same amount of material content.

4.1.2Charge Pump

Table 4.2presents the summary of material balance across the Charge Pump (P-100). Materials from the Surge Drum (V-100) are sucked by the pump, therefore, Stream-1 (outlet of V-100) serves as the inlet of P-100 (Stream-2). This implies that both streams will have the same material content. Because it is assumed that there is no material accumulation within the Charge Pump, inlet (Stream-1) of the pump will also have the same material content with the discharge (Stream-2) of the pump. Hence, Stream-1’,Stream-1, and Stream-2 are all of equal material content.

4.1.3 Feed Preheater

Table 4.3 presents the material balance across the Feed Preheater (E-100). Discharge of P-100 (Stream-2) serves as the inlet of E-100. Because it is assumed that there is no chemical reaction or material accumulation within the preheater, inlet (Stream-2) of the preheater will also have the same material content with the discharge (Stream-3) of the preheater. Hence,Stream-2, and Stream-3 are all of equal material content.

4.1.4 Stripping Column

Table 4.4 presents the material balance across the Stripping Column (C-100). Outlet stream of the feed preheater (Stream-3) serves as the inlet stream of C-100. This implies that both streams will have the same material content. Because there is a physical separation of the volatile components in the feed (Sour Water) via stripping, thence, there is change in the chemical compositing of the constituent of the feed in the bottom (stripped water) stream. The material composition is calculated using appropriate technique and reported in table 4.4.

4.1.5 Stripping Column Overhead Condenser

Table 4.5 presents the material balance across the overhead condenser (E-101). Overhead product of C-100 (Stream-4) serves as the inlet of E-101. Because it is assumed that there is no chemical reaction or material accumulation within the overhead condenser, inlet (Stream-4) of the overhead condenser will also have the same material content with the discharge (Stream-5) of the overhead condenser. Hence,Stream-4, and Stream-5 are all of equal material content.

4.1.6 Reflux Drum

Table 4.6(a) presents the material balance across the Reflux Drum (V-101) top. Outlet (Stream-5) of the overhead condenser serves as the inlet of V-101. Because it is there is a phase (weight) separation within the Reflux Drum, the inlet (Stream-5) splits into two streams as Top (Streame-6) and Bottom (Streame-7). The material composition of Stream-6 and that of Streame-7 were calculated and reported in tables 4.6(a) and 4.6(b) respectively.

Table 4.6(b): Summary of Material Balance Input across

Table 4.7(b) presents the material balance across the Reflux Drum (V-101) bottom. Outlet (Stream-5) of the overhead condenser serves as the inlet of V-101. Because it is there is a phase (weight) separation within the Reflux Drum, the inlet (Stream-5) splits into two streams as Top (Streame-6) and Bottom (Streame-7). The material composition of Stream-6 and that of Streame-7 were calculated and reported in tables 4.6(a) and 4.7(b) respectively.

4.1.7 Reflux Pump

Table 4.7presents the summary of material balance across the Reflux Pump (P-102). Materials from the Reflux Drum (V-101) are sucked by the pump, therefore, Stream-7 (bottom outlet of V-101) serves as the inlet of P-102. This implies that both streams will have the same material content. Because it is assumed that there is no material accumulation within the Reflux Pump, inlet (Stream-7) of the pump will also have the same material content with the discharge (Stream-8) of the pump. Hence, Stream-7, and Stream-8 are all of equal material content.

4.1.8 Bottom Reboiler

Table 4.8 presents the material balance across the Bottom Reboiler (E-102). Bottom product of C-100 (Stream-11) serves as the inlet of E-102. Because it is assumed that there is no chemical reaction or material accumulation within the Bottom Reboiler, inlet (Stream-11) of the overhead condenser will also have the same material content with the discharge (Stream-10) of the Bottom Reboiler. Hence,Stream-11, and Stream-10 are all of equal material content.

4.1.9 Product Pump

Table 4.9presents the summary of material balance across the Product Pump (P-101). Materials from the Bottom of C-100 are sucked by the pump, therefore, Stream-11 (bottom outlet of C-100) serves as the inlet of P-101. This implies that both streams will have the same material content. Because it is assumed that there is no material accumulation within the Product Pump, inlet (Stream-11) of the pump will also have the same material content with the discharge (Stream-12) of the pump. Hence, Stream-11, and Stream-12 are all of equal material content.

4.1.10 Feed Preheater (Tube)

Table 4.10 presents the material balance across the Feed Preheater (E-100) tube. Discharge of Product Pump of P-101 (Stream-12) serves as the inlet of the tube of E-100. Because it is assumed that there is no chemical reaction or material accumulation within the E-100, inlet (Stream-12) of the Feed Preheater will also have the same material content with the outlet (Stream-13) of the Feed Preheater. Hence,Stream-12, and Stream-13 are all of equal material content.

4.1.11 Product Cooler

Table 4.11 presents the material balance across the Product Cooler (E-103) tube. Outlet of E-100 tube (Stream-13) serves as the inlet of the tube of E-103. Because it is assumed that there is no chemical reaction or material accumulation within the E-103, inlet (Stream-13) of the Product Cooler will also have the same material content with the outlet (Stream-14) of the Product Cooler. Hence,Stream-13, and Stream-14 are all of equal material content.

4.3 Energy Balance

This part takes account of the heating and cooling requirements for the SWS Unit process. This is indeed crucial as it gives a clear insight as regards to energy requirements for the hydro-treatment process. The 4.11 to 4.13 tables contain summaries of Energy Balances (duties) across each non-reactive unit; while details are contained in Appendix II of this report.

4.2.1 Sour water Surge Drum

Table 4.12 presents the energy balance across the Surge Drum (V-100). Sour Water feed from various unit of the Mini-Refinery serves as the inlet of V-100 (Stream-1'). Because there is no exchange of heat and heat loss to the surrounding is assumed to be negligible, the enthalpy of inlet stream will be equal to the enthalpy of the outlet stream, hence the overall heat duty of the drum will be zero.

4.2.2 Sour Water Pump

Table 4.13 presents the energy balance across the Feed Charge Pump (P-100). Sour Water feed from the feed surge drum (V-100) serves as the inlet stream (Stream-1) ofP-100. Because there is no exchange of heat and heat loss to the surrounding is considered to be negligible, the enthalpy of inlet stream will be equal to the enthalpy of the outlet stream, hence the overall heat duty of the feed charge pump will be zero.

Table 4.14 presents the energy balance across the Feed Preheater (E-100). Discharge of the feed charge pump (Stream-2) serves as the inlet stream ofP-100. Because there is exchange of heat energy (preheating) of this stream, the energy balance for E-100 was calculated and reported in Table 4.14. The Heat Duty of the feed preheater, which is the difference in the total enthalpy of the outlet and the inlet stream was also calculated and reported as shown. This value is 2740 kJ/hr of heat gain by stream-2.

4.2.4Stripping Column

Table 4.15 presents the energy balance across the Stripping Column (C-100). There is tremendous exchange of heat energy that results in the stripping of the most volatile components from the feed, hence, the enthalpy changes between the inlet and the outlet streams. The energy balance across C-100 was calculated and reported in Table 4.15. The Heat Duty of the column, which is the difference in the total enthalpy of the outlet and the inlet stream was also calculated and reported as shown. This value is 3079.814 kJ/hr.

4.2.5Column Overhead Condenser

Table 4.16 presents the energy balance across the stripping column overhead condenser (E-101). In this equipment there is tremendous loss of heat by the inlet stream that results in the condensation of the overhead product into liquid, hence, the enthalpy changes between the inlet and the outlet streams. The energy balance across E-101 was calculated and reported in Table 4.16. The Heat Duty of the condenser, which is the difference in the total enthalpy of the outlet and the inlet stream was also calculated and reported as shown. This value is calculated to be -850.742 kJ/hr. The negative sign indicates loss of heat.

4.2.6Column Overhead Reflux Drum

Table 4.17 presents the energy balance across the column overhead reflux drum (V-100). In this equipment there is a slight loss of heat, hence, the enthalpy changes between the inlet and the outlet streams. The energy balance across V-100 was calculated and reported in Table 4.17. The duty of the drum, which is the difference in the total enthalpy of the outlet and the inlet stream was also calculated and reported as shown. This value is calculated to be -11.185 kJ/hr. The negative sign indicates loss of heat.

4.2.7Reflux Pump

Table 4.18 presents the energy balance across the Reflux Pump (P-102). Part of the condensed overhead product from the reflux drum (Stream-7) serves as the inlet stream ofP-102. Because there is no exchange of heat and heat loss to the surrounding is considered to be negligible, the enthalpy of inlet stream will be equal to the enthalpy of the outlet stream, hence the overall heat duty of the feed charge pump will be zero.

4.2.8Column Bottom Reboiler

Table 4.19 presents the energy balance across the Bottom Reboiler (E-102). Part of the bottom product of C-100 (Stream-9) is syphoned and used as a boil-up for the column (Stream-10). Because there is exchange of heat for this stream, the energy balance for E-101 was calculated and reported in Table 4.19. The Heat Duty of the Bottom reboiler, which is the difference in the total enthalpy of the outlet and the inlet stream was also calculated and reported as shown. This value is 666.048 kJ/hr of heat gain by stream-10.

4.2.9Bottom Product Pump

Table 4.20 presents the energy balance across the Product Pump (P-101). Stripped Water from the bottom of the stripping column (C-100) serves as the inlet stream (Stream-11) ofP-101. Because there is no exchange of heat and heat loss to the surrounding is considered to be negligible, the enthalpy of inlet stream will be equal to the enthalpy of the outlet stream, hence the overall heat duty of the feed charge pump will be zero.

4.2.10Product Cooler

Table 4.21 presents the energy balance across the stripping unit Product Cooler (E-103). In this equipment there is tremendous loss of heat by the inlet stream that results in the cooling of the product to acceptable storage temperature, hence, the enthalpy changes between the inlet and the outlet streams. The energy balance across E-103 was calculated and reported in Table 4.21. The

Heat Duty of the product cooler, which is the difference in the total enthalpy of the outlet and the inlet stream was also calculated and reported as shown. This value is calculated to be -3039.768 kJ/hr. The negative sign indicates loss of heat by the inlet stream.

4.4Equipment Design

4.4.1 Feed Surge Drum

The pilot SWS Unit was designed to process Sour water generated at the ABU Mini Refinery. Throughput of the designed unit is 5 bbl of sour water per day. The unit required three steps to perform the entire operation. They include feed preheating, separation, and cooling. A total number of seven pieces of process equipment were designed and interlinked to perform this three-step operation. They include a surge drum (V-100), a feed preheater (E-100), a Bottom reboiler (E101), and overhead condenser (E102), a product cooler (E-103), a reflux drum (V-102) and a stripper column (C-100). The adopted design approach yielded results, however, at fabrication stage, slight changes between the equipment specification and the actual design were made. Tables 4.22 - 4.28 present results of the actual design and those of the actual fabrication values.

For the surge drum (V-100), the designed parameters were presented in Table 4.14; which contains designed and actual values. A L/D ratio of 2 was obtained in design, of which according to Silla, 2003; the drum orientation should take a horizontal orientation for L/D ratios ≤ 2.5(Silla, 2003). This was adhered to during the fabrication.

4.4.2 Reflux Drum

For the reflux drum (V-101), the designed parameters were presented in Table 4.23; which contains designed and actual values. A L/D ratio of 3 was obtained in design, of which according to Silla, 2003; the drum orientation should take a vertical orientation for L/D ratios ≤ 2.5. This was adhered to during the fabrication(Silla, 2003).

4.4.3 Feed Preheater

The feed preheater has a double-pipe configuration with a tube length of 900 mm and counter-current mode of flow. As reported in Table 4.24, the fabricated preheater is of six number of tubes as against the 4.83 as suggested by the design calculation. So also, the fabricated length of tubes is 900 mm as against the 1000 mm from the design calculation. This is excellent as the fabricated heat transfer area turned out to be 0.34 m^2, a better transfer area than the 0.3 m^2 from the design. This technical manipulation is always welcome so as to minimize offcuts of materials during fabrication, thereby, minimizing the cost of production.

4.4.4Column Overhead Condenser

The feed preheater has a double-pipe configuration with a tube length of 900 mm and counter-current mode of flow. As reported in Table 4.25, the fabricated preheater is of 4 number of tubes as against the 3.2 as suggested by the design calculation. So also, the fabricated length of tubes is 900 mm as against the 1000 mm from the design calculation. This is excellent as the fabricated heat transfer area turned out to be 0.23 m^2, a better transfer area than the 0.19 m^2 from the design. This technical manipulation is always welcome so as to minimize offcuts of materials during fabrication, thereby, minimizing the cost of production.

4.4.5Column Bottom Reboiler

The feed preheater has a double-pipe configuration with a tube length of 900 mm and counter-current mode of flow. As reported in Table 4.26, the fabricated preheater is of 3 number of tubes as against the 1.54 as suggested by the design calculation. So also, the fabricated length of tubes is 900 mm as against the 1000 mm from the design calculation. This is excellent as the fabricated heat transfer area turned out to be 0.17 m^2, a better transfer area than the 0.10 m^2 from the design. This technical manipulation is always welcome so as to minimize offcuts of materials during fabrication, thereby, minimizing the cost of production.

4.4.6 Product Cooler

The feed preheater has a double-pipe configuration with a tube length of 900 mm and counter-current mode of flow. As reported in Table 4.27, the fabricated preheater is of 14 number of tubes as against the 12.33 as suggested by the design calculation. So also, the fabricated length of tubes is 900 mm as against the 1000 mm from the design calculation. This is excellent as the fabricated heat transfer area turned out to be 0.79 m^2, a better transfer area than the 0.77 m^2 from the design. This technical manipulation is always welcome so as to minimize offcuts of materials during fabrication, thereby, minimizing the cost of production.

4.4.7Stripping Column

A sieve tray column was selected because the process fluid is no-foaming and sieve tray are relatively lighter in weight, less expensive, easier and cheaper to install. From Aspen Hysys (2014), the reflux ratio for 97% water recovery at the top of the column is R = 2. Theoretical and actual number of plates were calculated using the Erbar-Maddox Correlation for its simplicity in Minimum number of Stages calculation. Column height, diameter, feed tray etc. were all calculated and reported see Appendix.

4.5 Process Controls and Instrumentation

The designed SWS Unit can only be operated by using suitable instrumentation and controls to run the process successfully and safely. They were specified at various points to measure and control temperature, pressure and flows along process paths as shown in Figure 4.1. The Feed Surge Drum (V-100) has a level indicator and controller (LIC-100), Pressure indicator and controller (PIL-101) and flow indicator and controller (FIC-102) to control level to 80% using a flow control valve (CV-100). CV-102 is a drain valve on the feed line, which when opened, sends in feed into the stripping column via E-100 and using the feed Charge Pump (P-100). When the level in V-100 is very low – below the set point – LIC-100 senses it and sends a signal to CV-100 to open automatically so than more fluid can come-in to compensate for the shortfall. In the same way, when the level in V-100 is too high – above the set point – LIC-100 senses it and sends a signal to CV-100 to close, automatically.

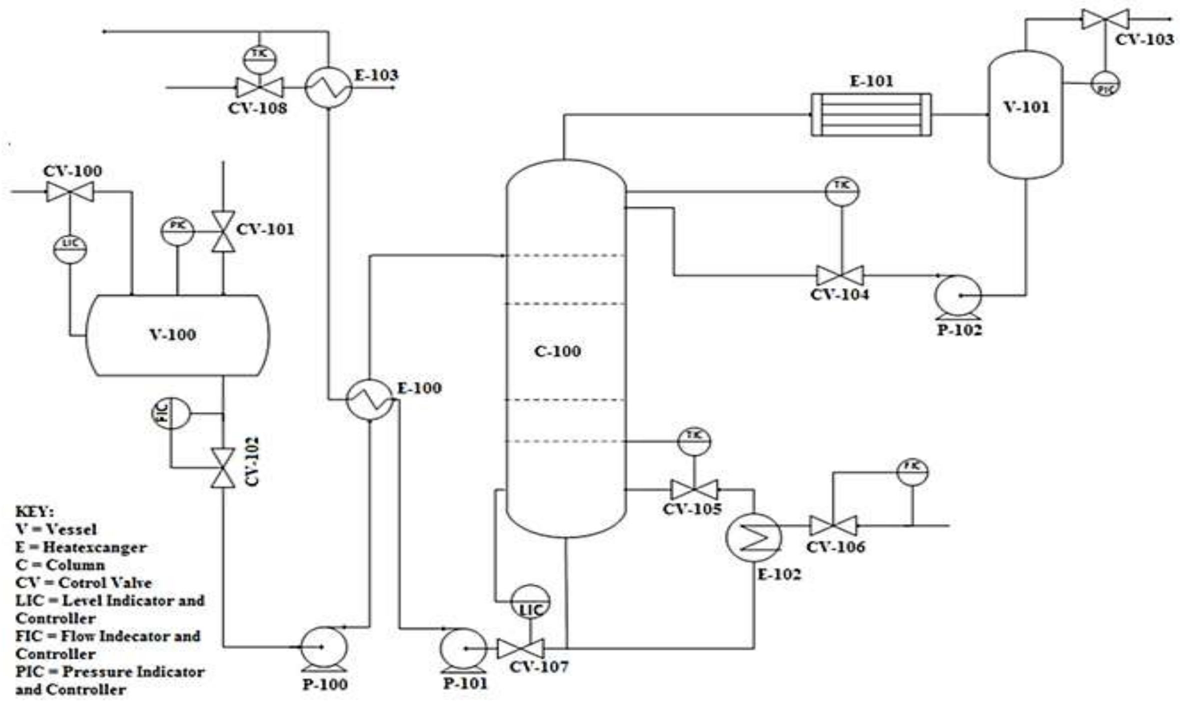


Figure 4.1: Process Control and Instrumentation

The set-point for FIC-102 is the feed flow rate. When the feed flowrate is above normal, the FIC-102 senses it and sends a signal to CV-102 to slightly open/close so as to regulate and maintain the feed flowrate within specified set point. TIC-107 and TIC-104 are to sense, record and indicate the bottom and overhead temperatures of the stripping column (C-100) respectively. When the operation temperature is too low below the set point, TIC-107 senses it and sends a signal to CV-107 to open and send-in hot reboiler fluid into C-100 so that its temperature can the kept within normal set point. In the same way, when the operation temperature is too high above the set point, TIC-104 senses it and sends a signal to CV-104 to open and send-in cold condenser fluid into C-100 so that its temperature can the kept within normal set point.

PIC-101 and PIC-103 are each pressure indicator and controller on the surge drum (V-100) and the reflux drum (V-101) respectively. When there is too much accumulation of gasses in either of the drums, the pressure therein will rise significantly above a specified set point. If in V-100, PIC-101 will sense it and will send a signal to the vent valve CV-101 to open and release the gases into the flare line. In the same way, if it is in V-101, PIC-103 will sense it and will send a signal to the vent valve CV-103 to open and release the gases into the flare line.

4.6 SWS Unit Start-up and Shut-down Procedure

The Pilot SWS Unit have sequence of activities to be performed in the course of its start-up and shut down in order to ensure accident-free start-up, operation, and shut-down. The procedure is done by controlling the process variables using the various controllers presented in Figure 4.1. A step-wise procedure for the unit start-up and shut-down are presented thus;

4.6.1 PREPARATION FOR INITIAL START-UP

The following should be completed before leakage test in order to prepare the SWS unit for operation;

(a). Removing of all scaffoldings, temporary pipping and supports.

(b). Inspection of vessels for cleanness and conformity with design specifications.

(c). Hydrostatic or pneumatic test of all lines and equipment.

(d). Tightness test.

(e). Flushing out of alllines and equipment.

(f). Checking of all lines for conformity with Process Flow Diagram.

(g). Run-in of pumps and motors.

(h). Commissioning of utility lines(s).

(i).Commissioning of flare and blowdown lines.

(j). Preparation of laboratory sampling and testing schedule.

4.6.2 INITIAL START-UP

After successful design, fabrication and installation of the SWS unit, the following procedures should be observed before the commissioning.

4.6.2.1 Confirmation of the Status of the Unit

(a). All manholes and flanges are tight.

(b). All blinds are removed or installed as required.

(c). All water drained from lines and/or equipment.

(d). All vents and drains are closed.

(e). All safety valves are installed and tested.

(f). All firefighting equipment are ready for use.

(g). Flare and blowdown system are ready for use.

(h). Utilities ready for use.

(i). All instrument ready for use.

(j). All pumps are ready for use.

(k). All steam tracing ready for use.

(l). Notify other units of the refinery that SWS will be start-up.

4.6.2.2 Air Freeing and Leakage Check

(a). Ensure that the cooling water to overhead condenser (E-101) are closed off and vents & drain in the cooling water line are open.

(b). Ensure all pumps are isolated.

(c). Open pressure control valves.

(d). Connect utility stream to stripping column (C-100).

(e). Slowly introduce steam to the stripping column (C-100) and slowly heat up the equipment and lines.

(f). Increase the pressure of the system by throttling the vents and drains and maintain this pressure until the leakage test is completed.

(g). Check leakage at all flanges as evidenced by escaping steam. Repair any leaks found.

(h). When the leakage test and repair are completed, float surge drum (D-100) to the flare pressure by opening gate valve in the vapor outlet line of D-100.

(i). Stop steam injection and close all the drains and vents.

(j). Float the C-100 to the flare pressure by opening gate valve in the gas line to the flare.

4.6.2.3Dummy Operation

(a). Regularly swing pumps and clean the suction strainer of the pump which is out of service.

(b). Introduce water into C-100.

(c). While step-(b) is in progress, line up the water circulation loop in preparation for the water circulation.

(e). When high water liquid level is established in the bottom of C-100, stop the water supply.

(f). Start the C-100 discharge pump and establish a flow through C-100 circulation loop. Adjust circulation rate to 25 m^3/hr by manipulating the feed control valve.

(g). Build-up high liquid level in C-100 by making up water.

4.6.2.4 Starting Reboiler Operation

(a). Start cooling water to OH condenser (E-101) as follows:

    (i). Fully open the gate valve in the cooling water intake line.

    (ii). Start cooling water circulation pump and establish a recycle flow.

    (iii). Increase the recycle water rate to 200 m^3/hr.

    (iv). Fully open the gate valve in the cooling water intake line.

(b). Manipulate the flow and gradually introduce steam to the reboiler.

(c). Gradually increase the steam rate to 4 tonne/hr.

(d). While step-(c) is in progress, maintain the cooling water outlet temperature at 50^oC by manipulating the steam rate.

4.6.2.5 Introducing Sour water to C-100

(a). Line up the sour water route from D-100 to C-100.

(b). Establish normal liquid level in bothD-100.

(c). Start cooling water to the Product cooler (E-103)

(d). When sufficient liquid level is established in V-100, start the sour water charge pump P-100 and direct the sour water flow to C-100.

(e). Ensure normal liquid level in C-100.

(f). Adjust total sour water flow rate of 25 m^3/hr by manipulating gate valve V-100.

(g). Adjust the cooling water rate for E-103 so that the treated water temperature may be 40^oC.

(h). Manipulate Pressure control valve and gradually raise the operating pressure to 0.7 kg/cm^2.

(i). As the sour water feed rate increases, decrease the recycle flow rate to C-100 by manipulating the inlet valve. Close the valve when the feed rate has reached 25 m^3/hr.

(j). Adjust the unit's operating conditions to meet product specifications.

4.6.2.6 Adjustment of Operating Conditions

(a). Adjust the reboiler steam rate so that the treated water quality meet specifications.

(b). Adjust the cooling water feed rate to E-103 to maintain a normal outlet temperature of 40^oC.

(c). Adjust and maintain sour water feed rate at (or slightly above) 25m^3/hr.

(d). When stable operation is established in the SWS unit, direct acid gases from SWS to the flare line.

4.6.3 NORMAL SHUTDOWN

In normal shutdown, the C-100 will be shut down for general inspection and maintenance.

4.6.3.1 Stop Reboiler Operation

(a). Draw off the water in the bottom of C-100 and send to secondary water treatment unit of the refinery.

(b). Stop the reboiler steam to E-102 b closing the inlet steam gate valve.

(c). Stop the cooling water circulation to the OH condenser (E-101) by shutting down the cooling water pump.

4.6.3.2 Depressurize the Unit

(a). Ensure that acid gas flow is diverted to the flare.

(b). Depressure C-100 to the flare line.

4.6.3.3 Steam Purge the Unit

(a). Start steaming to the flare by connecting steam horses to utility connection on C-100.

(b). Continue the steaming to the flare for, at least, one hour.

(c). Then, divert the steam flow to atmosphere by opening the top vent of C-100 and other appropriate vents while blocking the line to flare.

(d). Steam purging should continue for, at least, 24 hours and, at most, 36 hours.

(e). Control valves of all bypasses should be open during steam purging.

(f). Drain the steam condensate from all drain points during steaming operation.

4.6.3.4 Water Washing

When C-100 and associated equipment have been completely freed of hazardous atmosphere, wash the equipment with water, while opening manholes and/or vents as required.

4.6.3.5 Internal Inspection

(a). Necessary blinds should be installed in all connections to equipment to be entered for internal inspection.

(b). Each equipment should be tested for safety prior to entry permit.

(c). Appropriate maintenance work on equipment should be carried out as recommended during/after inspection.

4.6.4 SAFETY AND SAFETY PRECAUTIONS

The materials handled in the SWS unit consist, mostly, of water and small amount of Hydrogen Sulfide (H_2S) gas and Ammonia (NH_3). H_2S is toxic and flammable to a certain degree. At any vent, all employees and operators should be well experienced in the unit's operation techniques, guidelines and procedures. They should also be familiar with the applicable safety precautions and emergency procedures to be exercised at any point in time. Operations of emergency devices and procedures should be well taught, and understood as personnel and industrial safety always comes first.

4.6.4.1 EMERGENCY DEVICES

4.5.4.1.1 Alarm Systems

Alarm systems are provided to warn all personnel about upset and abnormal situations of the SWS unit. All alarms and their settings levels are listed in Table 4.30.

Table 4.29: Alarms and their Setting Points

Instrument Tag	Service	Mode	Advised Set-point	Normal Operation Set-point
C-100 PICA	C-100	High	0.84 kg/cm^2	0.7 kg/cm^2
D-100 LICA	D-100	High	80%	50%
		Low	20%	

4.6.4.1.2 Safety and Relief Valve

The locations, destination of discharge fluids, critical cases, set pressures and sizes of the safety and relief valves and rupture disks are summarized in Table 4.31

Table 4.30: Safety Relief Valves and their Set Points

Item No.	Service	Discharge to	Critical Case	Set Pressure (kg/cm^2)
PSV-01	C-100 O/Head	Flare	CW Failure	2.7
PSV-02	E-100 (shell)	SW Feed line	Fire	33.5
PSV-03	E-101 (shell)	SW Feed line	Fire	13.5
PVS-04	E-101 CW line	Sewer	Thermal Expansion	5.5
PVS-05	E-103	Sewer	Thermal Expansion	5.5
RD-01				2.7 (Rupture)
RD-02				2.7 (Rupture)

4.6.4.1.3 Fire Fighting Devices

The layout of firefighting equipment such as hydrants and fire monitors should be elaborate and well understood. Operating personnel must be familiar with the location and the use of all emergency firefighting equipment. Telephone line to the firefighting unit of the refinery should be placed/written at strategic points in the unit for easy communication.

4.6.5 EMERGENCY PROCEDURES

Emergency situations will occur unexpectedly and the best preparedness is having a thorough knowledge of the unit, anticipation of the most probable problems and their solutions, and a complete familiarity with all normal procedures. Emergency conditions are usually caused by equipment failure, utility failure, mal-operation and fire. If it is necessary to bring the unit off stream due to emergency situation, the procedures used for normal shutdown should be followed as closely and practically as possible.

There will be occasions when mechanical or utility failure brings about shutdown of a particular equipment or instrument. In such cases, the shutdown may be of a temporary nature and will not require total shutdown of the entire unit depending on the duration of such failures. However, in the event of total utility failure, whether steam, instrument air, cooling water, electricity etc, it is assumed that it will be necessary to shut down the unit.

4.6.5.1 Analyzing Emergency

In the event of an emergency, the following decisions have to be made before the unit is shut down.

(a). Determine the extent of the emergency condition(s).

(b). Notify the related departments for necessary action soon as possible.

(c). Decide how to handle the emergency at, if possible, a localized point without shutting down other units.

4.6.5.2 General Emergency Procedure

Considering easier restart of the unit, the following steps should be taken as general emergency procedure;

(a). Stop the reboiler operation by shutting the steam inlet.

(b). Divert acid gas to the flare.

(c). As long as this condition is on, Sour water feed should be diverted to WWT unit.

4.6.5.3 Utility Failure

4.6.5.3.1 Electricity Failure:

(i). Cause – External to SWS unit.

(ii). Effect – All flows with stop instantly due to power cut to pump motors and liquid level in D-100 will rise rapidly due to the stoppage of feed charge pump (P-100).

(iii). Procedure – Notify the preceding process unit to stop or reduce sour water feed flow.

– Close the discharge valves of all pumps.

– Run the “general emergency procedure” step-wisely.

4.6.5.3.2 Cooling water failure:

(i). Cause – External to SWS unit.

(ii). Effect – Acid gas temperature will rise above normal.

- Steam quantity in the acid gas will increase rapidly.
- The temperature of WWT unit feed will rise.

(iii). Procedure – Run the “general emergency procedure” step-wisely.

– Notify the preceding process unit to stop or reduce sour water feed flow.

4.6.5.3.3 Steam Failure:

(i). Cause – External to SWS unit.

(ii). Effect – Acid gas stripping can not be accomplished due to loss of steam to E-102.

(iii). Procedure – Run the “general emergency procedure” step-wisely.

–Notify the preceding process unit to stop or reduce sour water feed flow.

4.7 Pilot SWS Unit Equipment Working Drawings/Models

Figures 4.2 - 4.15 presents the working drawings and models derived from design calculations. The drawings were very essential as they served as working templates for fabrication.

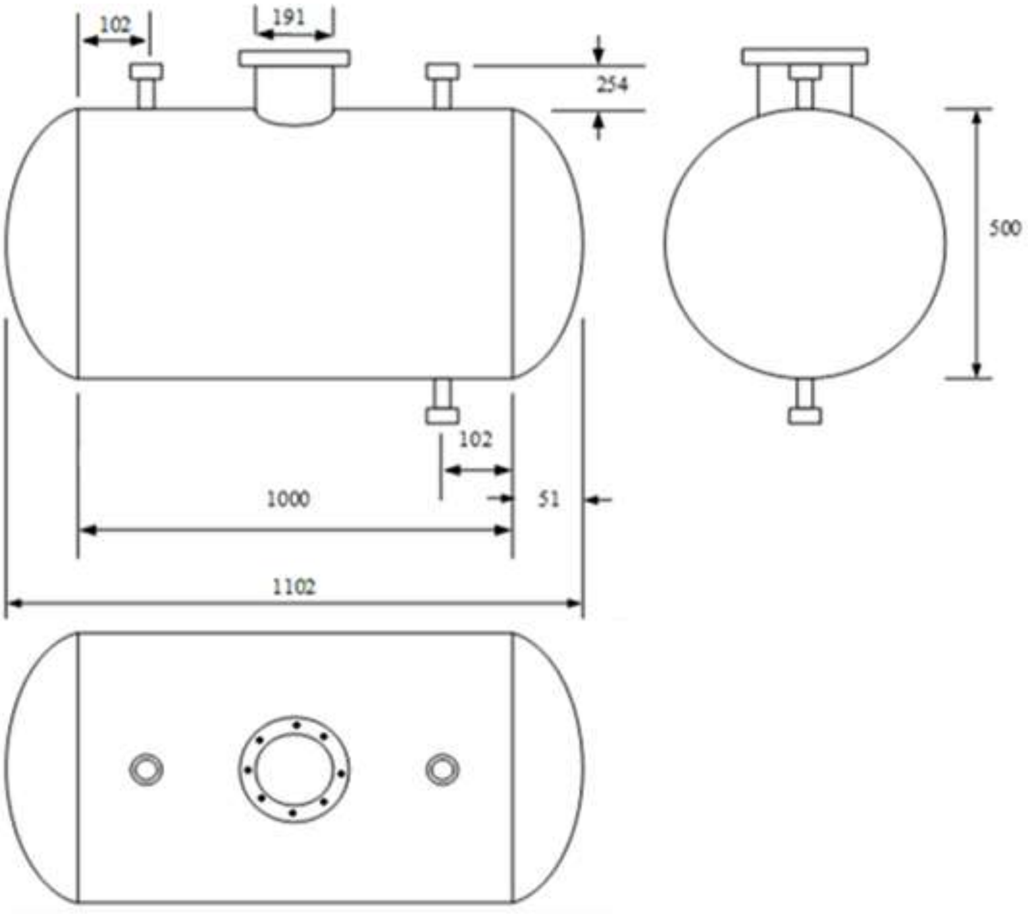


Figure 4.2: Working Drawings for SWS Unit Surge Drum

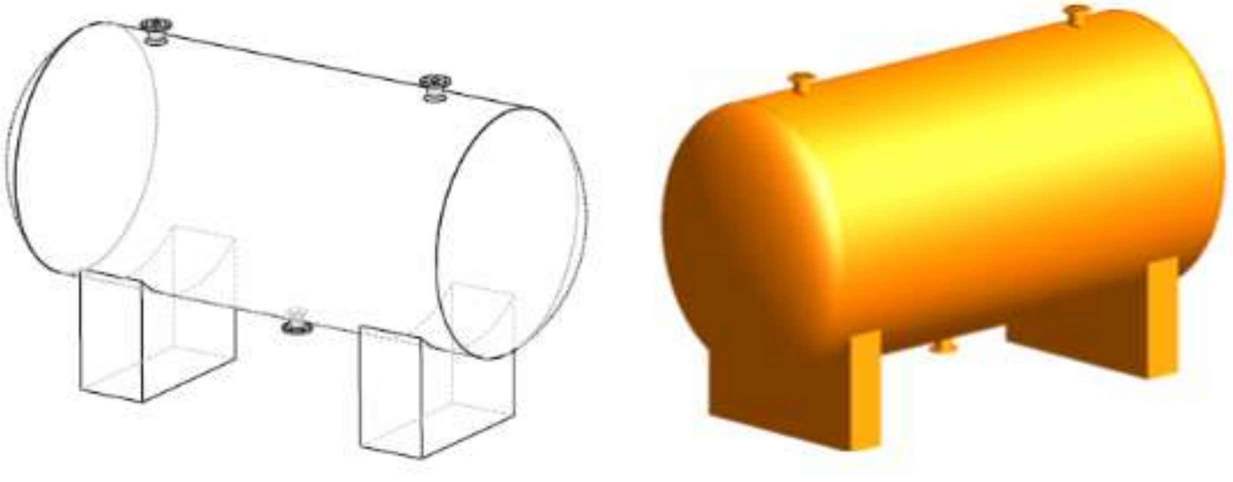


Figure 4.3: 3D Models of SWS Unit Surge Drum

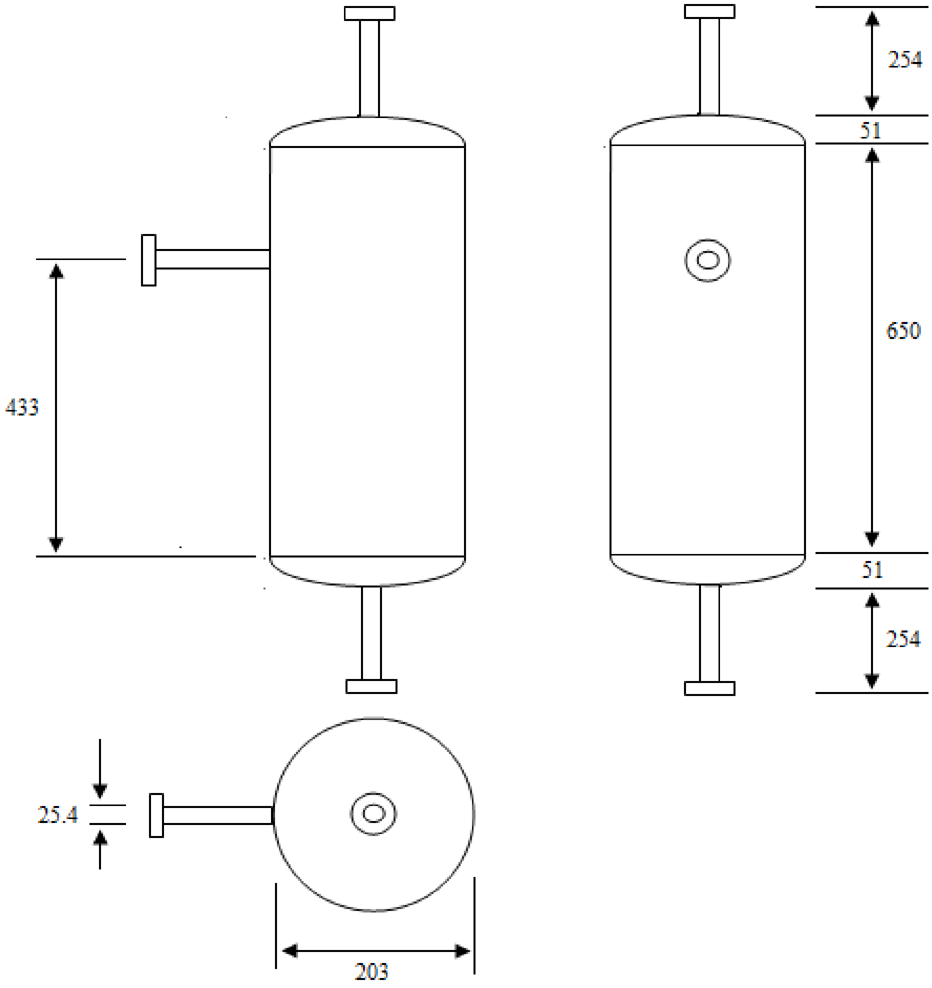


Figure 4.4: Working Drawing for Reflux Drum

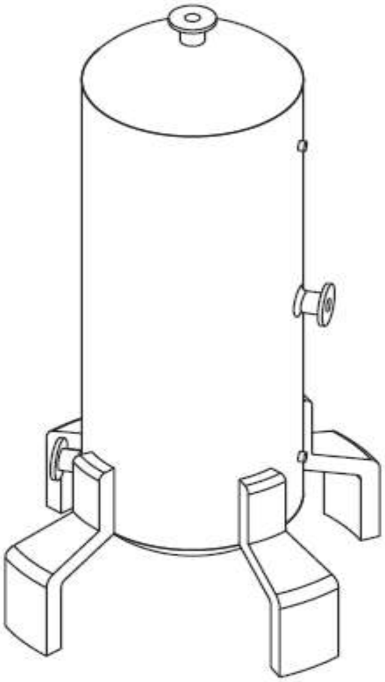


Figure 4.5: 3D Model of Reflux Drum

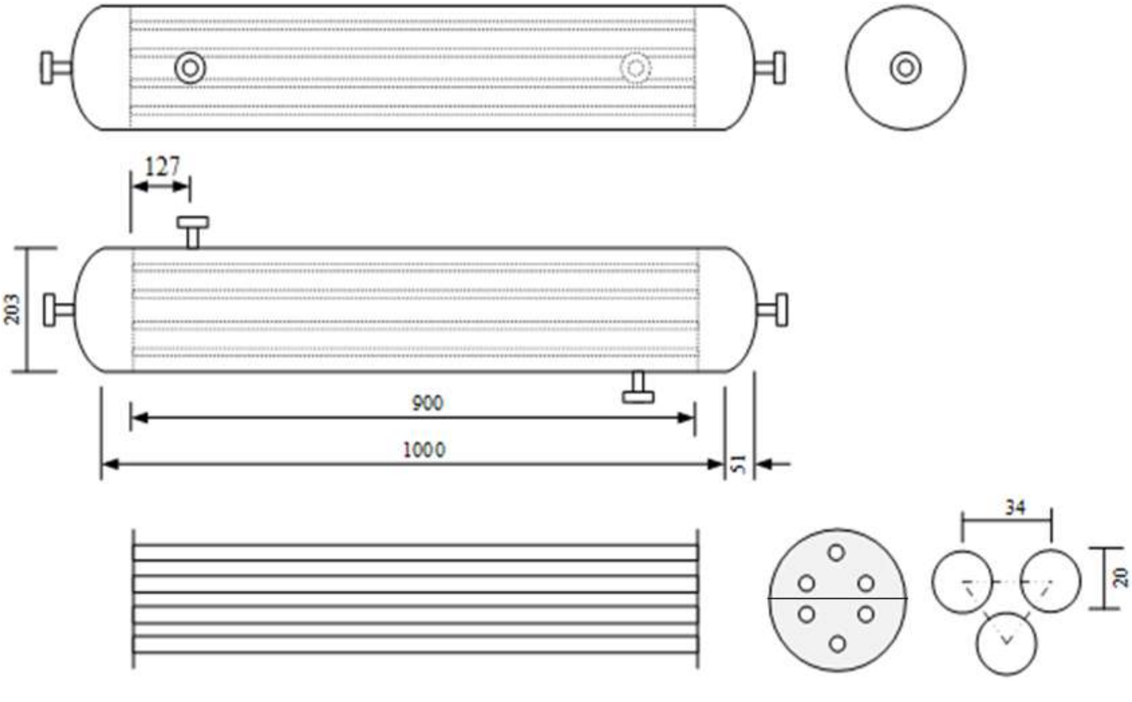


Figure 4.6: Working Drawing for Feed Preheater

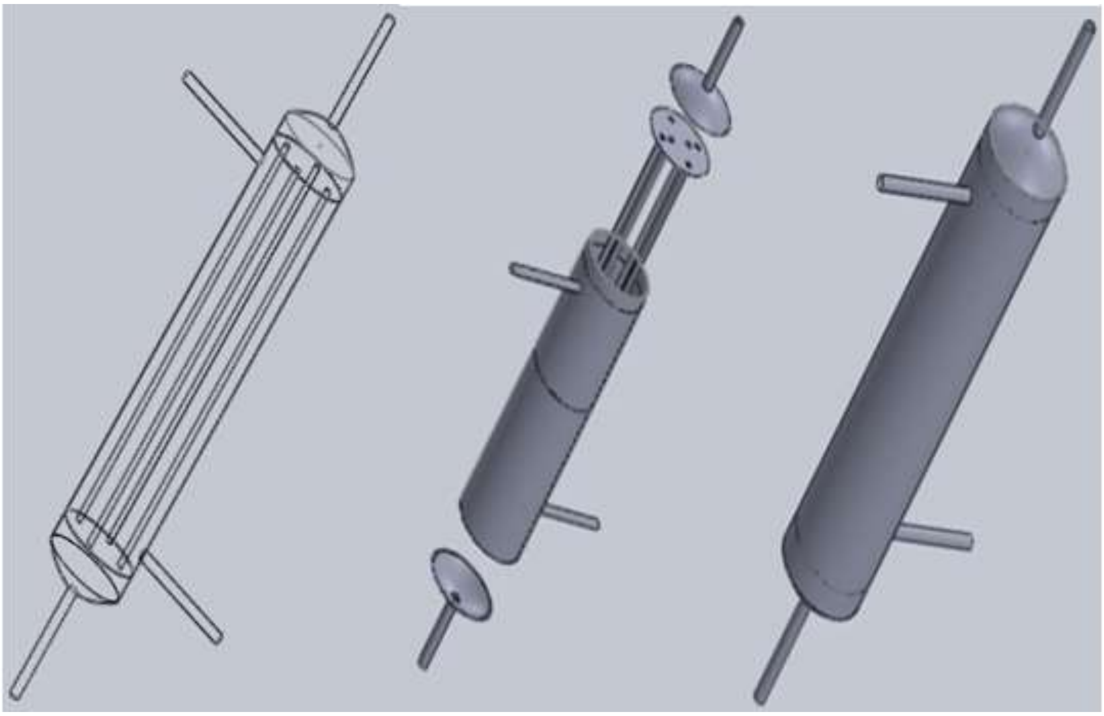


Figure 4.7: 3D Model for Feed Preheater

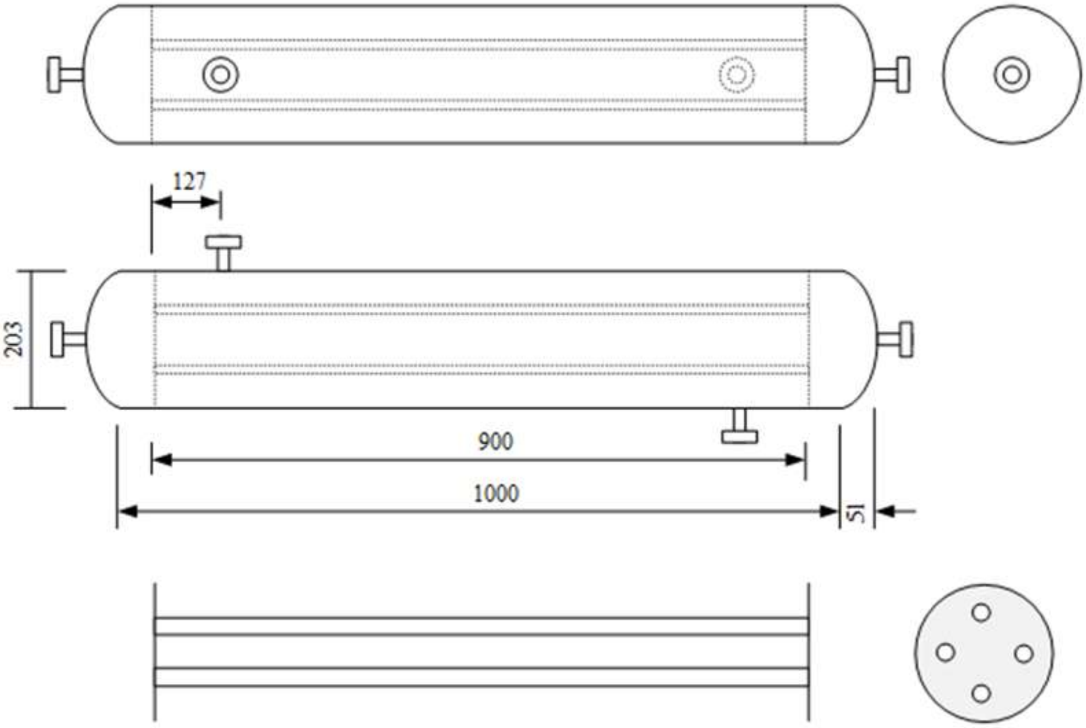


Figure 4.8: Working Drawing for Column Overhead Condenser

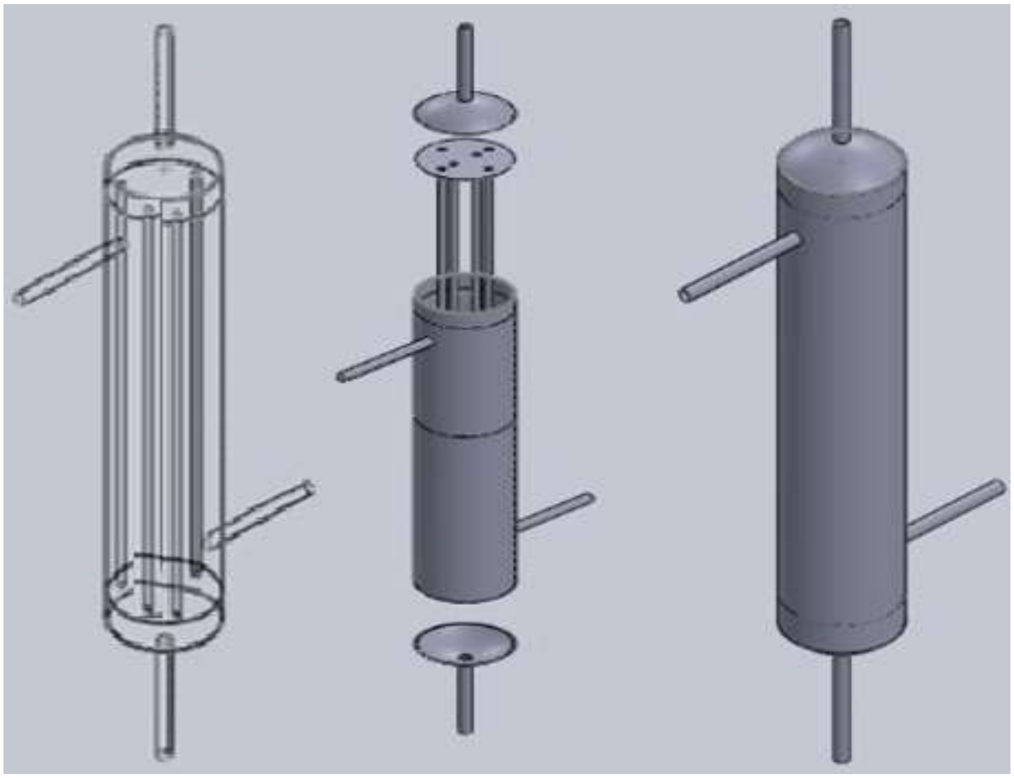


Figure 4.9: 3D Model for Column Overhead Condenser

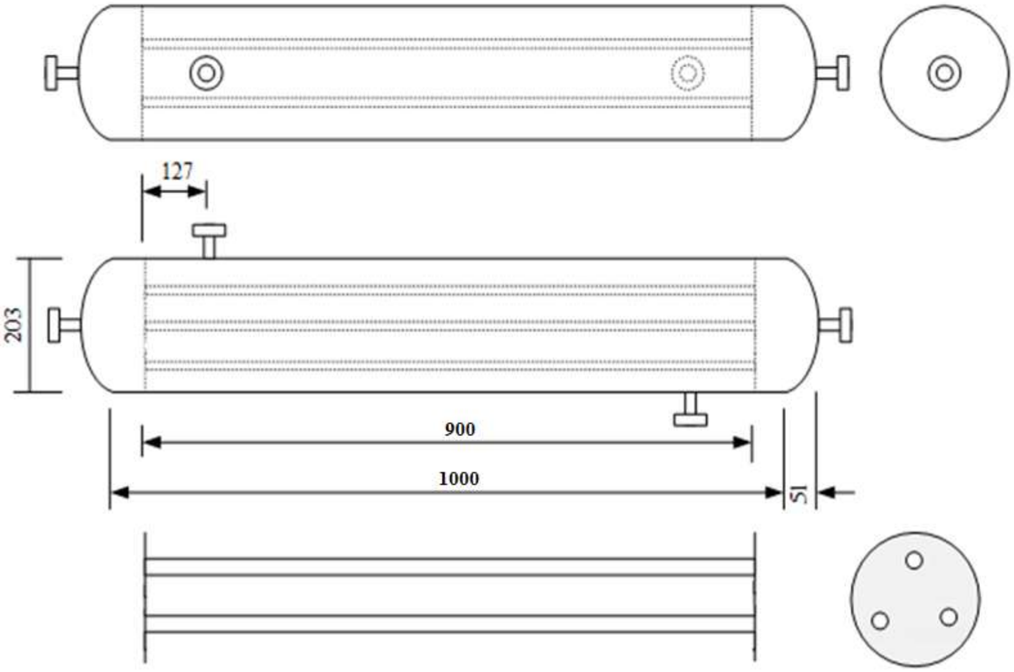


Figure 4.10: Working Drawing for Column Bottom Reboiler

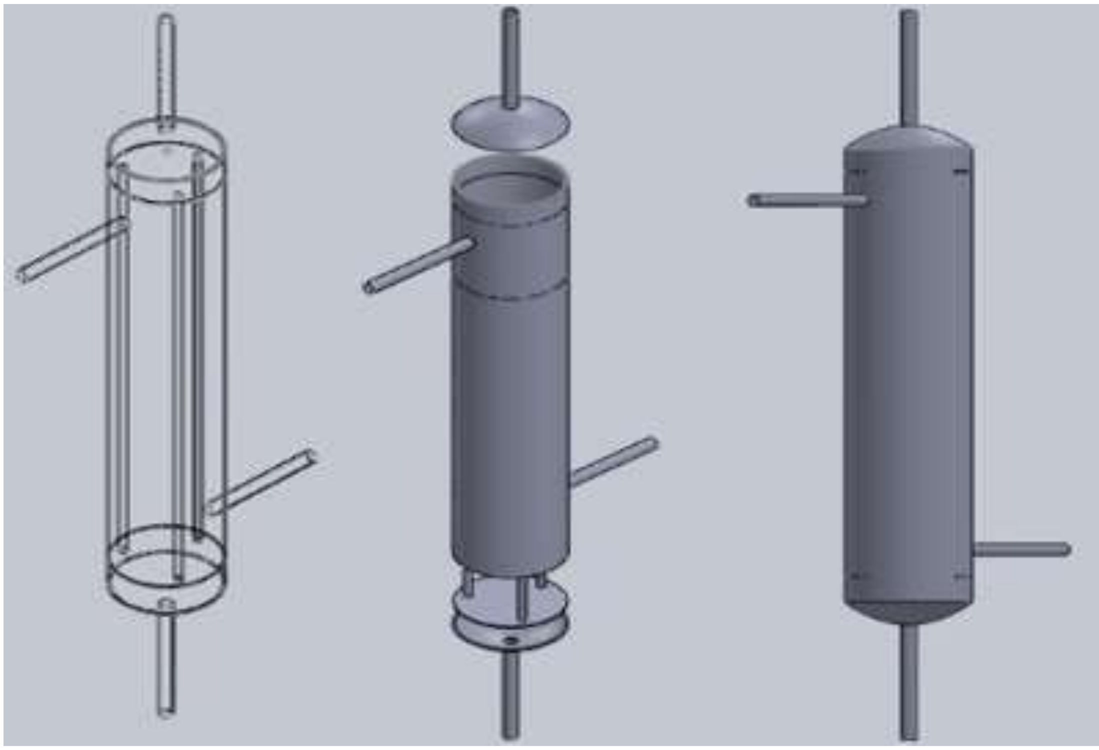


Figure 4.11: 3D Model for Column Bottom Reboiler

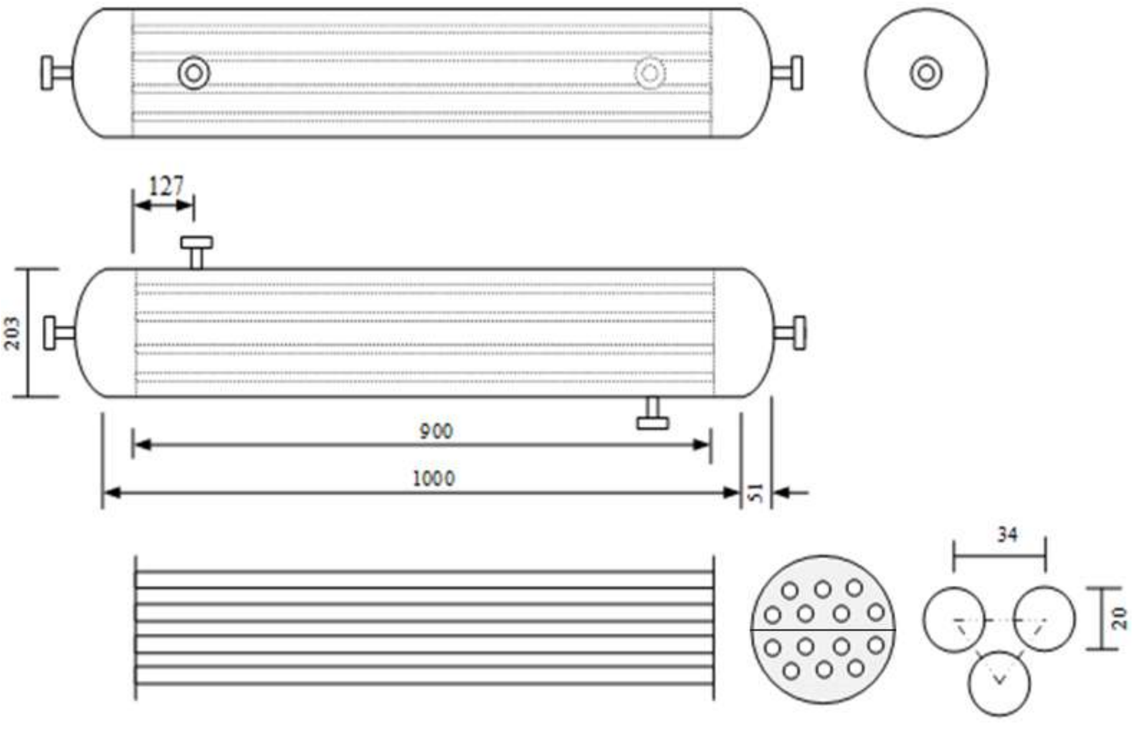


Figure 4.12 Working Drawing for Product Cooler

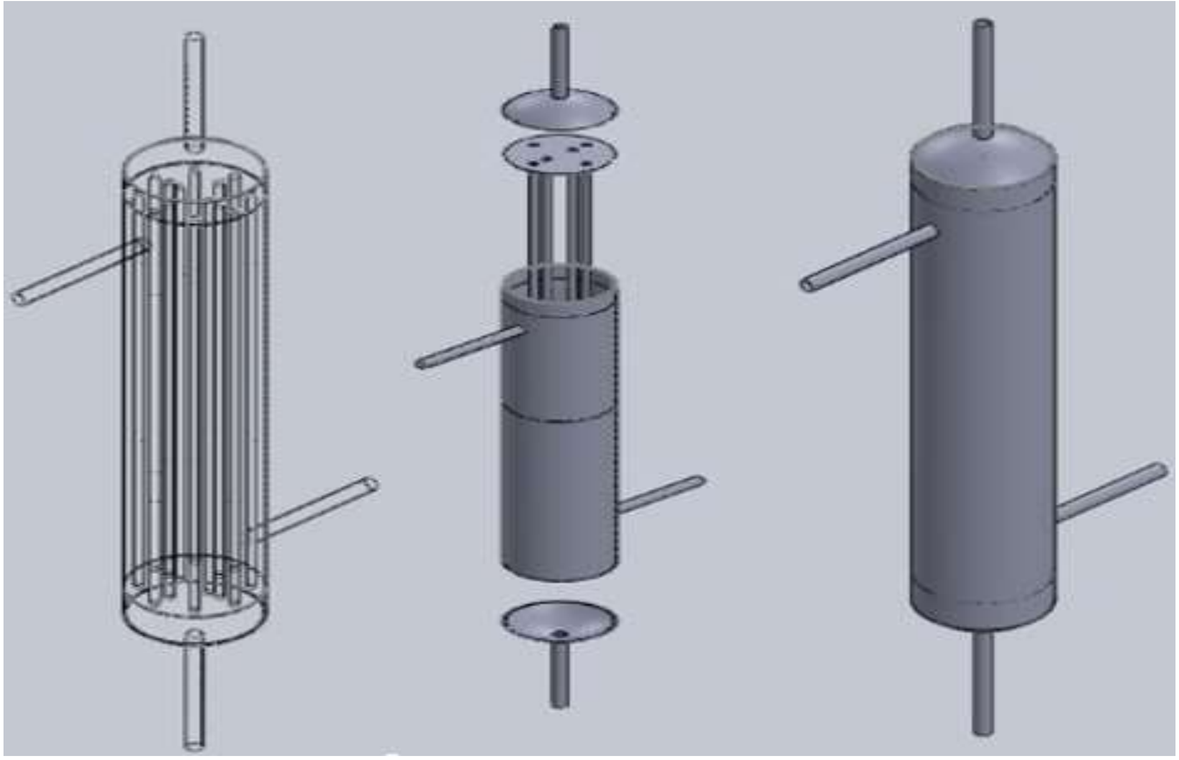


Figure 0.13: 3D Model for Product Cooler

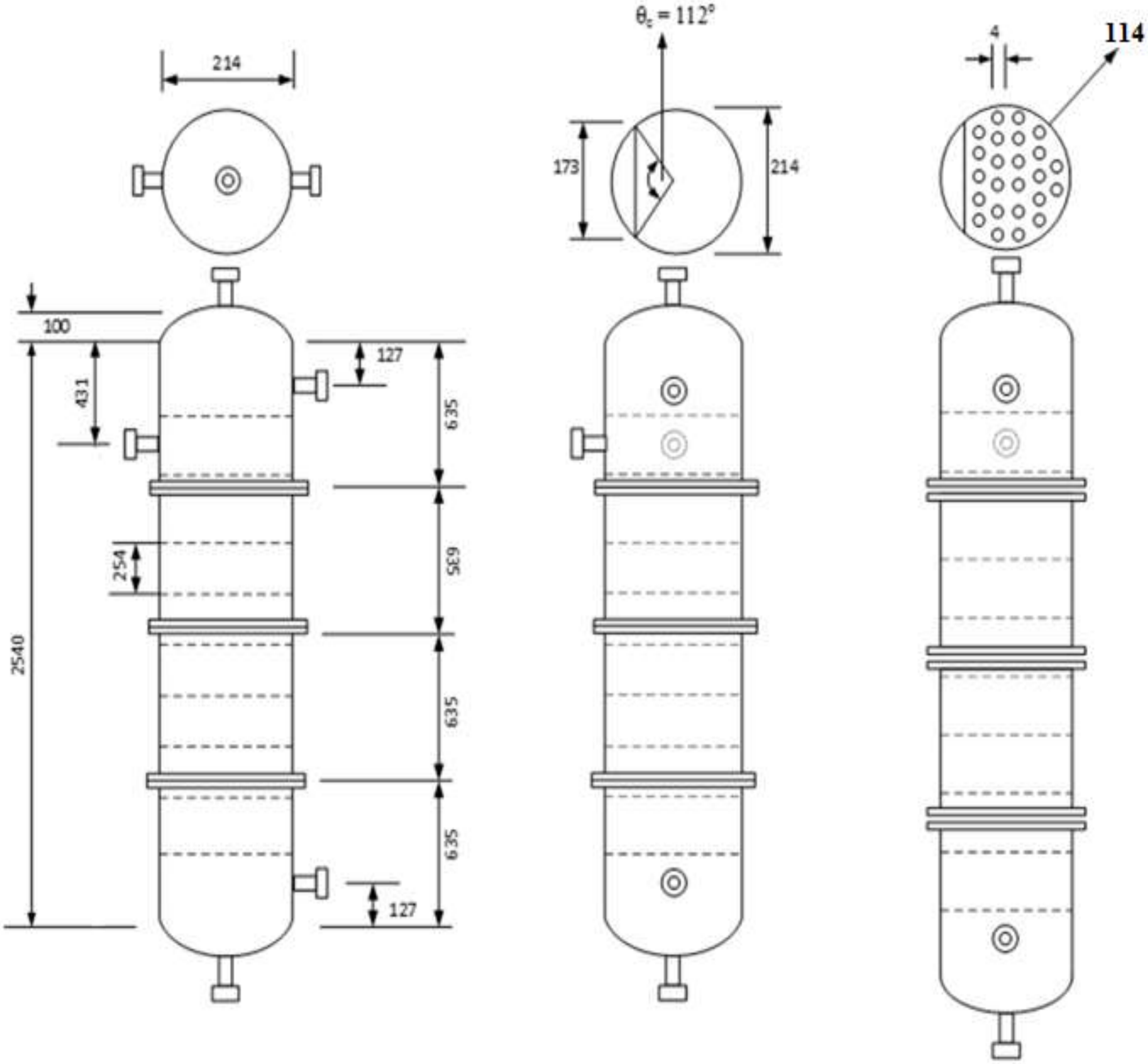


Figure 0.14: Working Drawing for Stripping Column and its internals

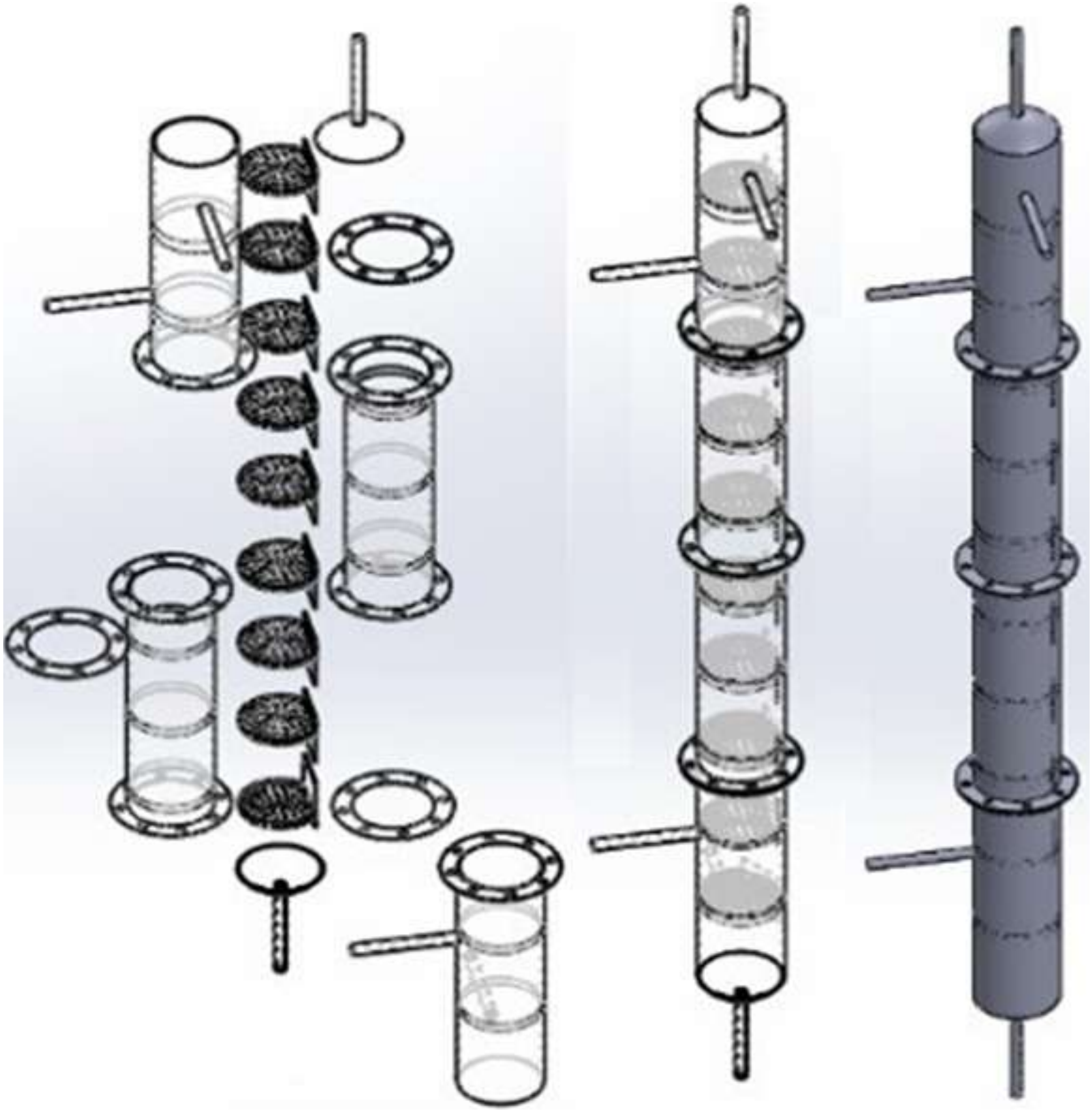


Figure 0.15: 3D Model for Stripping Column and its internals

4.8 Fabrication

The fabrication of the equipment for the pilot SWS Unit was performed by a certified fabricator under close supervision of both the student and the supervisors. Plates 4.1- 4.6 present images of the fabricated equipment.

In a nut shell, the major difference in the design and fabrication is the use of mild steel in the fabrication instead of stainless steel as specified in the material of construction. This was because stainless steel is very expensive in the market. However, the use of the most appropriate material is recommended for use in future as the technology attains perfection.

Front

Side

Plan

Plate 4.1: Image of SWS Unit Surge Drum (V-100)

Plate 4.2: Image of SWS Unit Reflux Drum (V-101)

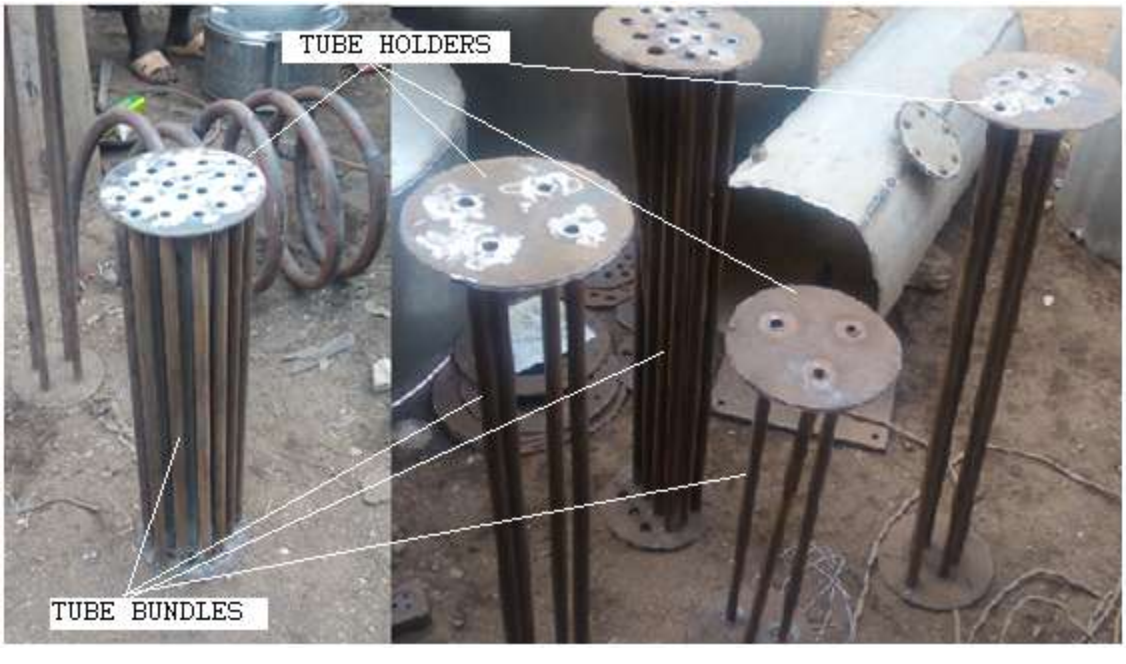
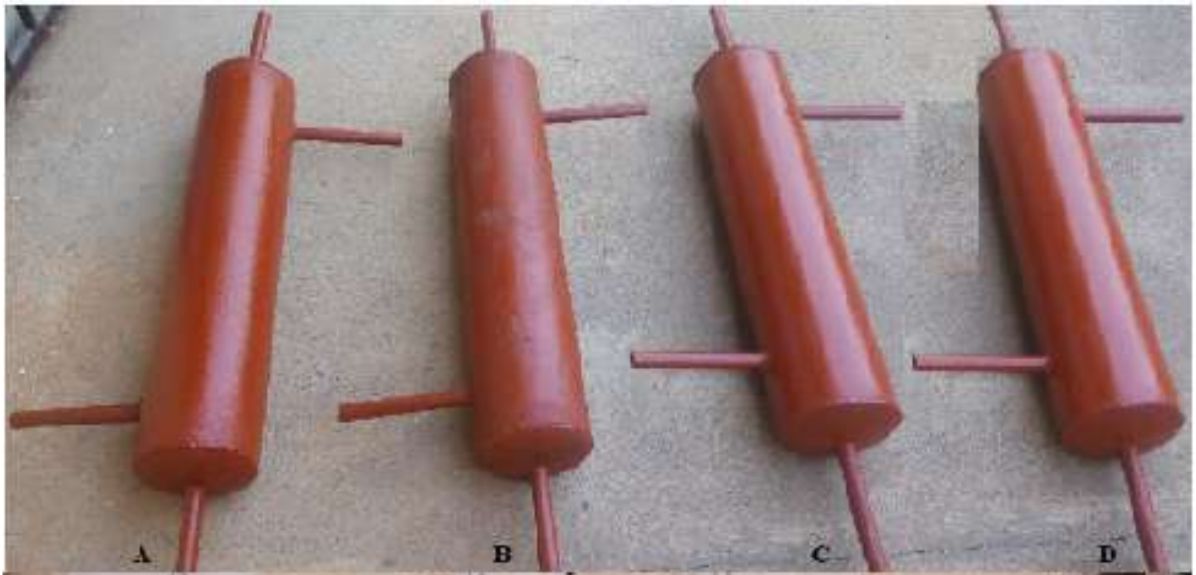


Plate 4.3: Images of Heat Exchangers (E-100 to E-103) Tube bundles



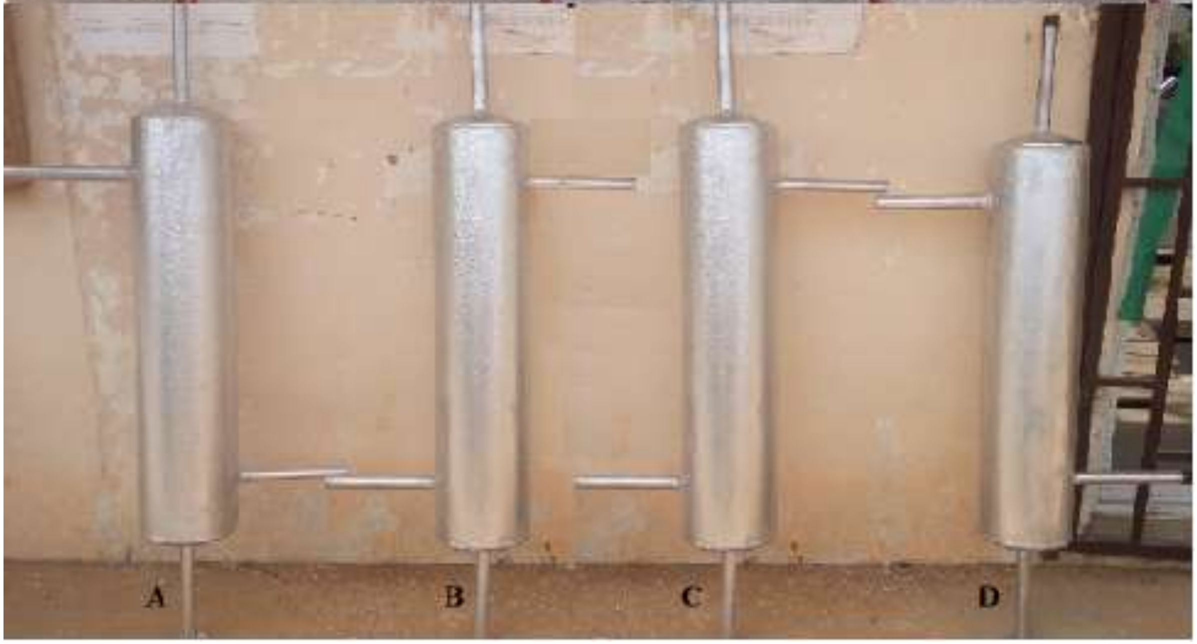


Plate 4.4: Images of Heat Exchangers (E-100 to E-103)

Plate 4.5: Image of Stripping Column (C-100) and its Internals During Fabrication

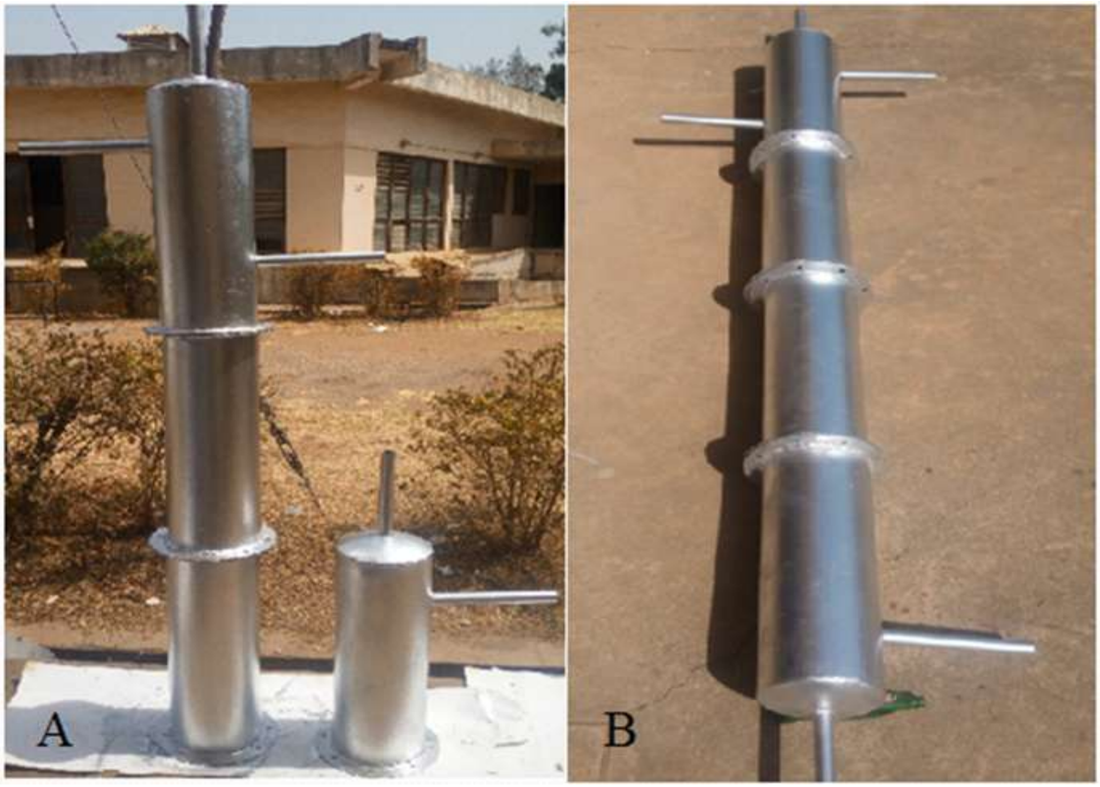


Plate 4.6: Final Image of Stripping Column (C-100) After Fabrication

4.9Leakage Detection Test

4.9.1 Leak detection methods

A leak-detection program (LPD) can comprise of one or more methods. Where practicable, pipeline operators should compare the results of one method of leak detection with the results of other applicable methods. This section describes leak detection methods and technologies that are currently available for a variety of uses. The decision of which of these to implement as part of a comprehensive LDP depends on a variety of factors related to the pipeline, including commodity transported, operating characteristics and environment setting (CAPP, 2018).

4.9.2 Leak Detection Principles and Methods

Although there are numerous leak detection methods available, the detection principles are limited and can be summarised as follows (Martins, DE 1998):

- Visual observation and other off line leak detection methods
- Comparison of input volume with output volume
- Analysis of pressure and/or flow rate measurement
- Monitoring of characteristic signals generated by a leak
- Leak detection pigs

4.9.2.1. Visual Observation

Where spillages have occurred they have often been detected through visual observation, either by company operators or by people passing by.

The source of spillage is not always easy to locate because of the migration of oil through the ground. The distance between the location of the leak and the site where the traces of oil are discovered may vary depending on soil conditions and nature of the terrain.

Visual observations can often generate false alarms because the spillage may be due to sources other than the pipeline, such as unauthorized disposal of products similar to that in the pipeline.

4.9.2.2. Comparison of Volume Input with Volume Output

If the condition of the product in a pipeline were perfectly constant, the volume pumped into the line would exactly equal the volume flowing out. Any difference between the two volumes would signify a leak.

The condition of a product entering a pipeline is, however, subject to variation in volume due to changes in temperature, pressure and density as the product is transported in the pipeline. The size of spillage which can be detected is dependent upon the accuracy with which these changes can be measured.

The volumes of product flowing into and out of the pipeline are measured by flow meters at each end of the pipeline which are compensated for temperature and pressure fluctuations.

Variations of the product within the pipeline can either be estimated at pre-set comparison times from measurements of the variables, at regular intervals along the pipeline, or predicted by computer model. The differences between the quantities flowing into and out of the pipeline are corrected to take account of the variations within the pipeline. If the difference exceeds a preset limit an automatic alarm is given. The more often a comparison is made, the faster a leak will be detected. However, this technique does not locate the leak nor does it necessarily recognise small, slow leaks.

If there are large changes in elevation in the pipeline profile, a condition called 'slack line' * can develop. In these sections the pipeline may not be full of liquid, which may cause difficulties in applying volume comparison.

4.9.2.3. Analysis of Pressure and/or Flow Rate Measurements

The flow of a product through a pipeline produces a pressure drop along the pipeline that is directly related to the flow velocity. Deviation from the expected flow velocities and pressure drops in normal operation can therefore indicate a leak.

The operator monitors the pipeline for such variations and an automatic alarm is raised if the change exceeds a set limit. Small variations in measured conditions can also be caused by sources other than leak and consequently the accuracy is related to the size of the leak. It is becoming possible to generate a computer model of the pipeline behaviour, and if the measurements received deviate significantly from the computer model, an alarm is raised. This technique does not generally locate the leak. Recent experience of such modelling techniques is that these systems may not reliably detect leaks for more complex multi-ingress, multi-egress pipeline systems transporting multiple products.Static pressure tests can be performed while the pipeline is shut down in order to confirm its integrity.

4.9.2.4. Monitoring of Characteristic Signals Generated by a Leak

A rapidly occurring leak in a pipeline generates a transient negative pressure wave which travels away from the leak location in both directions at the velocity of sound (approximately 1,000 m/s in crude oil).

Detectors located at regular intervals along the pipeline will detect immediately the negative pressure wave and will give an estimate of the location of the leak. However, pressure transients generated by upstream and downstream facilities can cause false alarms so that a sophisticated system is required to eliminate spurious signals. Small and slowly developing leaks cannot be detected by this method.

4.9.2.5. Leak Detection Pigs

Liquid escaping under pressure through a defect in the pipeline wall generates ultrasonic noise. This noise can be measured and recorded by a pig propelled through the pipeline by the normal flow of the product. Even small leaks can be detected and located with a good level of accuracy.

This method will not alert the operator immediately the leak occurs nor will it indicate the size of it. The technique is used instead for locating and assessing suspected leaks, or conversely, to confirm the integrity of the line.

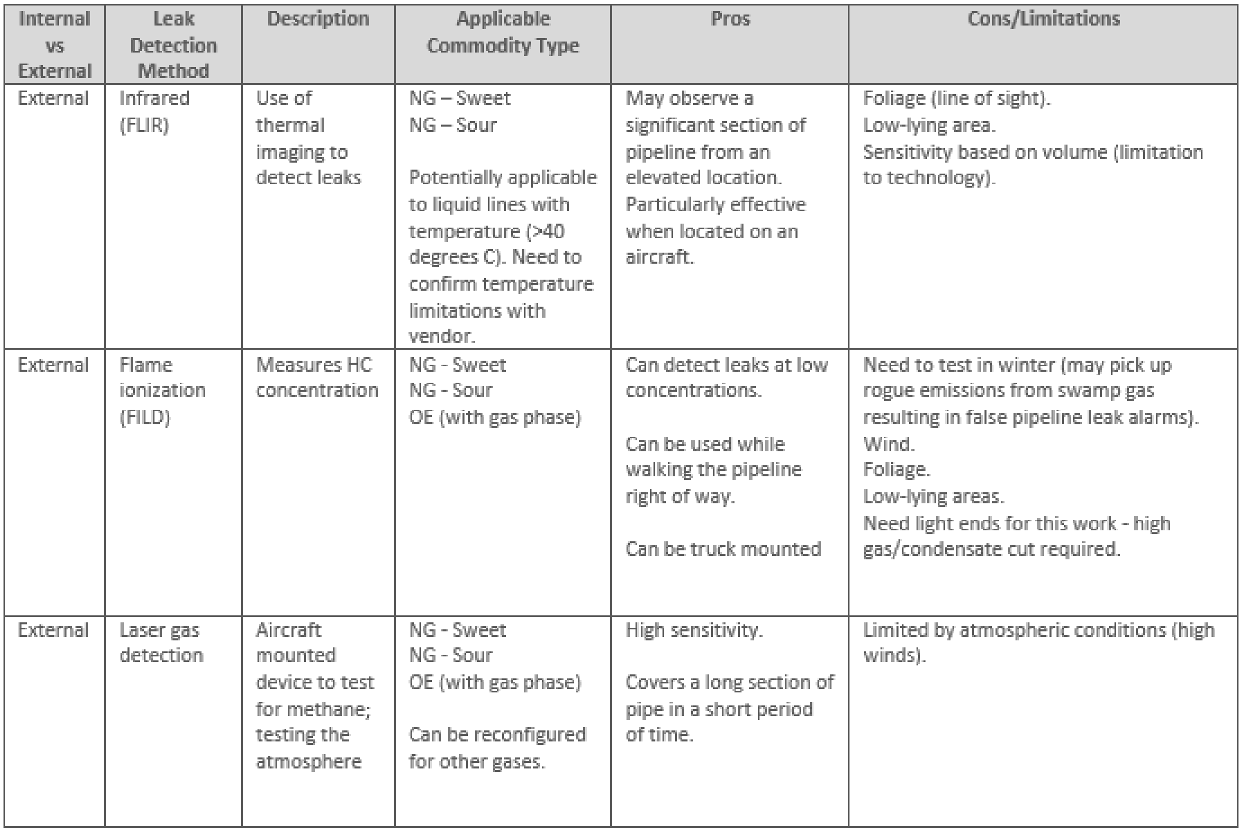
4.9.3 Leak Detection Methods

There is a wide range of possible pipeline leak detection methods, recognizing, however, that no single leak detection method is applicable to all pipeline situations. These methods include;

- Gas Sensor Technology
- Visual Surveillance
- Tracer and Sensory method
- Computational methods
- Line balance
- Imagery technology
- Others

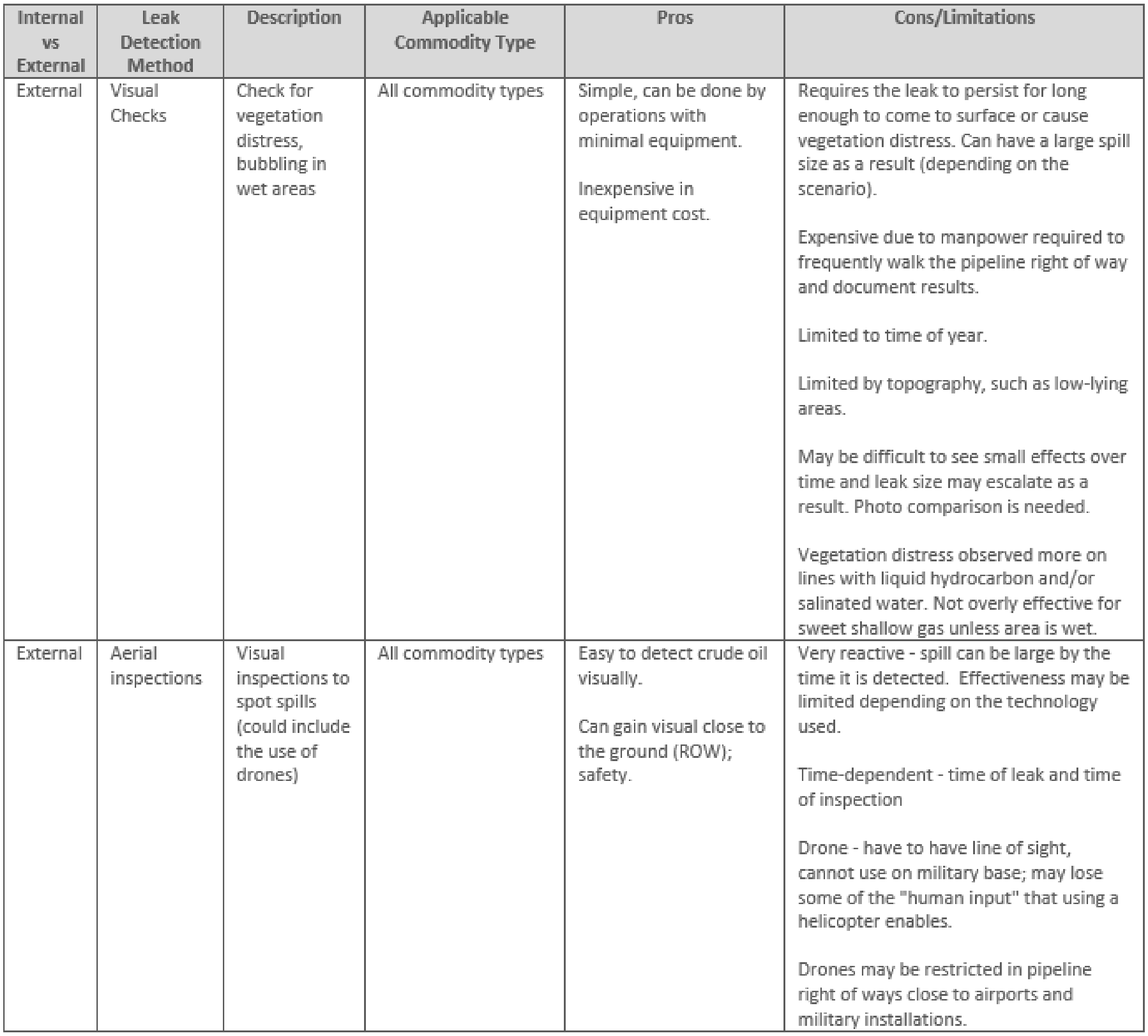
The following tables provide a brief explanation of each of these methods. The tables do not rank the possible leak detection methods. Each situation requires an evaluation of the applicability of the methods used to determine the correct choice (CAPP, 2018).

Table 4.31: Gas Sensor Technology (CAPP, 2018).



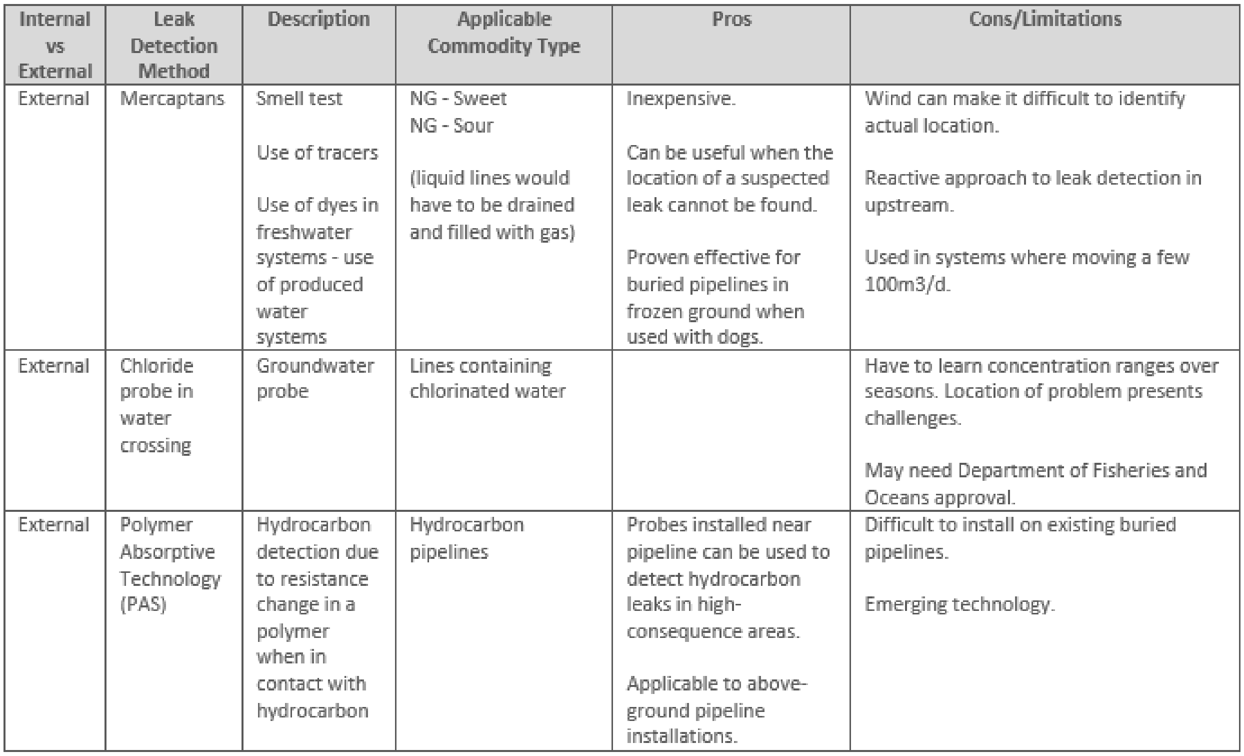
Internal vs External	Leak Detection Method	Description	Applicable Commodity Type	Pros	Cons/Limitations
External	Infrared (FLIR)	Use of thermal imaging to detect leaks	NG – Sweet NG – Sour Potentially applicable to liquid lines with temperature (>40 degrees C). Need to confirm temperature limitations with vendor.	May observe a significant section of pipeline from an elevated location. Particularly effective when located on an aircraft.	Foliage (line of sight). Low-lying area. Sensitivity based on volume (limitation to technology).
External	Flame ionization (FILD)	Measures HC concentration	NG - Sweet NG - Sour OE (with gas phase)	Can detect leaks at low concentrations. Can be used while walking the pipeline right of way. Can be truck mounted	Need to test in winter (may pick up rogue emissions from swamp gas resulting in false pipeline leak alarms). Wind. Foliage. Low-lying areas. Need light ends for this work - high gas/condensate cut required.
External	Laser gas detection	Aircraft mounted device to test for methane; testing the atmosphere	NG - Sweet NG - Sour OE (with gas phase) Can be reconfigured for other gases.	High sensitivity. Covers a long section of pipe in a short period of time.	Limited by atmospheric conditions (high winds).

Table 4.32: Visual Surveillance (CAPP, 2018).



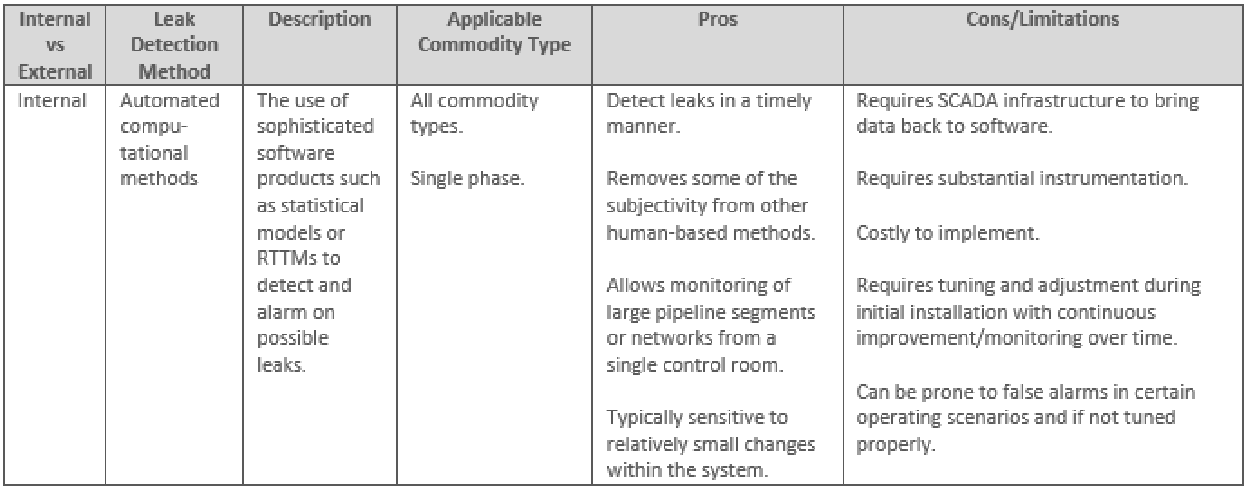
Internal vs External	Leak Detection Method	Description	Applicable Commodity Type	Pros	Cons/Limitations
External	Visual Checks	Check for vegetation distress, bubbling in wet areas	All commodity types	Simple, can be done by operations with minimal equipment. Inexpensive in equipment cost.	Requires the leak to persist for long enough to come to surface or cause vegetation distress. Can have a large spill size as a result (depending on the scenario). Expensive due to manpower required to frequently walk the pipeline right of way and document results. Limited to time of year. Limited by topography, such as low-lying areas. May be difficult to see small effects over time and leak size may escalate as a result. Photo comparison is needed. Vegetation distress observed more on lines with liquid hydrocarbon and/or salinated water. Not overly effective for sweet shallow gas unless area is wet.
External	Aerial inspections	Visual inspections to spot spills (could include the use of drones)	All commodity types	Easy to detect crude oil visually. Can gain visual close to the ground (ROW); safety.	Very reactive - spill can be large by the time it is detected. Effectiveness may be limited depending on the technology used. Time-dependent - time of leak and time of inspection Drone - have to have line of sight, cannot use on military base; may lose some of the "human input" that using a helicopter enables. Drones may be restricted in pipeline right of ways close to airports and military installations.

Table 4.33: Tracer and Sensory method (CAPP, 2018).



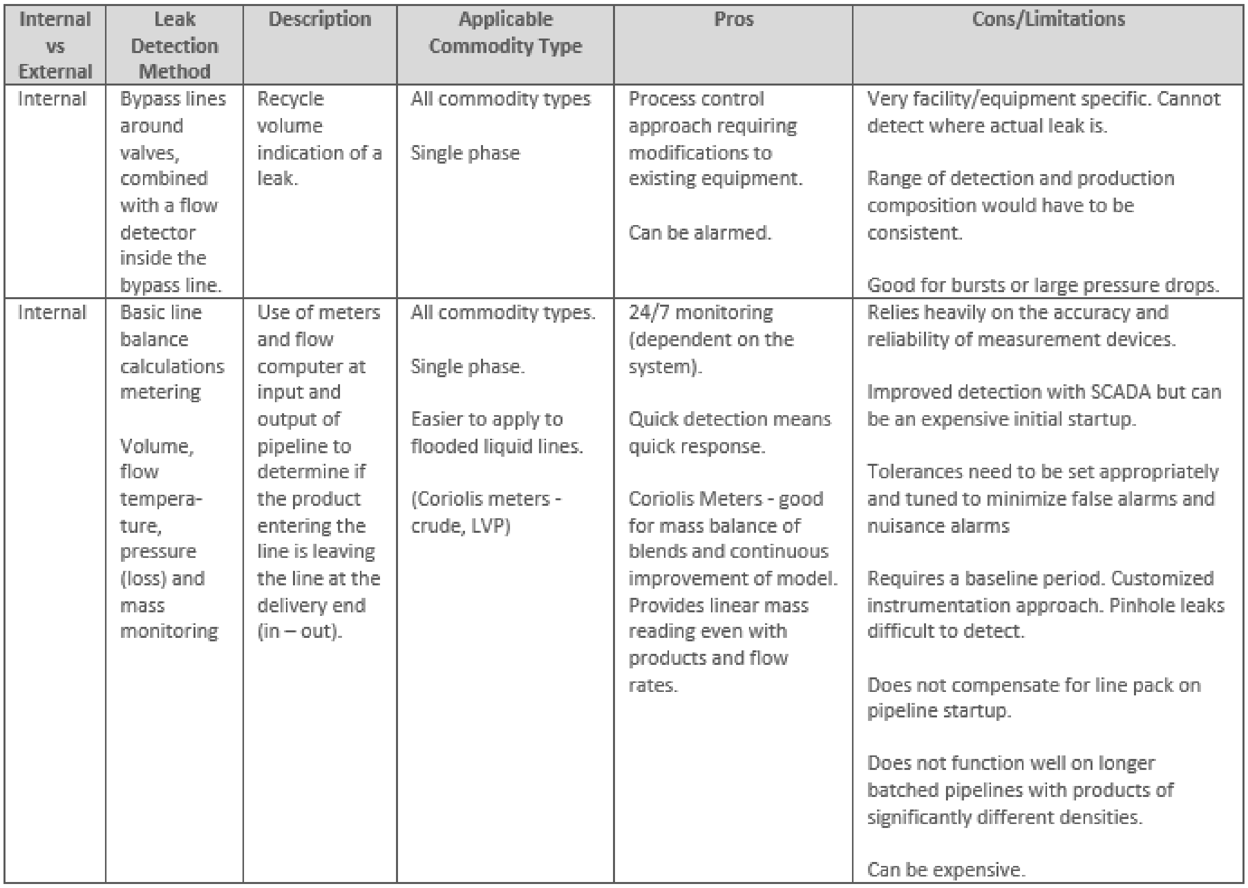
Internal vs External	Leak Detection Method	Description	Applicable Commodity Type	Pros	Cons/Limitations
External	Mercaptans	Smell test Use of tracers Use of dyes in freshwater systems - use of produced water systems	NG - Sweet NG - Sour (liquid lines would have to be drained and filled with gas)	Inexpensive. Can be useful when the location of a suspected leak cannot be found. Proven effective for buried pipelines in frozen ground when used with dogs.	Wind can make it difficult to identify actual location. Reactive approach to leak detection in upstream. Used in systems where moving a few 100m3/d.
External	Chloride probe in water crossing	Groundwater probe	Lines containing chlorinated water		Have to learn concentration ranges over seasons. Location of problem presents challenges. May need Department of Fisheries and Oceans approval.
External	Polymer Absorptive Technology (PAS)	Hydrocarbon detection due to resistance change in a polymer when in contact with hydrocarbon	Hydrocarbon pipelines	Probes installed near pipeline can be used to detect hydrocarbon leaks in high-consequence areas. Applicable to above-ground pipeline installations.	Difficult to install on existing buried pipelines. Emerging technology.

Table 4.34: Computational methods (CAPP, 2018).



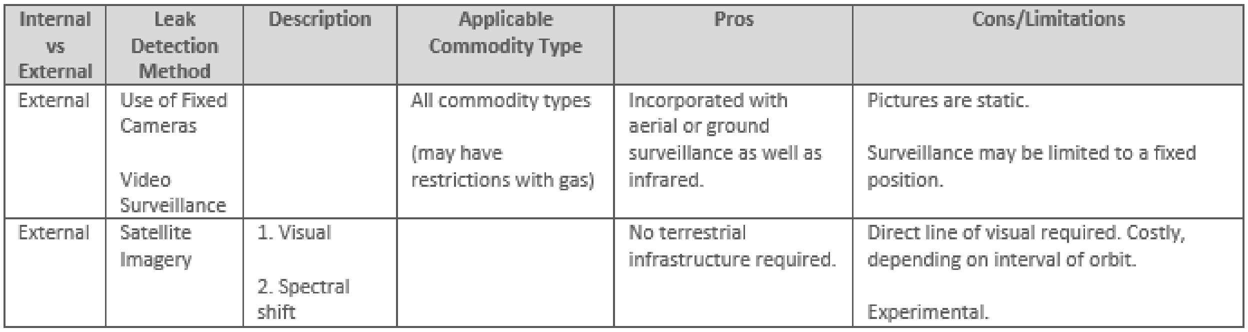
Internal vs External	Leak Detection Method	Description	Applicable Commodity Type	Pros	Cons/Limitations
Internal	Automated compu-tational methods	The use of sophisticated software products such as statistical models or RTTMs to detect and alarm on possible leaks.	All commodity types. Single phase.	Detect leaks in a timely manner. Removes some of the subjectivity from other human-based methods. Allows monitoring of large pipeline segments or networks from a single control room. Typically sensitive to relatively small changes within the system.	Requires SCADA infrastructure to bring data back to software. Requires substantial instrumentation. Costly to implement. Requires tuning and adjustment during initial installation with continuous improvement/monitoring over time. Can be prone to false alarms in certain operating scenarios and if not tuned properly.

Table 4.35: Line balance (CAPP, 2018).



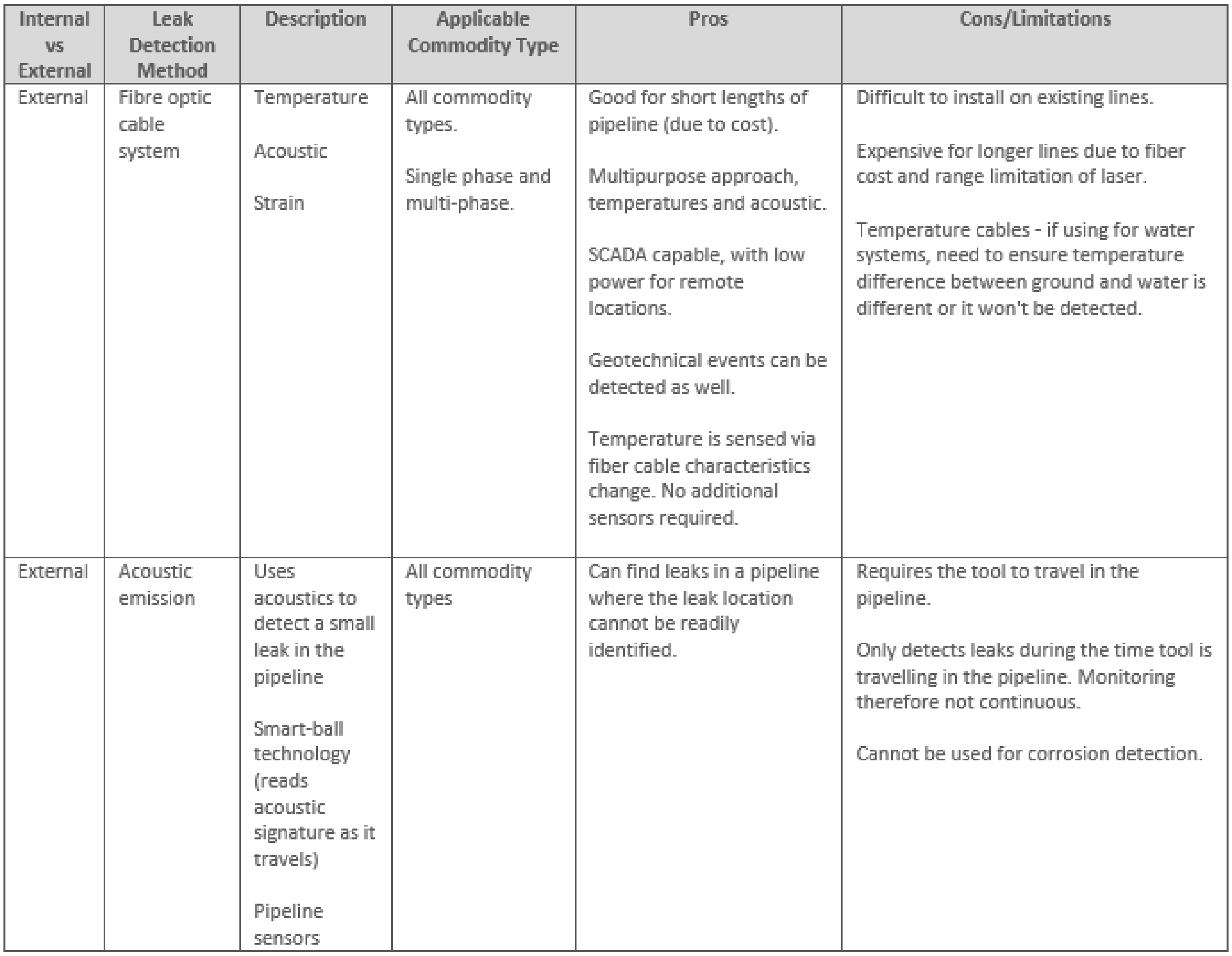
Internal vs External	Leak Detection Method	Description	Applicable Commodity Type	Pros	Cons/Limitations
Internal	Bypass lines around valves, combined with a flow detector inside the bypass line.	Recycle volume indication of a leak.	All commodity types Single phase	Process control approach requiring modifications to existing equipment. Can be alarmed.	Very facility/equipment specific. Cannot detect where actual leak is. Range of detection and production composition would have to be consistent. Good for bursts or large pressure drops.
Internal	Basic line balance calculations metering Volume, flow tempera-ture, pressure (loss) and mass monitoring	Use of meters and flow computer at input and output of pipeline to determine if the product entering the line is leaving the line at the delivery end (in – out).	All commodity types. Single phase. Easier to apply to flooded liquid lines. (Coriolis meters - crude, LVP)	24/7 monitoring (dependent on the system). Quick detection means quick response. Coriolis Meters - good for mass balance of blends and continuous improvement of model. Provides linear mass reading even with products and flow rates.	Relies heavily on the accuracy and reliability of measurement devices. Improved detection with SCADA but can be an expensive initial startup. Tolerances need to be set appropriately and tuned to minimize false alarms and nuisance alarms Requires a baseline period. Customized instrumentation approach. Pinhole leaks difficult to detect. Does not compensate for line pack on pipeline startup. Does not function well on longer batched pipelines with products of significantly different densities. Can be expensive.

Table 4.36: Imagery Technology (CAPP, 2018).



Internal vs External	Leak Detection Method	Description	Applicable Commodity Type	Pros	Cons/Limitations
External	Use of Fixed Cameras Video Surveillance		All commodity types (may have restrictions with gas)	Incorporated with aerial or ground surveillance as well as infrared.	Pictures are static. Surveillance may be limited to a fixed position.
External	Satellite Imagery	1. Visual 2. Spectral shift		No terrestrial infrastructure required.	Direct line of visual required. Costly, depending on interval of orbit. Experimental.

Table 4.37: Other Technologies (CAPP, 2018).



Internal vs External	Leak Detection Method	Description	Applicable Commodity Type	Pros	Cons/Limitations
External	Fibre optic cable system	Temperature Acoustic Strain	All commodity types. Single phase and multi-phase.	Good for short lengths of pipeline (due to cost). Multipurpose approach, temperatures and acoustic. SCADA capable, with low power for remote locations. Geotechnical events can be detected as well. Temperature is sensed via fiber cable characteristics change. No additional sensors required.	Difficult to install on existing lines. Expensive for longer lines due to fiber cost and range limitation of laser. Temperature cables - if using for water systems, need to ensure temperature difference between ground and water is different or it won't be detected.
External	Acoustic emission	Uses acoustics to detect a small leak in the pipeline Smart-ball technology (reads acoustic signature as it travels) Pipeline sensors	All commodity types	Can find leaks in a pipeline where the leak location cannot be readily identified.	Requires the tool to travel in the pipeline. Only detects leaks during the time tool is travelling in the pipeline. Monitoring therefore not continuous. Cannot be used for corrosion detection.

4.9.4 Used Method

Two methods were employed for leakage testing, hydraulic test (using water) and foam spraying test. The test was conducted in two stages:

1. Individual equipment testing

   The exit of equipment is blocked while water was introduced until pressure begins to build after it has filled up. This makes water to jet out of openings if any. The opening(s) were then marked and re-welded. The process is then repeated to confirm the sealing of the leakage.

2. The second method was achieved by brushing surfactant solution all over the equipment. Leaks are detected when escaping gas/water forms soap bubbles at the leak points. The opening(s) were then marked and re-welded. The process is then repeated to confirm the sealing of the leakage.

4.10 Installation

The fabricated equipment were installed, and coupled together according to the Process Flow Diagram (PFD) of the SWS Unit. The installation was, for lack of proper funding, done on a skid instead of reinforced concrete as, not only suggested by the design, but as it is the global best practice. For heat energy economy and efficiency, the installed equipment were lagged using ISO-9001 Fiberglass and were cladded with reflective galvanized iron sheets. Plates 4.8 – 4.10 presents images of the installed, lagged and cladded SWS Unit.

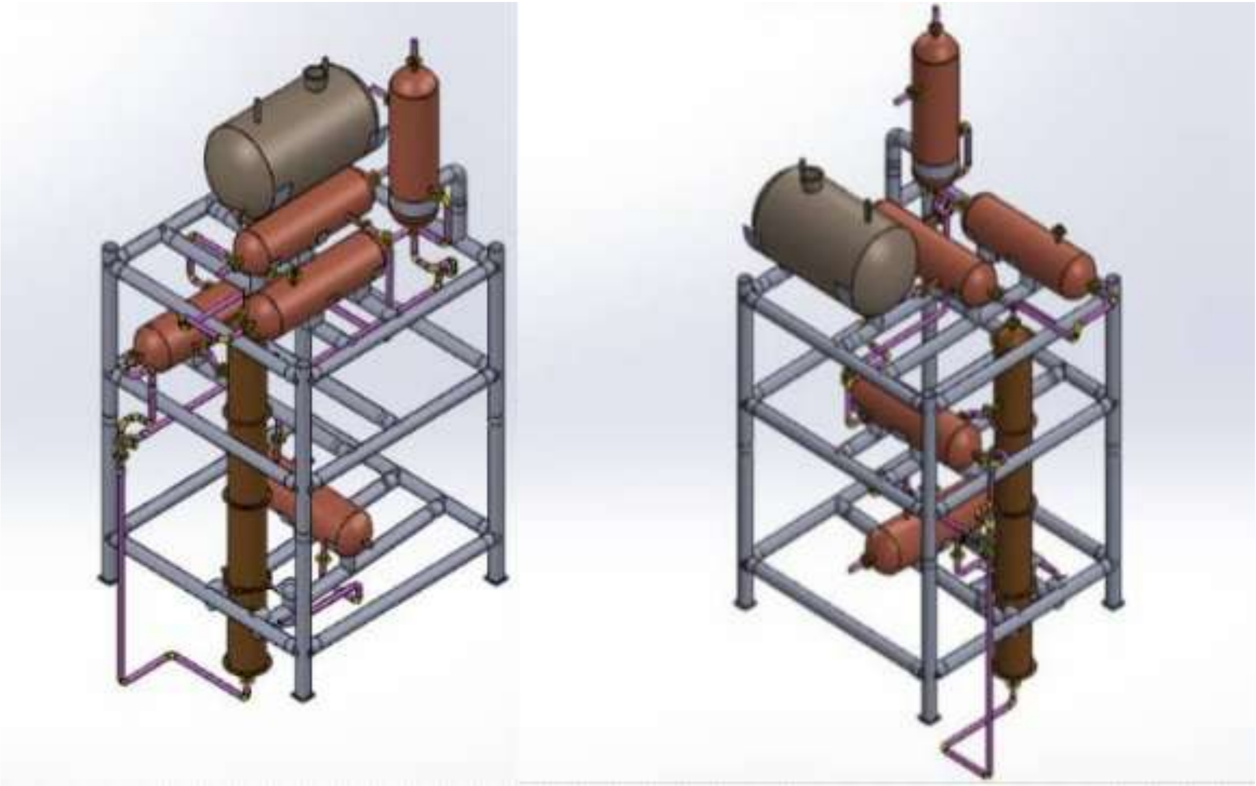


Figure4.16: Solid Works 3D Model of the installed SWS Unit

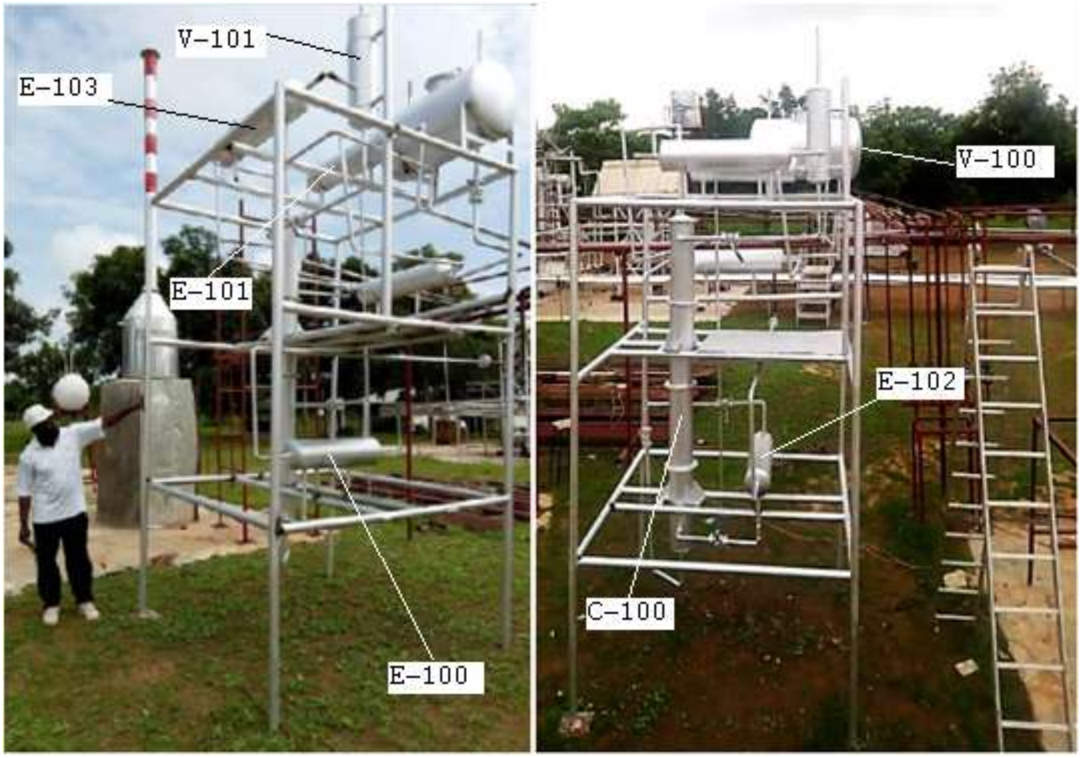


Plate 4.7: The installed SWS Unit

4.10 Lagging

For energy economy, ISO-9-001 Fiberglass was used in lagging the unit. This was done to avoid heat loss, hence money, during operation. This particular brand of fiberglass was used because of the following properties;

- Low Cost.
- Availability.
- Endurance.
- Low Density.
- Non-rotting.
- Incombustibility etc.

Plate 4.8: The installed SWS Unit during Lagging

Plate 4.9: The installed SWS Unit after Lagging and Cladding

4.11 Test-Running

After step-wisely following the start-up procedure, the SWS Unit was test-ran for a number of times. Leakages were observed and arrested. For the operation, saturated steam for the stripper column bottom reboiler was supplied by the Utility Section of the Mini refinery – precisely, the boiler. Plate 4.10 shows the SWS Unit during test running.

Plate 4.10: SWS Unit During Test Running.

After successful test-run, sample of the product was collected and sent to the laboratory for qualitative analysis. The laboratory results were compared against the quality of the raw sour water and presented in Table 4.32.

4.12 Results

Table 4.38: Result of Laboratory Analysis

Parameter	Sour Water (Feed)	Stripped Water (Product)	Percentage Removal (%)
pH	**6.8**	**7.5**	**- - -**
VOCs (mgl^{-1})	**1800**	**478.8**	**73.40**
Hydrogen sulfide (mgl^{-1})	**16.0**	**12.26**	**23.48**
Ammonia (mgl^{-1})	**11.8**	**6.2**	**47.46**
Temperature (^{o}C)	**24.7**	**39.5.0**	**- - -**

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be drawn from this research work:

a) Sour water feed from the CDU of ABU Zaria mini Refinery was characterize. It was found out that the amount of VOCs and H_2S are 1800 mgl^{-1}and 16 mgl^{-1}, respectively.

b) Single Tower process unit was selected. This was due to its ease of operation and maintenance, lower cost of fabrication, and little amount of Sourwater produced by the Mini Refinery for handling.

c) Detailed material & energy balance for each equipment were carried out. The enthalpy-in and enthalpy-out across the stripping column were found to be 228.57 and 7583.30 kJ/hr respectively, hence the overall heat-duty of the column was calculated as 3079.86 kJ/hr.

d) Detailed design of each equipment of the pilot scale Sour Water Stripping Unit was successfully carried outand materials of construction were selected. The effective height of the stripping column was calculated to be 2500 mm (2.5 m). The column diameter was calculated to be 214 mm. The number of trays was calculated to be 9, while the feed tray was found to be the 8th tray. Mild steel of competent thickness was selected to be the material of construct for cost consideration.

e) Designed equipment were fabricated and sequentially installed in accordance with the Unit's Process Flow Diagram. These are; The Stripping Column (C-100), Surge Drum

(V-100), Feed Preheater (E-100), Overhead Condenser (E-101), Bottom Reboiler (E-102), Product cooler (E-103) & the Reflux Drum (V-101).

g) The unit was successfully test-ran. Feed andproduct samples were collected, analyzed in the laboratory, and the following data was generated; the acidity of the Sour water was reduced from a pH of 6.8 to 7.5. This is within the acceptable standard pH range of 6.5 to 8.5. Volatile Organic Compounds were reduced from 1800 mgl^{-1} to 478.8 mgl^{-1}. This value is far above the standard value of <10 mgl^{-1}. The hydrogen sulfide was reduced from 16 mgl^{-1} to 12.26 mgl^{-1}. This value is also far above the standard value of <0.2 mgl^{-1}. This value is also far above the standard value of <0.2 mgl^{-1}. For better result and efficiency, optimization and upgrading of the SWS unit is recommended.

5.2 Recommendations

- Hot air stripping, instead of a steam stripping, should be carried out and the two results compared.
- Optimization and upgrading of the unit should be considered to improve its efficiency.
- Double Tower Unit should be considered for its efficiency and flexibility.
- The developed start-up and shut-down procedure should be followed during operation.
- For safety, automated control & alarm systems should be installed to notify personnel of abnormal & off-spec operations.
- Costing and techno-economics analysis should be carried out to ascertain the profitability of the unit for possible commercialization.
- Research Grant should be made readily available by authorities to encourage local content technology.

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Table 1: PHYSICOCHEMICAL PARAMETERS OF WATER SAMPLES A AND B

S/N	PARAMETERS	UNIT	A	B	EFFLUENT DISCHARGE STANDARD
1	pH	-	7.0	6.8	6-9
2	TURBIDITY	NTU	93	157	5
3	TEMPERATURE	°C	24.8	24.7	AMBIENT
4	ELECTRICAL CONDUCTIVITY	mS/cm	0.13	0.14	
5	TOTAL DISSOLVED SOLID	ppm	97	110	
6	VOLATILE ORGANIC COMPOUNDS	ppm	1200	1800	
7	DISSOLVED OXYGEN	ppm	1.99	1.01	
8	BIOLOGICAL OXYGEN DEMAND	ppm	359	403	10
9	CHEMICAL OXYGEN DEMAND	ppm	810	856	100
10	SULPHATE	ppm	20	21.3	
11	HYDROGEN SULPHIDE	ppm	12	16	1.0
12	AMMONIA	ppm	9.3	11.8	15

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Result of Laboratory Analysis