DESIGN OF COOLING WATER SYSTEM FOR ATTOCK REFINERY LIMITED

By

Aimen Rabbani

Asnia Zahra

Mohammad Jarrar Haider

School of Chemical and Materials Engineering

National University of Sciences and Technology

2021

DESIGN OF COOLING WATER SYSTEM FOR ATTOCK REFINERY LIMITED

By

Leader - 00000224832 Aimen Rabbani
Member 1 – 00000223272 Asnia Zahra
Member 2 - 00000237874 Mohammad Jarrar Haider

A THESIS
Submitted to
National University of Sciences and Technology
in partial fulfilment of the requirements
for the degree of

B.E. CHEMICAL ENGINEERING

School of Chemical and Materials Engineering (SCME)
National University of Sciences and Technology (NUST)
June, 2021

CERTIFICATE

This is to certify that work in this thesis has been completed by Ms. Aimen Rabbani, Ms. Asnia Zahra and Mr. Mohammad Jarrar Haider under the supervision of Dr. Taqi Mehran at School of Chemical and Materials Engineering (SCME), National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Advisor:

Dr. Taqi Mehran
Department of Chemical Engineering
School of Chemical and Materials Engineering
National University of Sciences and Technology

Submitted Through:

HOD ------------------------------------
Dr. Erum Pervaiz
Department of Chemical Engineering
School of Chemical and Materials Engineering
National University of Sciences and Technology

Principal/Dean ------------------------------------
Dr. Amir Azam Khan
School of Chemical and Materials Engineering
National University of Sciences and Technology

DEDICATION
TO

OUR PARENTS

Without whom none of this would have been possible and for their support throughout our lives.

AND TEACHERS

For inspiring us and supporting us throughout the entirety of this project.

ACKNOWLEDGEMENTS

First of all, we bow before Allah Almighty to thank for His countless blessings and rewards who gave us the strength and ability to complete the thesis. It is a pleasure and a deep sense of indebtedness that we acknowledge the valuable help of our respected supervisor who has enriched the text by their generous contribution and patronage. We express our cordial gratitude to our supervisor **Dr. Taqi Mehran** for his encouragement, guidance, enthusiastic support, constructive suggestions and ever helping supervision. We are thankful to our Industrial supervisor **Mr. Saleem Hasrat**, utilities supervisor, Attock Refinery Limited, Pakistan for being an ideal mentor and inspiring us and being there for us in each and every problem we encountered during our project. We are thankful to the **Attock Refinery Limited** for reducing the student-industry gap, giving us industrial exposure and giving us a chance to apply our knowledge and learning in practical industry problems and situations. We are also thankful to our parents, without their assistance and encouragement; it was not possible to complete the project successfully.

ABSTRACT

Cooling tower is crucial piece of equipment for any refinery as it is used to reject waste heat. It operates on the principle of heat and mass transfer and cools water on the mechanism of evaporation. Cooling water system has a wet-cooling tower which provides cooling water to heat exchangers in parallel. Our project aims to reduce both energy and water consumption by replacing three existing cooling towers with one, along with devising an efficient exchanger network. For the design of the tower Merkel's Method is used through which an enthalpy –temperature diagram is constructed and used to find the number of stages. Manually designed cooling tower was simulated on Aspen Plus to find out the targeted relative humidity. Packed bed sand filter was used to purify the blowdown stream and centrifugal pumps installed in different streams. For the optimization of heat exchanger networks Aspen Energy analyzer was used which gave the least possible heat transfer area further utilized to calculate the purchase cost of equipment.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

T_{G1}	Wet bulb Temperature
T_W	Dry Bulb Temperature
Y'_1	Humidity
H'	Enthalpy of Air
P_A^v	Saturation Pressure
$\dot{v}_L$	Volumetric flow rate
L	Water flux
G_s	Air Flux
P_f	Power Required
P_A^v	Saturation Pressure
c_{wL}	Heat Capacity of Water
$h_L\bar{a}$	Heat Transfer Co-efficient
$k_y\bar{a}$	Mass Transfer Co-efficient
$H_L\bar{a}$	Overall Heat Transfer Co-efficient
$K_y\bar{a}$	Overall Mass Transfer Co-efficient
Me	Merkel’s Number
H	Height of Cooling tower
h	Height of fill zone
D_p	Particle Diameter of Sand
□	Density of Water
μ	Viscosity of Water
$\emptyset_s$	Sphericity

$\boldsymbol{\rho_p}$	Density of sand
$\boldsymbol{A}$	Area
$\boldsymbol{a_S}$	Flow Area on Shell Side
$\boldsymbol{a_t}$	Flow Area on Tube Side
$\boldsymbol{\dot{G}_s}$	Mass Velocity on Shell Side
$\boldsymbol{\dot{G}_t}$	Mass Velocity on Tube Side
$\boldsymbol{h_o}$	Heat Transfer Co-efficient on Shell Side
$\boldsymbol{h_i}$	Heat Transfer Co-efficient on inner side of tube
$\boldsymbol{h_{io}}$	Heat Transfer Co-efficient on outer side of tube
$\boldsymbol{U_c}$	Clean Heat Transfer Co-efficient
$\boldsymbol{U_D}$	Design Heat Transfer Co-efficient
$\boldsymbol{R_D}$	Dirt Factor
$\boldsymbol{f}$	Friction Factor
$\boldsymbol{Q_{Air}}$	Fan Capacity
$\boldsymbol{P_1}$	Inlet Pressure of Cooling Tower
$\boldsymbol{P_2}$	Outlet Pressure of Cooling Tower
$\boldsymbol{P_a}$	Inlet Pressure of Pump
$\boldsymbol{P_b}$	Outlet Pressure of Pump
$\Delta\boldsymbol{H}$	Pump head
$\Delta\boldsymbol{T_{LM}}$	Log-mean Temperature Difference
$\boldsymbol{D_e}$	Equivalent Diameter
$\boldsymbol{J_H}$	Chilton-Colburn Factor
$\boldsymbol{k}$	Thermal Conductivity

$\boldsymbol{v}$	Velocity of fluid inside the tubes
$\Delta \boldsymbol{P_t}$	Pressure Drop of Tube Side
$\Delta \boldsymbol{P_r}$	Pressure Drop due to flow inside the tubes
$\Delta \boldsymbol{P_S}$	Pressure Drop on Shell Side
$\boldsymbol{N}$	Number of baffles installed
$\boldsymbol{B}$	Baffle Spacing
$\boldsymbol{C'}$	Clearance between the tubes
$\boldsymbol{P_T}$	Pitch between the tubes
$\mathbf{Q}$	Heat Load

PROBLEM STATEMENT

The existing cooling water system at Attock Refinery Limited has three cooling towers to which all the networks in the plants are connected. However, their system is very obsolete and inefficient and has to be replaced with a single cooling water system which provides cooling water to all the plants. This will not only reduce energy and production cost but will also provide easier maintenance and cleaning facilities. Designing of this cooling water system includes:

- Detailed design of cooling tower including all the specifications such as type, height, length, width, packing and fan (in the case of mechanical draft)
- Installation of a filter in the blowdown stream to reduce dissolved and suspended solids including design specifications of the type, length and area
- Design of pumps in the make-up water and cooling water return streams which includes pump head, power required and net positive suction head (in the case of centrifugal pumps)
- Optimization of heat exchanger networks within plant battery limits.

CHAPTER 1

INTRODUCTION

1.1 Literature Review

Cooling water systems are extensively used to reject waste heat to the surroundings of various industries including chemical and petrochemical plants, power plants, refrigeration systems, and air conditioning plants. The cooling water consists of a centralized cooling tower which supplies cooling water to different heat exchanger networks. Power required for the pumps consumes a large amount of energy and thereby cost. This energy is directly proportional to water circulation rate and the pump head required. Cooling tower is an integral equipment for the system and many relationships between the tower and network have been investigated. Innovations in the system have been devised as well which consists of a tower comprising of multiple cells which can be employed if a higher fan capacity or area is required for a single system.

Operation and performance of cooling towers have also been the subject of research for many years. The fundamentals of cooling tower performance were first proposed by Walker et al. and Merkel who developed mathematical equations for air and water system in the form of differential equations. Mohiuddin & Kant further modified the design by explaining packing, different types of cooling tower flows and the types of cooling towers due to the presence and absence of fans for mechanical and natural draft towers respectively. Number of gas-enthalpy transfer units along with the effectiveness of the tower based upon range and approach were investigated by Braun while Khan et al. discussed the operating features of a counter-flow wet cooling tower. Although, the study on the design of cooling towers has been extensive, little attention has been given for its optimization and greater efficiency. Milosavljevic & Heikkila presented a detailed approach to cooling tower design. Söylemez also discussed the e-NTU method for the design. However, all these design methods only incorporate heat and mass transfer within the fill zone and do not take into account other factors which could affect the cooling tower performance. This is of concern because it has been reported by Kröger that 15% of the cooling may occur in the spray zone of large cooling towers. Not only this but 10-20% of the total heat rejection takes place in the rain zone of industrial scale cooling towers. Hence, more areas of the tower must be included in investigating thermal performance and its effect on the design parameters.

For efficient heat exchanger networks, different methods have been utilized over the years. First a series and parallel arrangement was proposed by Kim and Smith which later went on to specify intermediate coolers, weather conditions and cycles of concentration in the blowdown stream. As the network of exchangers is altered from parallel combination to series, the pressure drop is bound to increase. This change in combination not only affects the pumping system but also have an impact on the required power. Wand and Smith conducted pinch analysis which ensured the reuse of water between the exchanger networks which reduced the demand of cooling water. This method has been further utilized in debottlenecking problems. Many researches have been done on the effect of cost due to the decrease in pressure and water circulation rate. To investigate the effect of pressure drop Pico´n-Nu´n˜ez et al. considered the networks of pipes and the resistances to flow. Different mathematical models are used to solve exchanger networks which include pinch analysis done manually and through software like Aspen Energy Analyzer, programming through MATLAB, calculations using graphs and MILP method. It will affect the pressure head of pumps as well as power consumption.

1.2 Methods

1.2.1 Merkel's Method

Merkel's theory is the most widely used method for the design of cooling towers. Merkel introduced the concept of enthalpy and developed relationships based upon sensible and latent heats in both air and water stream. However, it assumes no change in the water flow rate due to evaporation. The balances are applied on a differential volume (shell) of the cooling tower.

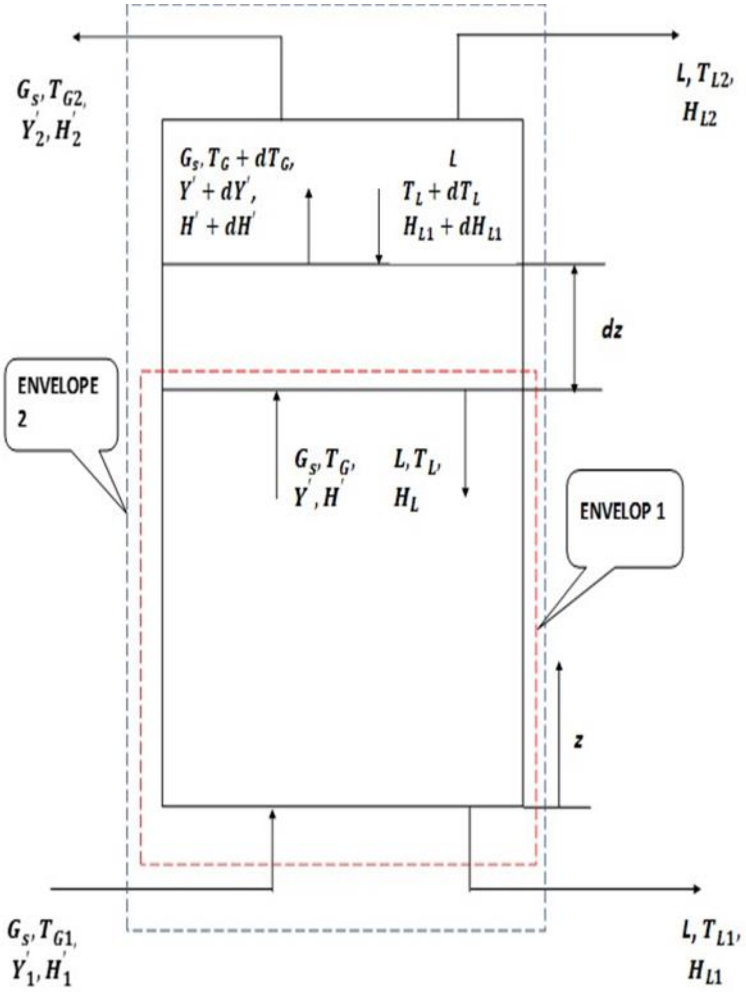


Figure 1 Shell Balance on cooling tower

Let, L is the constant water flow rate (kg/m^{2}s) and G_s is the flow rate of dry air in kg dry air/m^{2}s. Across a differential thickness dz of the bed, water temperature reduces by dT_L while air enthalpy increases by dH'.

Hence, change in enthalpy of water= $Lc_{WL}dT_L$

And change in enthalpy of air= $G_s dH'$

Differential enthalpy balance over dz is

$$Lc_{WL}dT_L = G_s dH'$$

Enthalpy balance over envelope 1 is

$$Lc_{WL}(T_L - T_{L1}) = G_s(H' - H'_1)$$

The equation above gives us the operating line for the system.

Enthalpy balance over entire tower (envelope 2) is

$$Lc_{WL}(T_{L2} - T_{L1}) = G_s(H'_2 - H'_1)$$

The equilibrium curve for air-water system on $T_l - H'$ plane is a graph between air and water system at saturated conditions.

Along the shell, rate of mass transfer og water into air is given by

$$G_s dY' = k'_y \bar{a}(Y'_i - Y')$$

The decrease in temperature of air for sensible heat transfer to water is

$$-G_s c_H dT_G = h_G \bar{a}(T_G - T_i)$$

Upon differentiation of equation

$$H' = c_H(T_G - T_O) + Y'\lambda_0 = (1.005 + 1.88Y')(T_G - T_O) + 2500Y'$$

And multiplication with G_s gives

$$G_s dH' = G_s c_H dT_G + G_s dY'\lambda_0$$

$$G_s dH' = -h_G \bar{a} dz(T_G - T_i) + k'_y \bar{a} dz(Y'_i - Y')\lambda_0$$

$$G_s dH' = k'_y \bar{a} dz\left[\frac{h_G}{k'_y}(T_i - T_G) + (Y'_i - Y')\lambda_0\right]$$

$$G_s dH' = k'_y \bar{a} dz [c_H(T_i - T_G) + (Y'_i - Y')\lambda_0]$$

$$G_s dH' = k'_y \bar{a} dz [c_H(T_i - T_O) + c_H(T_O - T_G) + Y'_i \lambda_0 - Y' \lambda_0]$$

$$G_s dH' = k'_y \bar{a} dz [c_H(T_i - T_O) + Y'_i \lambda_0 - \{c_H(T_O - T_G) + Y' \lambda_0\}]$$

$$G_s dH' = k'_y \bar{a} dz (H'_i - H')$$

Using the integrals, the height of packing(z) in the tower is calculated as

$$\int_{H'_1}^{H'_2} \frac{dH'}{(H'_i - H')} = \frac{k'_y \bar{a}}{G_s} \int_o^z dz = \frac{k'_y \bar{a}}{G_s} z$$

Number of transfer units on the basis of gas-enthalpy :

$$N_{tG} = \int_{H'_1}^{H'_2} \frac{dH'}{(H'_i - H')}$$

Height of transfer units on the basis of gas-enthalpy:

$$H_{tG} = \frac{k'_y \bar{a}}{G_s}$$

Hence, height of cooling tower (packing section),z

$$z = N_{tG} H_{tG}$$

Manual calculation is not possible hence a graphical approach is used and to do that values of interfacial enthalpy H'_i for a set of values of H' to be determined.

Let, $h_L \bar{a}$ is volumetric heat transfer co-efficient on the water side,

$$G_s dH' = L c_{WL} dT_L = h_L \bar{a} (T_L - T_{Li})$$

$$k'_y \bar{a} dz (H'_i - H') = -h_L \bar{a} (T_L - T_{Li})$$

$$\frac{(H'_i - H')}{(T_L - T_{Li})} = -\frac{h_L}{k'_y}$$

(T_L, H') on the operating line meets the equilibrium line at the point (T_{Li}, H'_i).

Substituting,

$$G_s dH' = L c_{WL} dT_L$$

In equation

$$G_s dH' = k'_y \bar{a} dz (H'_i - H')$$

We have,

$$Lc_{WL} dT_L = k'_y \bar{a} dz (H'_i - H')$$

Finally, the **Merkel's Equation** is:

$$\int_{T_{Li}}^{T_{LO}} \frac{dT_L}{(H'_i - H')} = \frac{k'_y \bar{a}}{Lc_{WL}} \int_0^z dz = \frac{k'_y \bar{a}}{Lc_{WL}} z$$

Merkel further went on to derive further simplified equations based upon overall enthalpy transfer co-efficient K'_y, differential mass balance equation becomes:

$$G_s dH' = K'_y \bar{a} dz (H^{*\prime} - H')$$

Where $H^{*\prime}$ is the enthalpy of saturated air at T_L (bulk liquid temperature).

Overall enthalpy transfer units N_{t0G} then becomes,

$$\int_{H'_1}^{H'_2} \frac{dH'}{(H^{*\prime} - H')} = \frac{K'_y \bar{a}}{G_s} \int_o^z dz = \frac{K'_y \bar{a}}{G_s} z$$

Heat load of the cooling tower is equal to

$$q = k'_y (H'_i - H') = h_L (T_L - T_{Li}) = K'_Y \left(H^{*'} - H'\right)$$

$$(H^{*\prime} - H') = \left(H^{*\prime} - H_i^{\prime\prime}\right) + (H'_i - H')$$

$$\frac{q}{K'_Y} = q \frac{\left(H^{*'} - H_i^{\prime\prime}\right)}{h_L (T_L - T_{Li})} + \frac{q}{k'_y}$$

$$\frac{1}{K'_Y} = \frac{\left(H^{*'} - H_i^{\prime\prime}\right)}{h_L (T_L - T_{Li})} + \frac{1}{k'_y}$$

Hence, **Merkel's equation** is expressed as

$$\frac{K'_Y \bar{a} V}{L} = \int_{T_{Li}}^{T_{LO}} \frac{dT_L}{(H'_i - H')}$$

Left- hand side of the above equation is a tower characteristic where V is active cooling volume/plan area.

1.2.2 Poppe’s Method

For unsaturated air, not including the simplifying assumptions of Merkel, manipulating the mass and energy balances from Figs. 6 and 7 gives:

Equation 1:

$$\frac{dw}{dTw} = c_{pw}(w_{sw} - w)m_w/m_a/\left[i_{masw} - i_{ma} + (Le_f - 1)\{i_{masw} - i_{ma} - (w_{sw} - w)i_v\} - (w_{sw} - w)c_{pw}T_w\right]$$

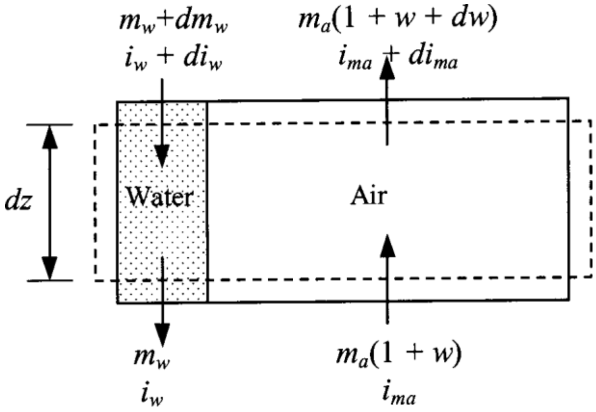


Figure 2. Control volume of counter flow fill

Equation 2:

$$di_{ma}/dT_w = c_{pw}(m_w/m_a)[1 + (w_{sw} - w)c_{pw}T_w/[i_{masw} - i_{ma} + (\mathrm{Le}_f - 1)\{i_{masw} - i_{ma} - (w_{sw} - w)i_v\} - (w_{sw} - w)c_{pw}T_w]]$$

where the Lewis factor, which indicates the relative rates of heat and mass transfer in a process involving evaporation, is described as $\mathrm{Le}_f = h / h_d c_{pa}$. The subsequent relation shows the Lewis factor for air-water vapor systems:

Equation 3:

$$Le_f = 0.865^{2/3} \left(\frac{w_{sw} + 0.622}{w + 0.622} - 1 \right) / \ln \left(\frac{w_{sw} + 0.622}{w + 0.622} \right)$$

According to the Poppe approach, the Merkel’s number or the transfer coefficient is given by:

Equation 4:

$$d\mathrm{Me}_P / dT_w = c_{pw} / [i_{masw} - i_{ma} + (\mathrm{Le}_f - 1) \{ i_{masw} - i_{ma} - (w_{sw} - w) i_v \} - (w_{sw} - w) c_{pw} T_w]$$

The control volume in the fill of Fig. 3 determines the varying mass flow rate ratio. A mass balance of the control volume gives:

Equation 5:

$$\frac{m_w}{m_a} = \frac{m_{wi}}{m_a} \left(1 - \frac{m_a}{m_{wi}} (w_a - w) \right)$$

Equations (1) – (4) are only valid if the air is unsaturated. In the case when the airis supersaturated, the ruling equations are,

Equation 6:

$$dw/dT_w = c_{pw} (w_{sw} - w_{sa}) m_w / m_a / [i_{masw} - i_{ss} + (Le_f - 1) \times \{ i_{masw} - i_{ss} - (w_{sw} - w_{sa}) i_v + (w - w_{sa}) c_{pw} T_w \} + (w - w_{sw}) c_{pw} T_w]$$

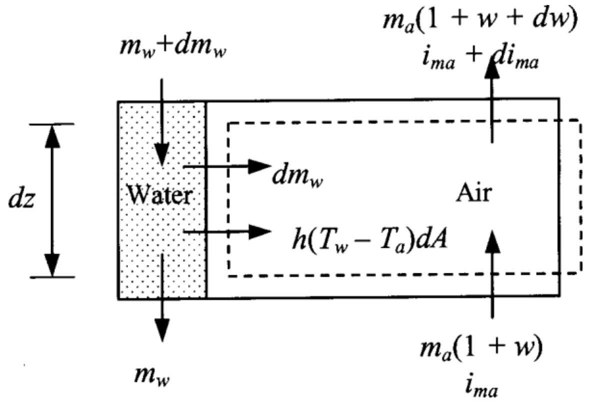


Figure 3. Air-side control volume of fill

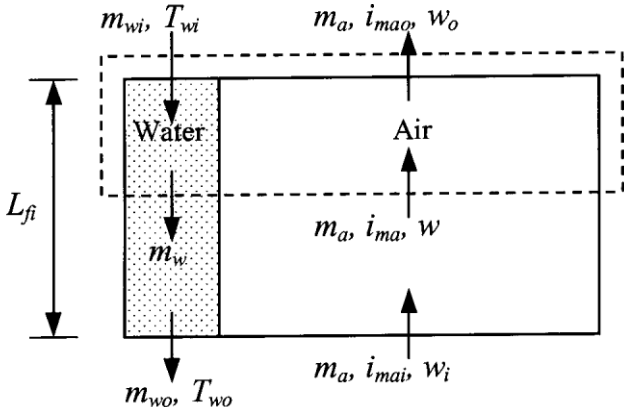


Figure 4 Control volume of the fill

Equation 7:

$di_{ma}\ /dT_w=c_{pw}(m_w\ /m_a)[1+(w_{sw}-w_{sa})c_{pw}T_w\ /[i_{masw}-i_{ss}+(\mathrm{Le}_f-1)\{i_{masw}-i_{ss}-(w_{sw}-w_{sa})i_v+(w-w_{sa})c_{pw}T_w\}+(w-w_{sa})c_{pw}T_w]]$

For supersaturated air is Lewis factor is given by,

Equation 8:

$$Le_f = 0.865^{2/3}\left(\frac{w_{sw}+0.622}{w_{sa}+0.622} - 1\right) / \ln\left(\frac{w_{sw}+0.622}{w_{sa}+0.622}\right)$$

According to the Poppe approach, the Merkel number is represented as:

Equation 9:

$dMe_P / dT_w = c_{pw} / [i_{masw} - i_{ss} + (Le_f - 1)\{i_{masw} - i_{ss} - (w_{sw} - w_{sa})i_v + (w - w_{sa})c_{pw}T_w\} + (w - w_{sw})c_{pw}T_w]$

Iterative procedure must be used in order to solve the equations of the Poppe method because the humidity ratio at the air outlet side of the fill, w_o in Eq. (5), is unknown.

1.2.3 e-NTU Method

It can be shown according to Jaber and Webb that

Equation 10:

$$\frac{d(i_{masw} - i_{ma})}{(i_{masw} - i_{ma})} = h_D \left(\frac{di_{masw} / dT_w}{m_w c_{pw}} - \frac{1}{m_a} \right) dA$$

Equation (13) corresponds to the heat exchanger *e*-NTU equation

Equation 11:

$$\frac{d(T_h - T_c)}{(T_h - T_c)} = -U \left(\frac{1}{m_h c_{ph}} - \frac{1}{m_c c_{pc}} \right) dA$$

Two possible cases of Eq. (10) can be considered where m_a is greater or less than $m_w c_{pw} / (di_{masw} / dT_w)$. The maximum of the dry air mass flow rate m_a and $m_w c_{pw} / (di_{masw} / dT_w)$ is called the maximum fluid capacity rate, denoted by $C_{\max}$ and the minimum by $C_{\min}$. The gradient of the saturated air enthalpy-temperature curve is:

Equation 12:

$$\frac{di_{masw}}{dT_w} = \frac{i_{maswi} - i_{maswo}}{T_{wi} - T_{wo}}$$

The fluid capacity rate ratio is defined as:

Equation 13:

$$C = C_{\min} / C_{\max}$$

The effectiveness is given by:

Equation 14:

$$e = \frac{Q}{Q_{max}} = \frac{m_w c_{pw} (T_{wi} - T_{wo})}{C_{\min} (i_{maswi} - f - i_{mai})}$$

The correction factor f is given by:

Equation 15:

$$f = (i_{maswo} + i_{maswi} — 2 i_{maswm}) / 4$$

where i_{maswm} represents the enthalpy of saturated air at the mean water temperature. The number of transfer units for counterflow cooling towers is formulated as,

Equation 16:

$$NTU = \frac{1}{1 - C} \ln \frac{1 - eC}{1 - e}$$

If the dry air mass flow rate m_a is greater than $m_w c_{pw} / (di_{masw} / dT_w)$ the Merkel number according to the$e$-NTU approach is given by

Equation 17:

$$Me_e = \frac{c_{pw}}{di_{masw} / dT_w} NTU$$

If m_a is less than $m_w c_{pw} / (di_{masw} / dT_w)$ the Merkel number ac-cording to the e-NTU approach is given by

Equation 18:

$$Me_e = m_a NTU / m_w$$

1.3 Cooling Tower

Cooling tower is an equipment in which cooling water is used as the cooling utility which rejects waste heat to the atmosphere in industries. The cooling tower is in a closed loop with heat exchanger networks, with pumps in between providing the desire flowrate. The heat transfer occurs between the hot process stream and cold water with the heat exchanger and its temperature increases. This hot stream of water is sent to the cooling tower where it direct contact between air and water occurs. Within the cooling tower evaporative cooling along with convective heat loss take place which results in the decreases in the temperature of cooling water. As continuous heat transfer takes place during the operation of cooling tower some of the heat transfer results in the evaporation of water which increases the concentration of salts in the tower. Due to this the blowdown stream is taken out of the cooling tower and this loss is compensated by the stream from the make-up water tank. The required concentration of salts (TSD) is maintained by using a filter e.g. A packed bed sand filter. The cold water exits the cooling tower at the bottom and goes into the heat exchangers and the process continues.

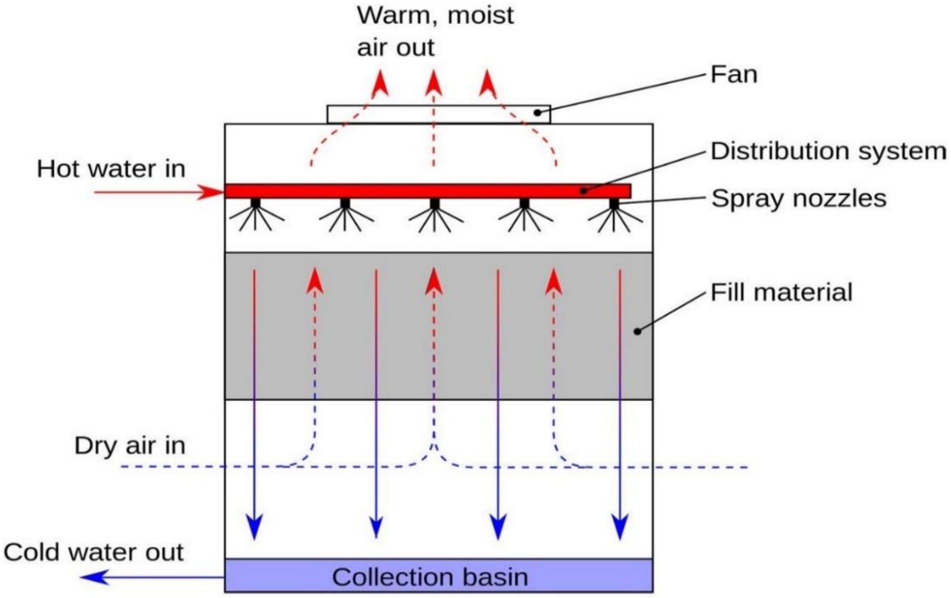


Figure 5. Working Principle of Cooling Tower

The cooling tower can be characterized into two types oon the basis of the contact of the two media i.e., on wet basis and on dry basis. In case of wet cooling tower, there is a direct contact between the air coming in with the hot water, causing water to cool down by evaporative cooling. In dry cooling tower, the water flows through a heat exchanger without coming directly in contact with the air. The cooling is by convective heat transfer.

Another classification of cooling towers is by their type of draft. There are two types in this category:

1.3.1 Natural draft

In case of natural draft cooling towers the overall size is larger and the cooling tower works on the principle of chimney effect. They draw in air because of difference in density as warmer air is less dense and rises up. As the warm and moist air rises up and exists the cooling tower, it draws in fresh air form the bottom, completing an air flow system. The hot water is sprayed on to fills from the top nozzles, as the fill area increases the surface area for air and water to come in contact. Evaporative cooling within the cooling tower results in cooling the water.

1.3.2 Mechanical draft

In Mechanical draft cooling towers, air is drawn in using a power-driven fan motor. The mechanical draft cooling tower is further divided into two types which are explained below.

- **Forced draft**

Forced draft cooling towers is a type of mechanical draft cooling tower in which a blower type fan is used at the air intake. The fan causes the air to blow into the tower which provides high values of the inlet and exit air velocities. More variations are expected at the outlet where the velocity much more likely to recirculate. Whereas at the intake position, more variation and complications are expected because of the freezing condition. Moreover, in case of forced draft cooling tower design the energy requirement for motor is also greater than the same design of an induced draft tower. One major advantage of using forced draft is that it can function in conditions when the static pressure is very high. operates with a high value of static The benefit of the forced draft design is its ability to work with high static pressure. Furthermore, for a cooling tower design like that of a forced draft, the area/ space requirement is less as compared to induced draft and this type of tower can be made more suitable for indoor situations.

- **Induced draft**

Induced draft cooling tower is the sub-category of mechanical draft cooling tower in which the fan is installed at top of the cooling tower which sucks the air up through the cooling tower and pulls it out of the tower. Due to this mechanism the hot, moist air is induced out of the cooling tower discharge. In in case of induced draft cooling tower the chance of recirculation is also less, and the design of the equipment produces low entering velocity of and higher exiting velocity. This arrangement of fan/fill is called as the draw-through.

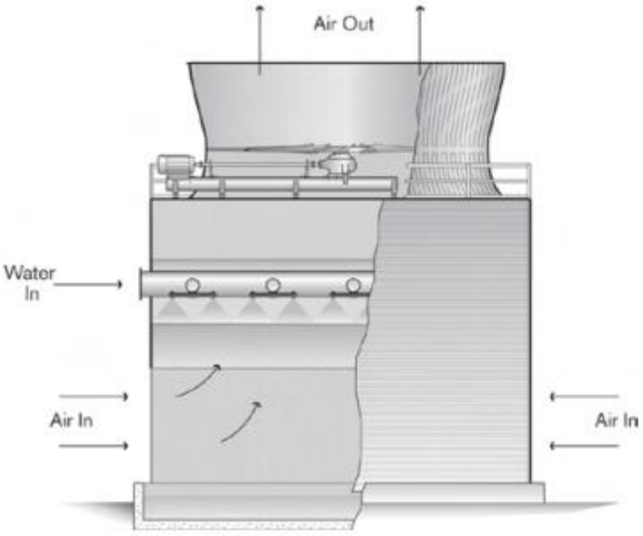


Figure 6. Induced draft counter flow

Another way of characterizing the cooling tower is done by defining them on the basis of the direction of air flow. These types are explained below.

1.3.3 Crossflow

It is basically the design of cooling tower in which the flow of air is circulated perpendicular to the flow of water which is falling from the top to the bottom. The fill is present in the center and the air stream is blown from one or more than one vertical faces of the tower, where it makes direct contact with the fill and water stream. The flow of water occurs due to the force of gravity falling perpendicularly with respect to the air stream. The flow of air remains continuous throughout the tower as it gets forced out by the fan out into the atmosphere. Lastly, a fan forces the air out into the atmosphere.

1.3.4 Counter flow

In this type of cooling tower design, the flow of air is opposite in direction to the flow of water, which is from top to bottom. The flow of air is in such a way that it first enters into the empty area below the fill media and is them made flow upwards vertically. From the top of the cooling tower the water is sprayed into the cooling tower by pressurizing through the nozzles which flow downwards opposite in direction to the flow of air stream. In counter current cooling tower there is more contact between the air and water streams flowing in the opposite direction. And in a refinery, for a induced draft cooling tower counter flow is chosen.

Cooling tower can exist as a single equipment and would perform the same function, or it can be constructed (operated) in such a way that is grouped to fulfil the required capacity. This assembly of two or more cooling tower units grouped together is known as "cells". Cooling tower consisting of multiple cells can be in different geometric arrangement i.e. square, round or lineal depending on the individual geometric structure of the cell as well as on the location of the air inlets, whether the inlets for air are present on the sides of the cooling tower or at the bottom.

1.4 Components of Cooling Tower

This section covers the main components of the cooling tower. The design calculations are carried out in the section later and all these components are determined for the desired design conditions. The basic components of a cooling tower are: the fill, frame and casing, cold water basin, drift eliminators, louvers, air inlet, fans and, nozzles.

1.4.1 Frame and casing

In most towers, the frame holds the structural importance which plays a role in supporting the casing (exterior enclosure) the fans and motor and other components. For cooling towers which are designed according to the small scale for example glass fiber units, the casing may take up the role of frame.

1.4.2 Fill

Fills play a very major role when it comes to the discussion of heat transfer area within the cooling tower. Most towers use fills that are made of wood or plastic in such a way that it provides greater area for heat transfer making the contact between air and water maximum. There are two types of fills which can be employed within a cooling tower, which can either be a film-type or splash-type fill. In case of splash fill, the water drops over consecutive layers of splash bars arranged horizontally, constantly crashing into smaller droplets, at the same time soaking the fill surface with water. In case of plastic splash fill the transfer of heat is better than in the case of same fill with wood material.

On the other hand, fill film can be described as consisting of thin plastic surfaces which are very closely spaced such that when water falls over them it spreads in the form of thin films exposing their surfaces to get in contact with air when the cooling tower is in operation. In case of film-type fills the exposed surfaces may be corrugating, flat, honeycombed or any other pattern depending on the requirement of desired area available for heat transfer. Even though film type fill provides more efficiency and same amount of transfer for a smaller volume than the splash fill, still in case of cooling tower in refineries splash type is preferred because of it gives lesser pressure drop within the fill area and prevent the algae growth.

1.4.3 Cold water basin

This component of cooling tower is located near or at the bottom of tower. It receives the cold water the falls down the tower through the fills. It normally has a low point (also known as sump) for the connection of discharge of cold water. In most of the cooling towers, the cold water basin takes up the area underneath the fill.

1.4.4 Drift eliminators

As the name suggests, this component captures the water droplets as they pass through the fill and get entrapped in the stream of air and prevents them from escaping the cooling tower system that would have otherwise been lost to the surroundings.

1.4.5 Air inlet

Within the tower, there is an opening from where the air is introduced into the system. It shows the point of entrance of the air stream. This point can be at the extreme lower end of the tower as making up the design of counter flow cooling tower or it may use up the whole side oof the tower giving cross low regime for air stream.

1.4.6 Louvers

The main functionality of louvers revolves around equalizing the flow of air stream within the fill to ensure its even distribution and contact with water and to retain the cooling water within the tower. Generally, louvers are incorporated as a key component in case of cooling towers with cross flow regime for air.

1.4.7 Nozzles

Nozzles is the component within a cooling tower which enables efficient entry of water into the cooling tower. The purpose of nozzles is to spray the water in such a way that it effectively wets the fill and enable even distribution of water onto each fill surface. Nozzles can be of different types, such as they be fixed in one place or be a part of moving assemble, with different types of spraying patterns such as round or square spray patterns etc.

1.4.8 Fans

Different types of fans can be used within a cooling tower depending on the type of cooling tower that is in operation. The fan used can be axial which is the propeller type as well as the centrifugal one. In case of induced draft towers propeller-type fans are employed whereas in case of forced draft cooling tower both centrifugal as well as propeller fans can be used.

1.5 Performance of Cooling Tower

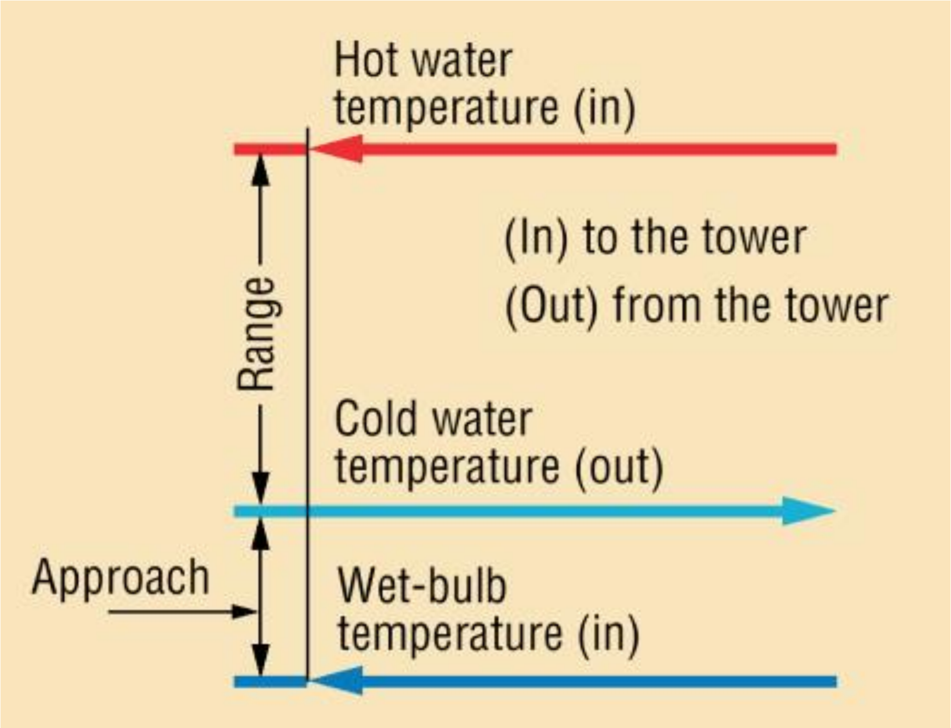


Figure 7. Performance parameters of cooling tower

The important parameters, from the point of determining the performance of cooling towers, are:

1.5.1 Range

The range of cooling tower is described as the difference between the cooling water supply and cooling water return temperature. It plays a major role in determining the effectiveness of cooling tower.

$$Range = cooling\ water\ supply - cooling\ water\ return$$

1.5.2 Approach

The difference between the cooling tower return (temperature of cold water) and ambient wet bulb temperature. Even Though, both range and approach should be observed, the 'Approach' is a much better representation of the performance of cooling tower.

$$Approach = cooling\ water\ return - wet\ bulb\ temerature$$

1.5.3 Cooling tower effectiveness

The effectiveness or in simpler terms the efficiency of cooling tower which is calculated as the range divided by the ideal range, i.e., difference between cold water inlet temperature and ambient wet bulb temperature, or writing in terms of equation:

$$Effectiveness = Range/(Range + Approach)$$

1.5.4 Cooling capacity

It is described as the heat eliminated from the system in *kCal/hr* or *TR,* which is given as product of mass flow rate of water, temperature difference and the specific heat of water. In mathematical form:

$$Q = mc_p\Delta T$$

1.5.5 Evaporation loss

It can be described as the quantity of water evaporated for cooling duty. Some of the higher energetic molecules of water gain enough kinetic more than their latent energy which enables them to be transformed into the vapor state.

1.5.6 Cycles of concentration (C.O.C)

As cooling tower operates, the TDS of water present increases because dissolved solids are left behind after the evaporation of water in the system. The COC describes how often a fresh water fed into the closed cycle can be utilized, or pumped around, before the water has to bleed off or clown down from the cooling tower. It is the ratio of dissolved solids in flowing out of the cooling tower to the dissolved solids in make-up water. Increasing the cycles of concentration results in decrease in the amount of make-up water as well as the amount of blow down.

1.5.7 Blowdown

The water losses as blowdown stream is calculated as result of the calculations of cycles of concentration as well as the evaporation losses. In form of equation, it is given by:

$$\text{Blow Down} = \text{Evaporation Loss} / (\text{C.O.C.} - 1)$$

1.5.8 Liquid/Gas ratio (L/G)

This parameter forms the basis of the design of cooling tower and is defined as the ratio of mass flowrate of water to the mass flowrate of air. Contrary To design values, seasonal changes involve modification and adjustment of air and water flow rates to find the best cooling tower effectiveness by using measures like water loading changes, blade angle adjustments.

1.5.9 Dry Bulb Temperature

The temperature of ambient air without any moisture present is called as dry bulb temperature. It is the commonly referred temperature of the air. It is called dry because the thermometer bulb that is used to determine the air temperature is not affected by moisture as it did in case of wet bulb temperature. Dry bulb temperature is the content of heat in a system and is used to calculate the condition of humid air from the psychometric chart.

1.5.10 Wet Bulb Temperature

The Wet bulb temperature of and air-water system is the lowest temperature that can be reached by the air through the process of evaporative cooling. It is the temperature measured when the thermometer bulb is covered in wet cloth. If the air is at less than 100% relative humidity – meaning it has the potential to take up more water – the water wetting the thermometer bulb will use latent energy from its surrounding and evaporate. For the relative humidity value of 100%, the wet bulb temperature becomes equal to the dry bulb temperature. It is also be found in literature as adiabatic saturation temperature. Using dry bulb and wet bulb temperatures, the state of humid air can be determined using psychometric charts.

1.5.11 Humidity

Humidity represents the quantity of water vapor that are present in air. It is a measure of moisture content and depends on the temperature and pressure of the air.

1.5.12 Relative Humidity

This parameter in cooling tower or air-water system is the ratio of the mole fraction of water-vapor to the mole fraction of moist saturated air at the same pressure and temperature. RH is a dimensionless parameter and is normally represented as a percentage. On a psychometric chart, the lines of constant RH show the physics of air and water: they are specified via experimental measurement.

1.5.13 Psychometric Chart

Psychometric chart is a chart used to determine state of humid air using humidity ratio, dry and wet bulb temperatures etc. It is a representation of thermodynamic parameters of moist air.

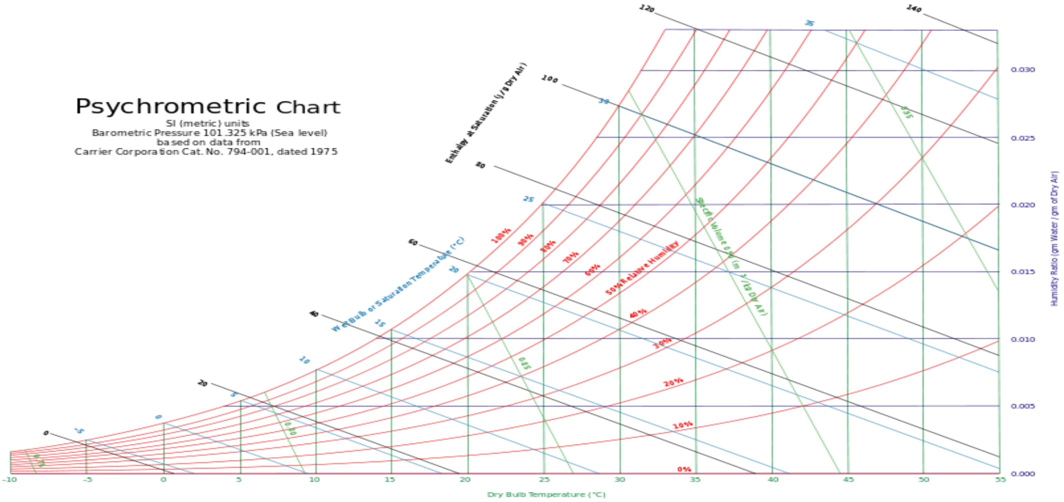


Figure 8. Psychometric Chart

The x-axis is dry-bulb temperature. Wet bulb temperature lines are sloping lines that vary slightly from the enthalpy lines. These lines are identically straight but are not just parallel to each other. These overlap the saturation curve at DBT point. The straight lines on the chart represent the humidity ratio.

CHAPTER 2

2.1 Process Flow Diagram

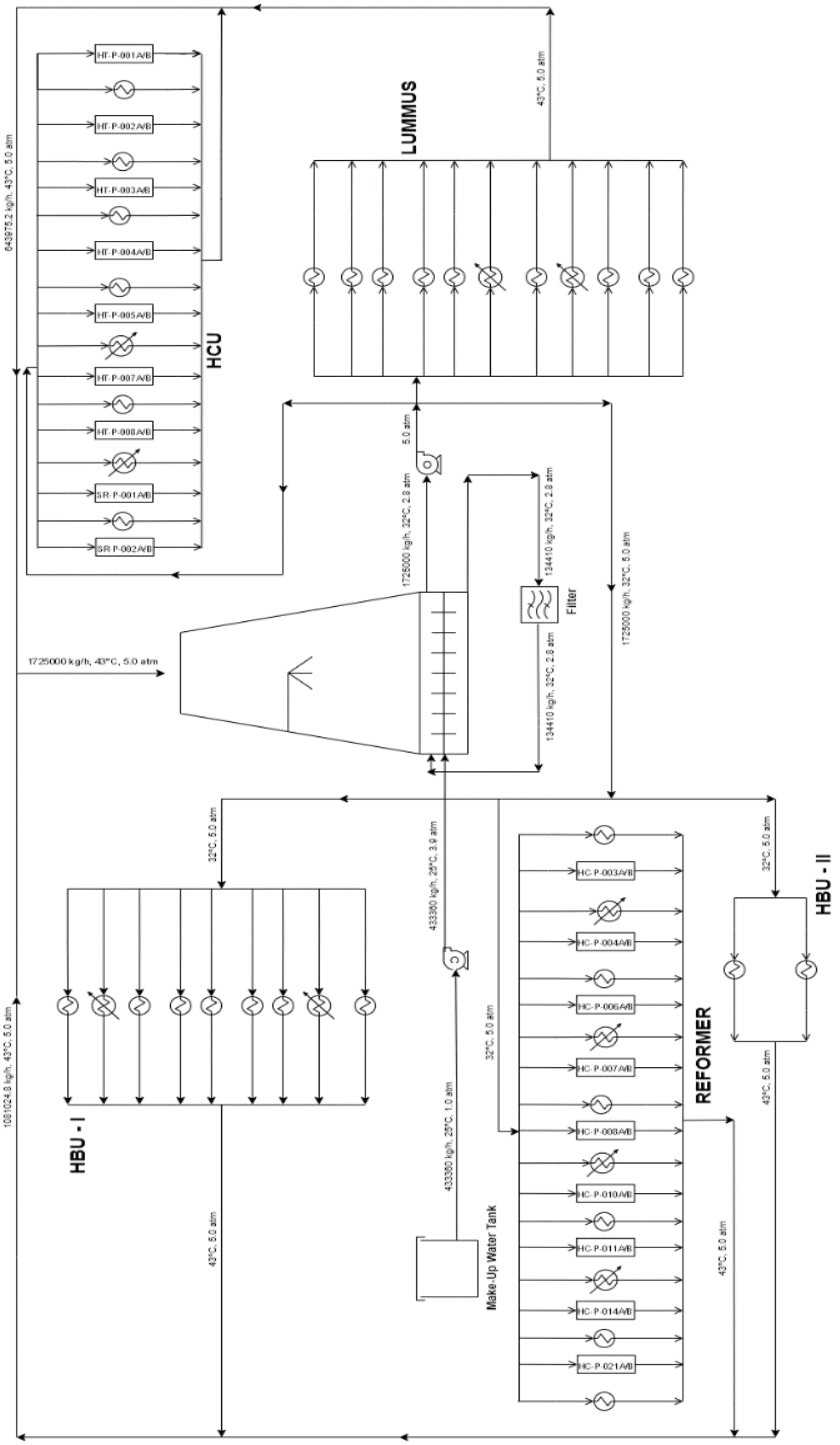


Figure 9. Process Flow Diagram

2.2 Process Description

The process flow diagram of our systems shows the cooling tower in the center which is connected to all the heat exchanger networks within plant battery limits whereby all the exchangers are connected in parallel in a single plant. Moreover, some of the cooling water is also being supplied to the mechanical seals of the pump which is used to prevent any excessive build-up of heat. Cooling water in ARL is supplied to:

- 9 exchangers and 2 condensers in LUMMUS
- 6 exchangers, 2 condensers and 9 pumps in HCU
- 7 exchangers and 2 condensers in HBU-I
- 6 exchangers, 4 condensers and 9 pumps in reformer
- 2 exchangers in HBU-II

Cooling water from all of the systems return to the top of the cooling tower at a flow rate of $1.725 \times 10^6\ kg/h$ and at a temperature of 43°C. This same flow rate is pumped back to all the exchangers from the bottom of the cooling tower at a temperature of 32°C. The pump in the cooling water supply line increases its pressure from 2.8 atm to 5.0 atm. It is also shown that every exchanger increases the water temperature up to 43°C . However, each exchanger has different water flow rate which depends upon the heat load and requirement from the process stream.

A make-up water tank is also connected via a pump to the cooling tower basin. It supplies water at ambient conditions of 25°C and 1.0 atm and at a flow rate of $5.11 \text{ x } 10^4\ kg/h$. The make-up water pump increases the pressure of this stream to 3.9 atm which is the average pressure of cooling water return and supply pressure without any increase in temperature. Blowdown stream taken out from the bottom of the cooling tower passes through a packed bed sand filter which reduces its TDS fraction from 3000ppm to 950ppm at a flow rate of 13441 kg/h. The purified stream is also being added to the cooling tower as make-up. Level in the basin has to be maintained for smooth operation of the tower.

CHAPTER 3

Material and Energy Balance

3.1 Make-Up Water Tank

3.1.1 Mass Balance

Make-up water is constantly being added to the cooling tower to maintain a constant water level inside the cooling tower basin. This is crucial for smooth operation of the tower maintaining dissolved and suspended solids as well as turbidity. The amount of make-up water exactly equals all of the losses taking place from the tower namely:

Evaporation Loss

Evaporation loss accounts for the loss of water along the outlet air stream and is calculated using an empirical relation.

$$Evaporation\ Loss = 0.00085 \text{ x } 1.8 \text{ x } Circulation\ Rate \text{ x } (T_1 - T_2)$$

$$= 0.0085 \text{ x } 1.8 \text{ x } 1725\text{x}(43\text{-}32)$$

$$= 29.032\ m^3/h$$

Blowdown Losses

Constant evaporation of water makes the water in the basin to become more concentrated. Hence, a blowdown stream is taken out from the tower which depends on Cycles of Concentration which maintains a constant fraction of dissolved solids and depends mainly on chloride ion concentrations.

$$COC = \frac{TDS\ of\ Cooling\ Water}{TDS\ of\ Makeup\ Water}$$

$$COC = \frac{3000ppm}{950ppm} = 3.16$$

$$Blowdown = \frac{Evaporation\ Loss}{COC - 1}$$

$$= \frac{29.032\frac{m^3}{h}}{3.16 - 1}$$

$$= 13.441m^3/h$$

Drift Losses

A fraction of water from the circulation rate is lost as drift which leaves the tower in the form of small droplets via the air stream.

$$Drift\ Loss = 0.005 \text{ x } Circulation\ Rate$$

$$= 0.005 \text{ x } 1725$$

$$= 8.63\frac{m^3}{h}$$

Make-up Water

Make-up water is the summation of the losses.

$$Make - Up\ Water = Blowdown + Evaporation\ Loss + Drift\ Loss$$

$$= 13.441 + 29.032 + 8.63$$

$$= 51.10\frac{m^3}{h}$$

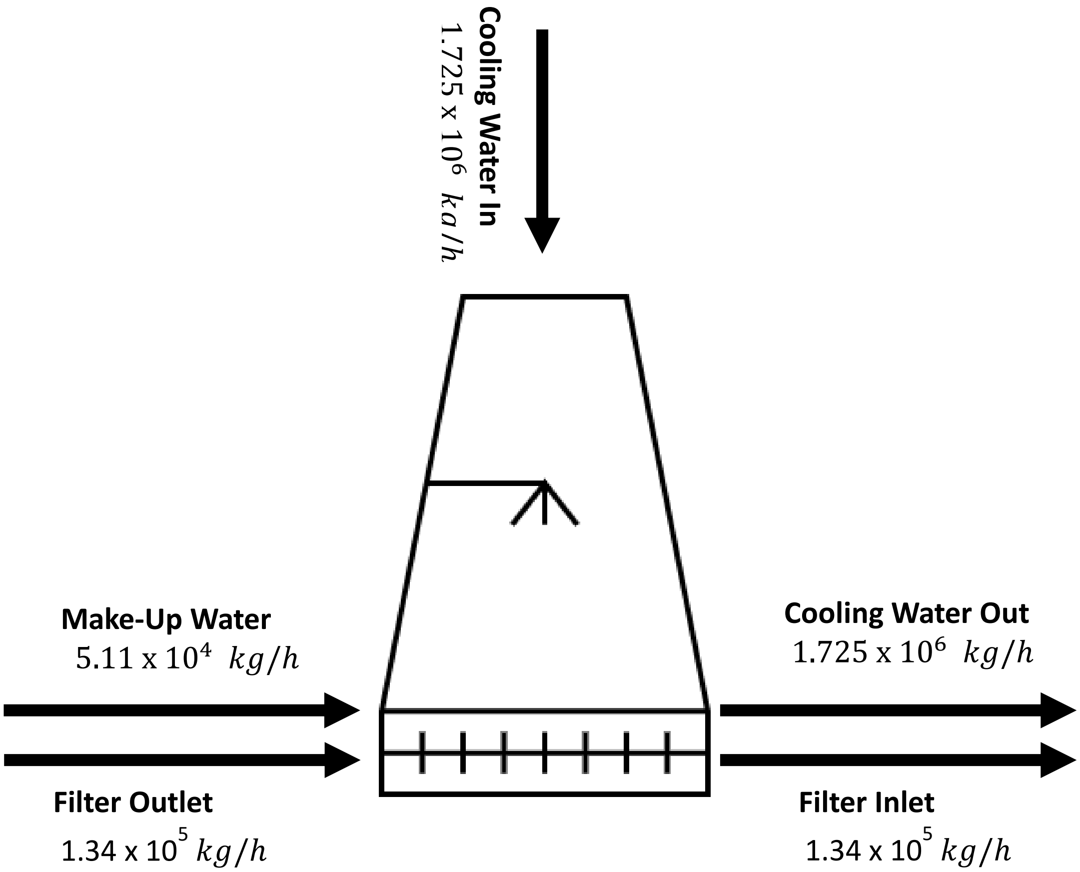
3.1.2 Energy Balance

A simple energy balance was carried out at the tank as both inlet and outlet temperatures were the same.

Parameter	In	Out
Temperature (^oC)	25	25
Molar Enthalpy (KJ/kg mole)	2.862 x 10^5	2.862 x 10^5
Molar Flow Rate (kg mole/h)	2.84 x 10^3	2.84 x 10^3
Enthalpy (kJ/s)	2.25 x 10^5	2.25 x 10^5

Table 1. Energy balance of make-up water tank

3.2 Cooling Tower



3.2.1 Mass Balance

Mass balance was carried out on cooling tower by identifying the inlet and outlet streams and sum of these streams shows that total mass flow rate in equals total mass flow rate out.

Stream	In	Out
Cooling Water (kg/h)	1.725×10^6	1.725×10^6
Make-Up Water (kg/h)	5.11×10^4	-
Evaporation Losses (kg/h)	-	2.90×10^4
Drift Losses (kg/h)	-	8.63×10^3
Blowdown Losses (kg/h)	-	1.34×10^4
Filter Stream (kg/h)	1.34×10^4	1.34×10^4
Total (kg/h)	1.79×10^6	1.79×10^6

Table 2. Mass balance of cooling tower

3.2.2 Energy Balance

The energy balance for cooling tower was divided into two parts for the streams of air and water. The specific enthalpies of water were found using steam tables at the specified temperatures. The inlet enthalpy of air was found using empirical relation using humidity while the outlet enthalpy was found be equalizing enthalpy changes of both streams.

Energy transferred by water = Energy transferred by air

$$LC_{wL}(T_{L2} - T_{L1}) = G_S(H_2' - H_1')$$

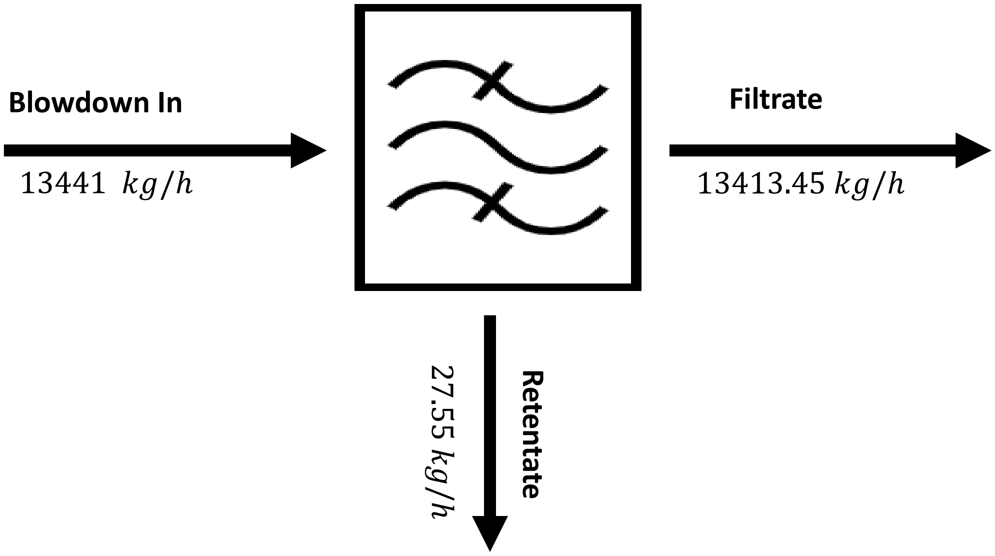
$$(8.785 \times 10^4)(4.187)(43 - 32) = (5.12 \times 10^4)(H_2' - 50.68)$$

$$H_2' = 129.70\ kJ/kg$$

Parameter	In	Out
Specific Enthalpy of Air (kJ/kg)	50.68	129.70
Air flow rate (kg/h)	5.37×10^4	5.37×10^4
Enthalpy (kJ/s)	7.56×10^2	1.93×10^3
Specific Enthalpy of Water (kJ/kg)	1.78×10^2	1.36×10^2
Water Flow Rate (kg/h)	1.725×10^6	1.725×10^6
Enthalpy (kJ/s)	8.53×10^4	6.52×10^4
Total Enthalpy (kJ/s)	8.61×10^4	6.71×10^4

Table 3. Energy balance of cooling tower

3.3 Filter



3.3.1 Mass Balance

Inlet stream of blowdown divided into filtrate and retentate while coming out of the filter where retentate only consisted of dissolved solids. The amount of dissolved solids was found by converting ppm to mass fractions and multiplying with the respective flow rates.

Component	**Feed**	**Filtrate**	**Retentate**
Blowdown without TDS (kg/h)	13400.68	13400.68	-
TDS (kg/h)	40.32	12.77	27.55
Blowdown (kg/h)	13441	13413.45	27.55

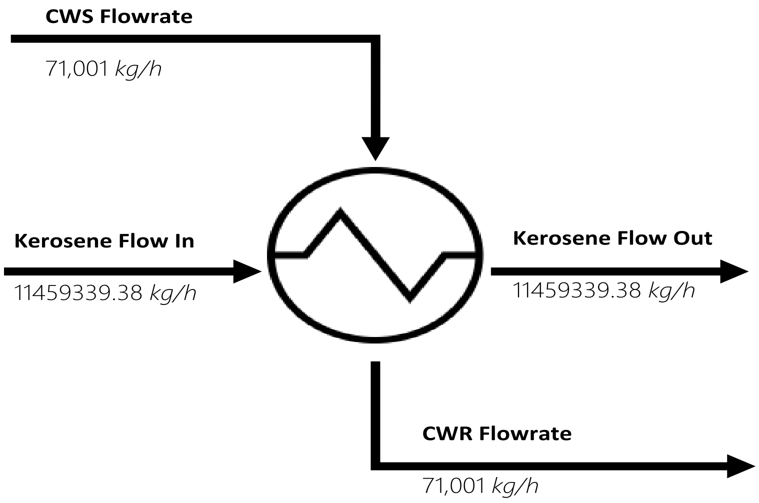
Table 4. Mass balance of filter

3.3.2 Energy Balance

	Blowdown In	**Filtrate**	**Retentate**
Temperature (^oC)	25	25	25
Molar Enthalpy (KJ/kg mole)	2.862×10^5	2.862×10^5	2.862×10^5
Molar Flow Rate (kg mole/h)	7.47×10^3	7.45×10^3	1.53×10^1
Enthalpy (kJ/s)	5.93×10^5	5.92×10^5	1.22×10^3

Table 5. Energy balance of filter

3.4 Heat Exchanger



3.4.1 Mass and Energy Balance

Simultaneous mass and energy was conducted at the exchanger to find the mass flow rate of process stream by equalizing the enthalpy changes at shell and tube sides assuming no heat loss.

$$Energy\ transferred\ by\ water = Energy\ transferred\ by\ feed$$

$$\dot{Q}_w = \dot{Q}_f$$

$$\dot{m}_w \dot{C}_{p_w}\left(T_{1_W} - T_{2_W}\right) = \dot{m}_f \dot{C}_{p_f} \Delta T_f$$

$$\left(71001\,\frac{kg}{h}\right)\left(4.187\,\frac{kJ}{kg\ ℃}\right)(43-32) =$$

$$\dot{m}_f\left(2.848870519\,\frac{kJ}{kg\ ℃}\right)(10℃)$$

$$\dot{m}_f = 1.15\text{x}10^5\,\frac{kg}{h}$$

Property	Tube Side	Shell Side
Flowrate (kg/h)	71,001	114786
Cp (kJ/kg°C)	4.18	2.85
delta T (°C)	11	10
Duty Q (kJ/s)	908.356	908.356

Table 6. Mass and energy balance of heat exchanger

Same mass and energy balance was done at all of the plants at ARL.

- **HBU-I**

TAG	**CWS Flowrate (kg/h)**	**Cp_f (kJ/kg°C)**	**m_f (kg/h)**	**Q_w (kJ/s)**	**Q_f(kJ/s)**
E-310	71,001	2.848870519	114593.3938	906.8382	906.8382
E-316	209,560	2.2210974	433819.5098	2676.543	2676.543
E-319	16,186	2.0808396	35765.9392	206.7311	206.7311
E-330	145,295	2.882874074	231735.7783	1855.736	1855.736
E-333A/B	106,330	2.848870519	171613.0694	1358.065	1358.065
E-405	127,732	2.868864709	204718.5939	1631.417	1631.417
E-406	9,071	2.95927583	14094.82579	115.8624	115.8624

Table 7. Mass and energy balance of HBU-I

- **HBU-II**

TAG	**CWS Flowrate (kg/h)**	**Cp_f (kJ/kg°C)**	**m_f (kg/h)**	**Q_w (kJ/s)**	**Q_f(kJ/s)**
E-107	16215.9	2.84887052	26172.0681	207.1134	207.1134
E-205	31932.9	2.88287407	50930.9403	407.8541	407.8541

Table 8. Mass and energy balance of HBU-II

- **HCU**

	Tube Side		Shell Side		
TAG	**CWS Flowrate (kg/h)**	**Q_w (kJ/s)**	**m_f (kg/h)**	**Cp_f (kJ/kg°C)**	**Q_f (kJ/s)**
HC-E-016	8400	107.466	13634.14	2.837573	104.466
HC-E-017	8900	113.86	14382.71	2.852988	113.86
HC-E-018				2.851363	
HC-E-018A/B	38300	489.99	59608.62	2.959276	489.99
HC-E-023	29300	374.85	46809.95	2.882874	374.85
HC-E-025	51000	652.47	81478.08	2.882874	652.47
HC-E-026	40300	515.58	65152.03	2.848871	515.58
HC-E-028	30000	383.81	46690.81	2.959276	383.81
HC-E-30				2.959276	
HC-E-016A	26000	332.63	42200.92	2.837573	332.63

Table 9. Mass and energy balance of HCU

- **LUMMUS**

		Tube Side		Shell Side		
TAG	**Component**	**CWS Flowrat (kg/h)**	**Q_w (kJ/s)**	**m_f (kg/h)**	**Cp_f (kJ/kg°C)**	**Q_f (kJ/s**
LE-101	**Heavy Naphtha**	51691.18	661.32	82582.19	2.882874074	661.32
LE-2A/2B		148498.8	1899.84	237242.7		1899.84
LE-12		35821.08	458.28	57228.01		458.28
LE-3		10202.21	130.52	16299.12		130.52
LE-15		8161.765	104.42	13039.29		104.42

LE-04	**Kerosene**	12469.36	159.53	20158.92	2.848870519	159.53
LE-4A		12469.36	159.53	20158.92		159.53
LE-7A		9068.627	116.02	14661.03		116.02
LE-7		9068.627	116.02	14661.03		116.02
LE-09		11335.78	145.02	18326.29		145.02
LE-11	**High-Speed Diesel**	5667.892	72.51	9199.625	2.837573321	72.51
LE-102		8161.765	104.42	13247.46		104.42
LE-103		8161.765	104.42	13247.46		104.42
LE-106		12469.36	159.53	20239.18		159.53
LE-13		8161.765	104.42	13247.46		104.42
LE-104		9522.059	121.82	15455.37		121.82
LE-105		9068.627	116.02	14719.4		116.02

Table 10. Mass and energy balance of LUMMUS

- **Reformer**

Table 11. Mass and energy balance of reformer

	Tube Side		**Shell Side**		
TAG	**CWS Flowrate (kg**	**Q_w (kJ/s)**	**m_f (kg/h)**	**Cp_f (kJ/kg°C)**	**Q_f (kJ/s)**
HT-E-003	36700	468.7406	58534.16	2.86886471	468.7406
HT-E-004	18300	233.7317	29187.33	2.86886471	233.7317
HT-E-008	16700	213.2961	26635.43	2.86886471	213.2961
SR-E-004	13300	169.8706	21212.65	2.86886471	169.8706

Chapter 4

Equipment Design

4.1 Cooling Tower

The scope of this project has cooling tower as its major design equipment and hence all of the parameters for the design were calculated and a specification sheet was also devised at the end.

4.1.1 Type

Induced draft counter-flow tower was selected for the operation due to the following reasons:

- Natural draft towers are not suitable for refinery operation as they are utilized in large power plants with 45000m^3/h water circulation rate and are employed in areas with greater wind velocity. However, in our case we have a far lesser circulation rate of 1725 m^3/h and do not have constant wind conditions.
- Induced draft towers are more flexible to operation due to different number of cells.
- They have constant airflow irrespective of the ambient weather conditions due to the installation of a fan.
- They are compatible with many types of heat exchangers and as in our system we have over 50 exchangers from different plants connected to a single tower, this is an important consideration.

4.1.2 Design Parameters

Parameter	**Units**	**Value**
Design Wet Bulb Temperature	°C	29
Design Dry Bulb Temperature	°C	47

Supply Temperature (Cooling Tower Outlet)	°C	32
Return Temperature (Cooling Tower In)	°C	43
Cooling Water Supply Pressure at Plant B/L	Kg/cm^2 g	5.0
Cooling Water Return Pressure at Plant B/L	Kg/cm^2 g	2.8
Total Circulation Rate	m^3/hr	2100
Total Dissolved Solids (TDS) Limit	ppm	> 3000
Total Suspended Solids (TSS) Limit	ppm	> 50
Turbidity Cooling Water Supply	NTU	> 4.0

Table 12. Design parameters of cooling tower

4.1.3 Height

To calculate height of the cooling tower Merkel's method was used which is an integration of heat and mass transfer for air and water streams and is employed on shell balance on a differential part of cooling tower. Through this method number of transfer units are calculated through the construction of an enthalpy-temperature diagram. The enthalpy of air is calculated against the inlet and outlet temperatures of water. The design conditions of the tower are given in the table below.

Equilibrium Curve

To plot enthalpy-temperature diagram, equilibrium curve has to be drawn first which exists at the saturated conditions between the two phases and hence use of thermodynamic relationships can be used.

From Antoine equation,

$$\ln P_A^v = 11.96481 - \frac{3984.923}{T - 39.724}$$

Rearranging the above equation,

$$P_A^v = \exp\,(11.96481 - \frac{3984.928}{T - 39.724})$$

$$Y' = \left(\frac{P^v}{P - P^v}\right) \times \frac{18.02}{28.97}$$

$$Y' = \left(\frac{P^v}{1 - P^v}\right) \times \frac{18.02}{28.97}$$

Upon substitution and using an empirical equation for enthalpy we have,

$$H_1' = 1.005 + 1.88Y'(T_{G1} - T_0) + 2500Y'$$

$$H_1' = 1.005 + 1.88Y'(47) + 2500Y'$$

$$H_1' = 1.005 + 2588.36Y'$$

This equation is further used to devise a table of taking different temperatures and calculating saturation temperature, humidity and finally enthalpy.

Temp (℃)	$\boldsymbol{Temp\ (K)}$	$\boldsymbol{P_A^v}$	$\boldsymbol{Y'}$	$\boldsymbol{H'}$
21	294	0.024555	0.015658	41.53362
23	296	0.027749	0.017753	46.95674
25	298	0.0313	0.020098	53.02662
27	300	0.03524	0.022721	59.8139
29	302	0.039604	0.02565	67.39704
31	304	0.04443	0.028921	75.86336
33	306	0.049757	0.032571	85.31032
35	308	0.05563	0.036642	95.84694
37	310	0.062094	0.041181	107.5956
39	312	0.069196	0.046241	120.6942
41	314	0.076989	0.051884	135.2985
43	316	0.085528	0.058176	151.5856
45	318	0.09487	0.065197	169.7573

Table 13. Data for equilibrium curve

The graph is then plotted using the table

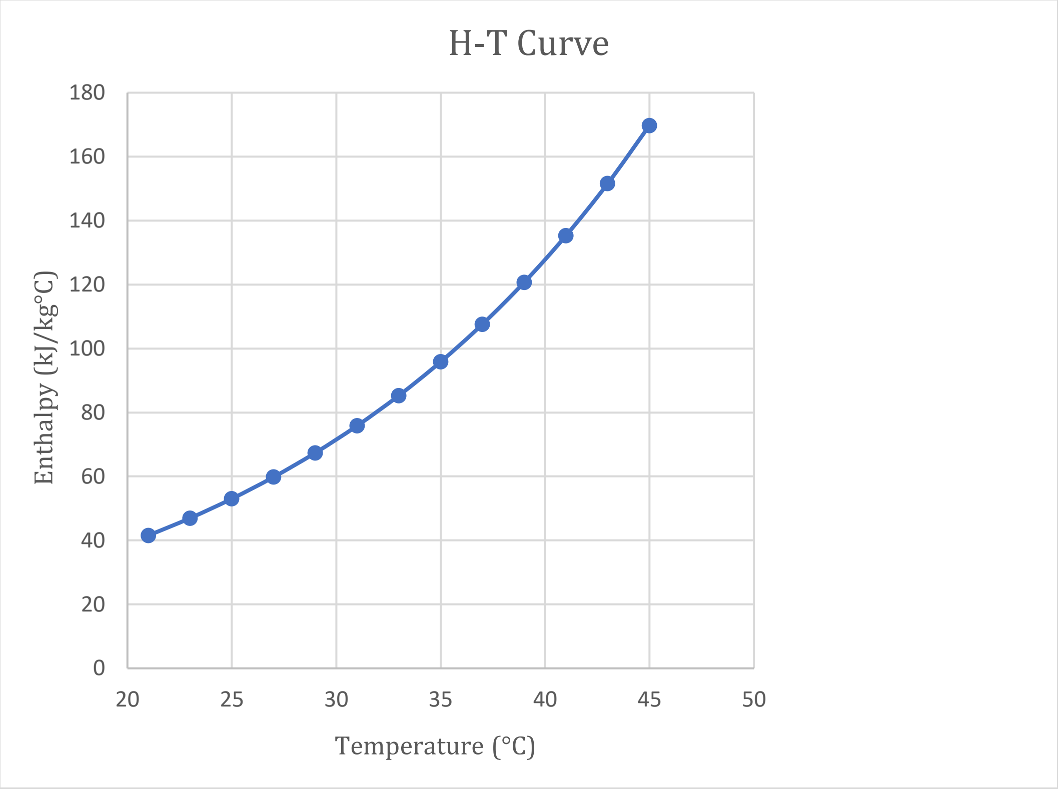


Figure 10. Equilibrium Curve

Air Flow Rate

To calculate the air flow rate, the inlet air enthalpy is first calculated using am empirical relation utilizing humidity and the value for this humidity is read off from the psychometric chart.

Using psychometric chart:

$$Y_1' = 0.019\ kg/kg$$

Enthalpy of cold air entering the bottom of the tower:

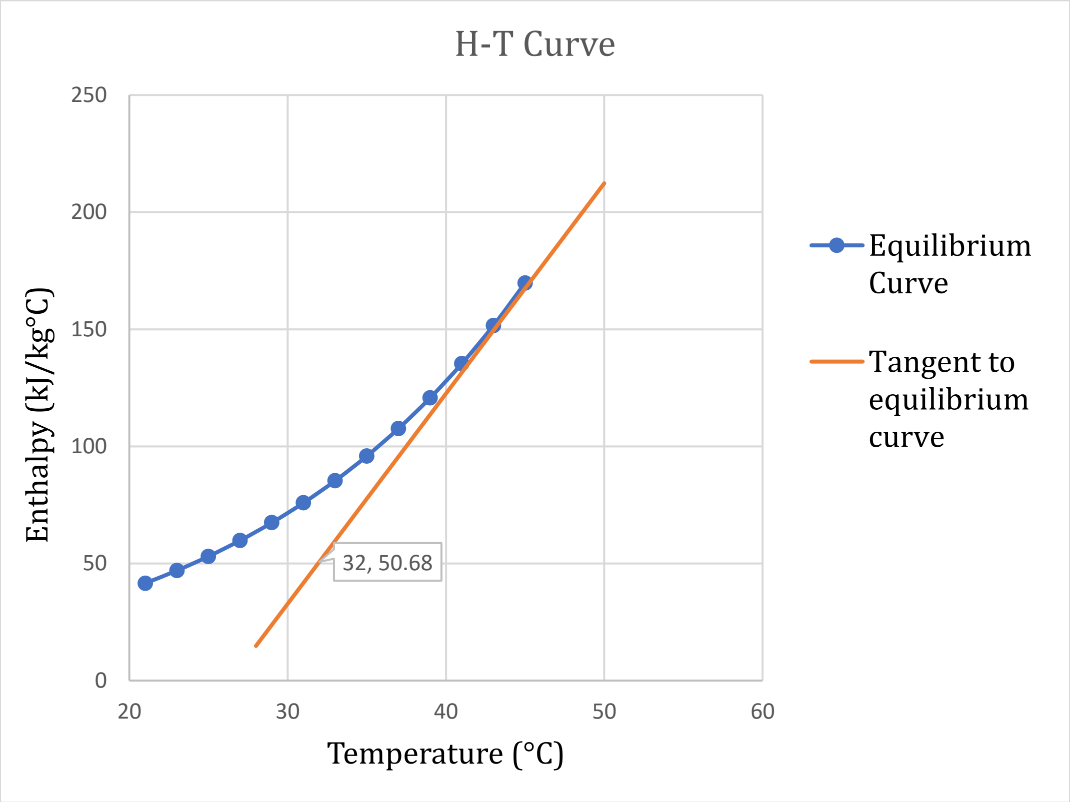
$$H_1' = 1.005 + 1.88Y'(T_{G1} - T_0) + 2500Y'$$

$$H_1' = 1.005 + 1.88(0.019)(47 - 0) + 2500(0.019)$$

$$H_1' = 50.68\ kg/kg$$

A point from these inlet conditions is marked on the graph and a tangent line is drawn from there to the equilibrium curve whose slop is calculated.

Figure 11. Equilibrium Curve and Tangent Line



Slope of tangent line found between (32, 50.68) and (41.5, 136):

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

$$m = \frac{136 - 50.68}{41.5 - 32}$$

$$m = 8.98$$

For the given area and circulation rate, the mass flux of water was calculated:

$$\dot{v}_L = 1725\ m^3/h$$

$$\dot{m} = 1725 \times 1000 = 1.725 \times 10^6\ kg/h$$

For a single cell

$$Area = 18.73\ m^2$$

$$L = \frac{\dot{m}}{A_1} = \frac{1.725 \times 10^6}{18.73}$$

$$L = 9.21 \times 10^4\ kg/m^2h$$

Mass flux of water along with the slope of tangent line were used to find the minimum air flow rate:

$$G_{s,min} = \frac{Lc_{wL}}{slope}$$

$$= \frac{(9.21 \times 10^4)(4.187)}{8.98}$$

$$G_{s,min} = 4.29 \times 10^4\ kg/m^2h$$

To find the actual air flow rate an accepted ratio was used:

$$G_s = 1.25 G_{s,min}$$

$$G_s = 1.25(4.29 \times 10^4\ )$$

$$\boldsymbol{G_s = 5.37 \times 10^4\ kg/m^2h}$$

Operating Line

To draw the operating line, enthalpy of outlet conditions was calculated using energy balance:

$$LC_{wL}(T_{L2} - T_{L1}) = G_S(H_2' - H_1')$$

$$(9.21 \times 10^4)(4.187)(43 - 32) = (5.37 \times 10^4)(H_2' - 50.68)$$

$$H_2' = 129.67 kJ/kg$$

This point is marked on the graph at the outlet temperature of water and a line drawn in between:

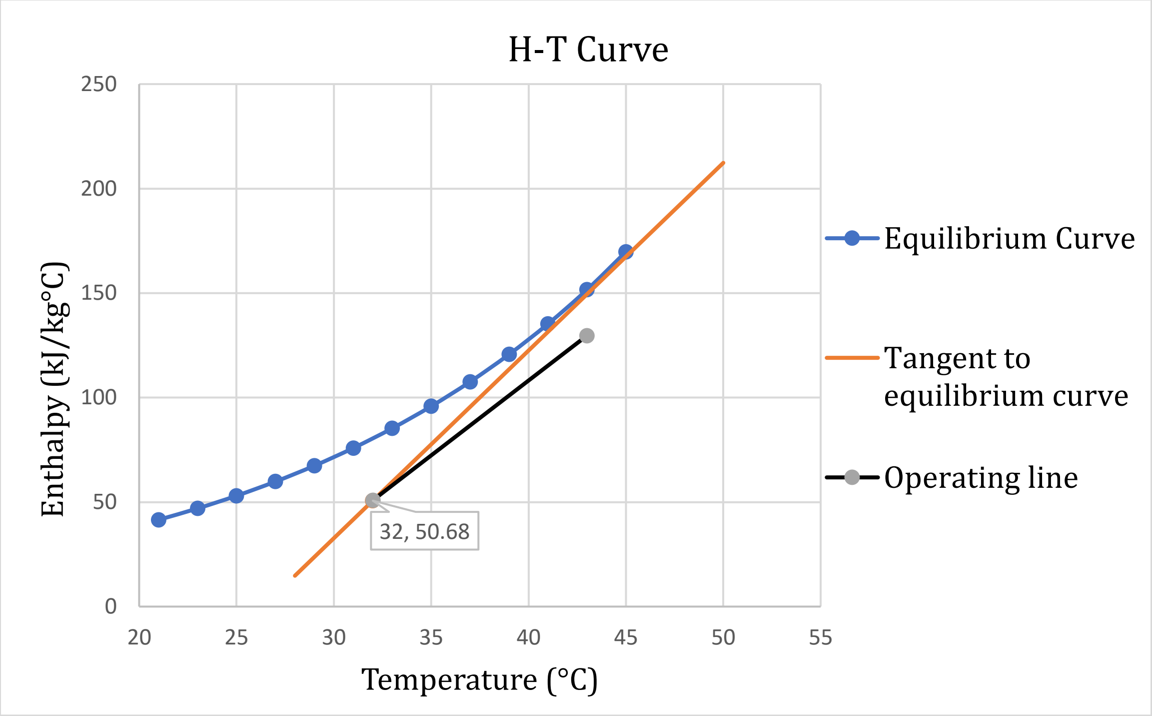


Figure 12. Operating Line

Number of Transfer Units

A number of tie lines were drawn between operating and equilibrium curves using the slopes calculated using the mass and heat transfer empirical equations.

Heat Transfer Coefficient:

$$h_L\bar{a} = 0.059L^{0.51}G_s$$

$$h_L\bar{a} = 0.059(9.21 \times 10^4)^{0.51}(5.37 \times 10^4)$$

$$h_L\bar{a} = 1.078 \times 10^6 \ kJ/m^3K.h$$

Slope of tie line:

$$m' = \frac{-h_L\bar{a}}{k_y\bar{a}}$$

From literature: $k_y\bar{a} = 5743.5 \ kg/m^3h$

$$m' = -\frac{1.078 \times 10^6}{5743.5}$$

$$m' = -87.68$$

From the value of m' it can be concluded that the tie lines are almost vertical.

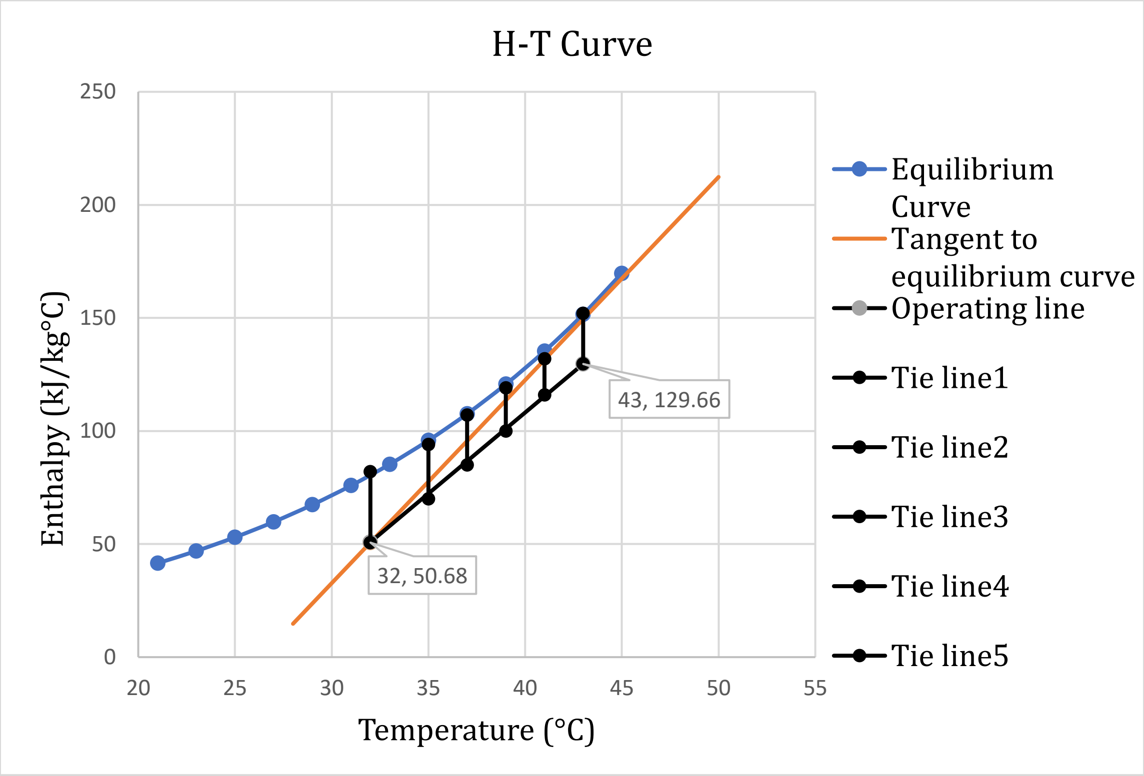


Figure 13 Tie Lines

Enthalpy value between these tie lines were tabulated as follows:

T_L	H'	T_{Li}	H'_i	$\frac{1}{H'_i - H'}$
32	50.68	32	82	0.0319
35	70	35	94	0.0417
37	85	37	107	0.045
39	100	39	119	0.0526
41	116	41	132	0.0625
43	129.70	43	152	0.0447

Table 14. Enthalpy-temperature data from tie lines

A graph was plotted between inverse enthalpy difference and temperature and area under that graph was calculated which gave the number of transfer units.

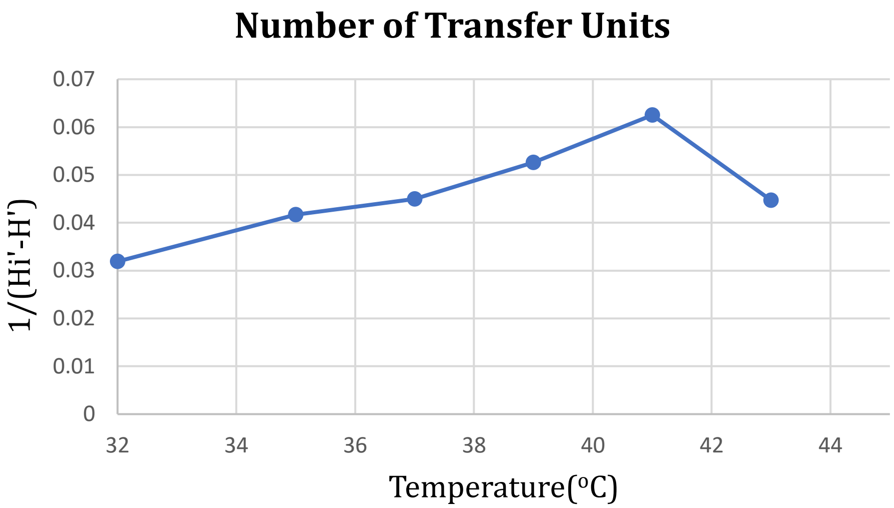


Figure 14. Number *of transfer units*

$$NTU = Area\ under\ the\ graph$$

$$NTU = 0.1104 + 0.0867 + 0.0976 + 0.1151 + 0.1072$$

$$NTU = 0.517$$

Height of the column was found by multiplying NTU with the height of transfer units.

Height of transfer units:

$$HTU = \frac{G_s}{k_y\bar{a}}$$

$$HTU = \frac{5.37 \times 10^4}{2500} = 21.48$$

Height of column

$$H = HTU \times NTU$$

$$H = 21.48 \times 0.517$$

$$H = 11.10m$$

4.1.4 Fills

Splash type fills were used due to their lesser pressure drop and compatibility with contaminated water system at refineries. Film type fills do have greater efficiency, but they are more suitable for systems for clean systems. The height of the fills were calculated using Merkel's number.

From Psychometric Charts

$$Y' = 0.018\frac{kg}{kg}$$

$$h_a = 95\frac{kJ}{kg}$$

Merkel's Number

$$Me = \frac{KaV}{L} = C_p\int_{T_2}^{T_1}\frac{dT}{h_{sa} - h_a}$$

$$Me = 4.18\int_{305}^{316}\frac{dT}{(1.005 + 1.88Y'(T - 0) + 2500Y') - h_a}$$

$$Me = 4.18\int_{305}^{316}\frac{dT}{[1.005 + 1.88(0.018)(T - 0) + 2500(0.018)] - 95}$$

$$Me = 4.18|ln(0.03384T - 48.995)|_{305}^{316}$$

$$Me = -1.19$$

Fill Height

$$Me_{fill\ zone} = 0.3672\ \left(\frac{L}{G}\right)^{-0.2794} h^{0.7}$$

$$-1.19 = 0.3672\ \left(\frac{1.12 \times 10^5}{6.54 \times 10^4}\right)^{-0.2794} h^{0.7}$$

$$h = 6.64m$$

4.1.5 Fan

Fan specifications are crucial for induced draft cooling tower and its specifications calculated using the required air flow rate.

Fan Capacity

$$G_s = 6.54 \times 10^4 \ kg/m^2h$$

$$Area = 18.73 \, m^2$$

$$Q_{Air} = (18.73 \, m^2)\left(6.54 \times 10^4 \ \frac{kg}{m^2h}\right)\left(\frac{1h}{3600s}\right)\left(\frac{m^3}{1.137kg}\right)$$

$$Q_{Air} = 299.26 \frac{m^3}{s}$$

Power required

$$1 \ hp = 8000acfm$$

$$P_f = \frac{F}{8000}$$

$$P_f = \frac{633614.84 \frac{ft^3}{m^3}}{8000 \frac{\frac{ft^3}{m^3}}{hp}}$$

$$P_f = 79.2hp$$

$$\boldsymbol{P_f = 59060.82W}$$

4.1.6 Cooling tower specification sheet

A cooling tower specification sheet is as follows:

EQUIPMENT DATA SHEETS - COOLING TOWER	
COOLING TOWER SPECIFICATION	
DESIGN & OPERATING CONDITION	**SPECIFICATION**
Cooling Tower Type	INDUCED DRAFT
Number of Cooling Tower Cells	3
Heat Load	18.99x106 kcal/hr
Inlet Water Temperature	43°C
Outlet Water Temperature	32°C
Ambient Wet Bulb Temperature	29°C
Total Water Flow Rate	1725 m^3/hr
Water Utility	COOLING WATER
Pump Head	29.98 m
Evaporation Loss	290.32 m^3/hr
Drift Loss	8.63 m^3/hr
Blow Down Loss	134.41 m^3/hr
Water Make-up	433.36 m^3/hr
COOLING TOWER PHYSICAL DIMENSIONS	**SPECIFICATION**
Overall Length	12983.45 mm
Overall Width	4327.81 mm
Height Up To fan deck	9382.92 mm
Total Height	11100 mm
Air Inlet Height	1876.58 mm
Water Inlet Height	7693.99 mm
MATERIAL OF CONSTRUCTION	**SPECIFICATION**
Main Framework	Reinforced Concrete (By Others)
Fan Deck	Reinforced Concrete (By Others)
Fan Cylinder Model: FC 4926-10-1830	FRP Moulded
Infill	PP Opti Grid
Infill Support	SS304 Hangers
Drift Eliminator	PVC
Louver	N/A
Casing	Reinforced Concrete (By Others)
Bolt & Nut	SS316
Stairway	Reinforced Concrete (By Others)
Handrail (Stairway)	HDG Steel for Both Side
Handrail (Fan deck)	HDG Steel
Internal Ladder	HDG Steel
Cage Ladder	N/A
Partition	N/A

Cold Water Basin	N/A
Cold Water Basin Frame	N/A
Basin Sump	N/A
Suction Screen	N/A
Float Valve c/w Ball	N/A
FAN	**SIZE/ SPECIFICATION**
Fan Model	4880-5-33F/33MT
Fan Manufacturer	COFIMCO
Air Volume Required	299.26 m^3/hr
Static Pressure	11.97 mm H2O
No of Fan Blades	5
Fan Pitch Angle To Be Set At	5.6
Fan Blade	FRP
Fan Hub x Keyway	Bore Size: 2.99" Keyway: 3/4" x 3/8"
Fan Discharge Duct	N/A
Fan Machinery Support	HDG Steel
Fan Guard	N/A
Other Instruction for Material of Construction:	
Internal vertical c/w platform from fan deck to above DE level.	
Maintenance walkway c/w handrail inside fan cylinder.	
Access hatch at fan deck	
For supply of embedded material, please refer to document VD-MR-9-1-43	

Table 15. Cooling tower specification sheet

4.2 Filter

A blowdown stream taken out from the cooling tower is passed through a filter and added back to tower as make-up thereby reducing make-up water consumption by maintaining a TDS value.

4.2.1 Design parameters

Particle Diameter of Sand, D_P (m)	0.9×10^{-3}
Density of Water, ρ (kg/m^3)	1000
Density of , ρ_p (kg/m^3)	1560
Viscosity , μ (Pa s)	8.90×10^{-4}
Sphericity , $\emptyset_s$	1.0
Uniformity Co-efficient , λ_O	1.6
TDS of Cooling Water (ppm)	3000
TDS of Makeup Water (ppm)	950

Table 16. Design parameters of filter

4.2.2 Type

A packed bed sand filter was used to purify the stream because:

- The value to dissolved solids has to be reduced from 3000 ppm to 950 ppm and that of suspended solids less than 50ppm. Sand filters have high affinity for the solids and removed them through the mechanism of adsorption.
- They are more cost effective as compared to other technologies such a membrane filter.
- Sand filters are easy to maintain through backwashing and are installed in pairs where one of the filters is in operation while the other is being cleaned.

4.2.3 Bed Length

The length of the packed bed was calculated using concentration difference and uniformity co-efficient for sand.

$$C = C_O \exp(-\lambda_O L)$$

$$950 = 3000 \exp[(-1.6)(L)]$$

$$L = 0.719m$$

4.2.4 Filter Area

Cross-sectional area of the filter was found using ergun equation for minimum fluidization velocity as it marks the limit to which bed remains in fixed state.

Minimum Fluidization Velocity

$$\frac{150\mu\mathbb{V}(1-\varepsilon)}{\emptyset_s^2\, D_p^2\varepsilon^3} + \frac{1.75\rho\mathbb{V}^2}{\emptyset_s D_p\varepsilon^3} = g(\rho_p - \rho)$$

$$\frac{150(8.9\mathrm{x}10^{-4})\mathbb{V}}{(1.0)(0.9x10^{-3})^2(0.41)^3} + \frac{1.75(1000)\mathbb{V}^2}{(1.0)(0.9\mathrm{x}10^{-3})(0.41)^3} = 9.81(1560-1000)$$

$$28212655.71\mathbb{V}^2 + 1410901.478\mathbb{V} - 5493.6 = 0$$

$$\mathbb{V} = 3.63 \mathrm{~x~} 10^{-3}\,\frac{m}{s}$$

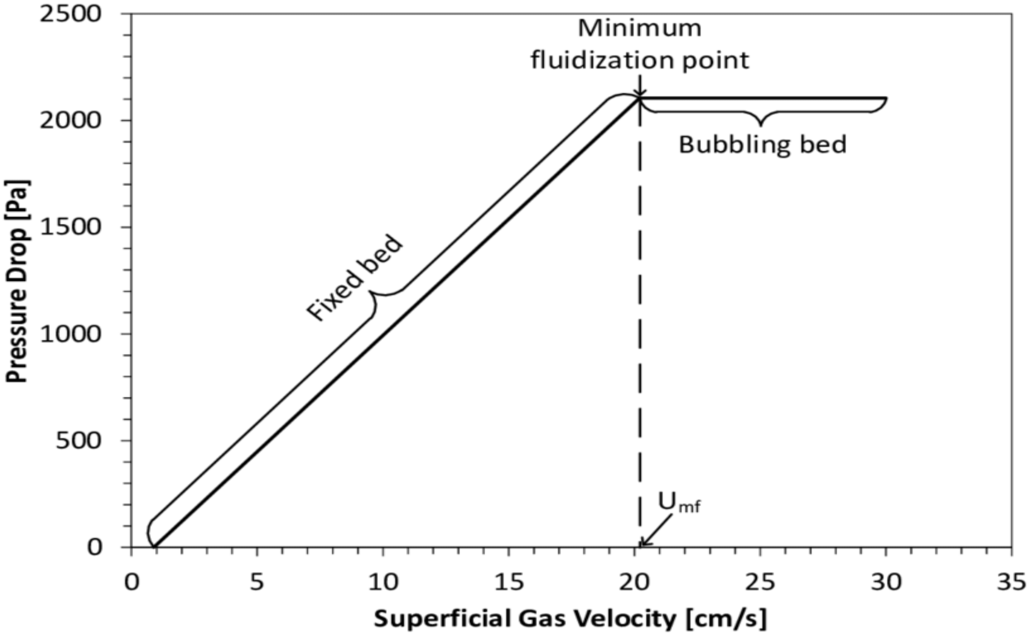


Figure 15. Relation of Pressure drop and Superficial gas velocity in bed column

Area

Minimum fluidization velocity was then incorporated with volumetric flow rate to calculate filter area.

$$Q = \mathbb{V} \text{ x } A$$

$$0.04545 \frac{m^3}{s} = A\left(3.63 \text{ x } 10^{-3} \frac{m}{s}\right)$$

$$A = 12.5m^2$$

4.2.5 Design specification

A list of specifications calculated is as follows:

Filter Type	Packed Bed Filter
Type of Packing	Sand Filter
Bed Length (m)	0.719
Filter Area (m^2)	12.5

Table 17. Design specifications of filter

4.3 Pump

Pumps were incorporated in two streams: make-up water stream to be sent back to the cooling tower and along the cooling water return stream which transport cooling water back to the heat exchanger networks.

4.3.1 Design parameters

Inlet Pressure of Cooling Tower,P_1(Pa)	506625 Pa
Outlet Pressure of Cooling Tower, P_2(Pa)	283710 Pa
Inlet Pressure of Pump, P_a(Pa)	101325 Pa
Outlet Pressure of Pump, P_b(Pa)	395167.5

Table 18. Design parameters of pump

4.3.2 Type

Centrifugal pumps were used in the streams because:

- They employ constant flow rates which are required for the tower inlet and outlet streams
- A high pump head is not required as the pumps are being employed at the same ground level
- Ease of operation which makes maintenance possible.

4.3.3 Pump head

The head required was calculated using Bernoulli's equation.

$$\Delta H = \left(\frac{P_b}{g\rho} + Z_b + \frac{\alpha_b V_b^2}{2g}\right) - \left(\frac{P_a}{g\rho} + Z_a + \frac{\alpha_a V_a^2}{2g}\right)$$

Assuming there are no velocity changes or changes in elevation,

$$\Delta H = \left(\frac{P_b}{g\rho}\right) - \left(\frac{P_a}{g\rho}\right)$$

$$\Delta H = \frac{395167.5 \text{ Pa}}{\left(9.8\frac{m}{s^2}\right)\left(1000\frac{kg}{m^3}\right)} - \frac{101325 \text{ Pa}}{\left(9.8\frac{m}{s^2}\right)\left(1000\frac{kg}{m^3}\right)}$$

$$\Delta H = 29.98m$$

Work Done by the pump

The calculated head was then converted to the work done by pump by multiplying with the mass flow rate and acceleration due to gravity.

Mass flow Rate entering the pump

$$\dot{m} = \rho\dot{v}$$

$$\dot{m} = \left(1000\frac{kg}{m^3}\right)\left(527.56\frac{m^3}{h}\right)$$

$$\dot{m} = 527560\frac{kg}{h}$$

$$\dot{m} = 146.54\frac{kg}{s}$$

$$W_p = \dot{m}gh$$

$$W_p = \left(146.54\frac{kg}{s}\right)\left(9.8\frac{m}{s^2}\right)(29.98m)$$

$$W_p = 43055.34\, W$$

4.3.4 Power required

Power required to operate the pump was calculated assuming an efficiency.

$$\eta = 75\%$$

$$P = \frac{W_p}{\eta}$$

$$P = \frac{43055.34\ W}{0.75}$$

$$P = 57407.12W$$

4.3.5 Net Positive Suction Head

NPSH calculation is crucial for centrifugal pumps to as to prevent cavitation.

$$NPSH = \left(\frac{p_i}{\rho g} + \frac{V_i^2}{2g}\right) - \frac{p_v}{\rho g}$$

$$NPSH = \left[\frac{283710}{(1000)(9.81)} + \frac{29.47}{2(9.81)}\right] - \frac{747.93}{(1000)(9.81)}$$

$$NPSH = 4.35m$$

4.3.6 Design specifications

A list of specifications calculated is as follows:

Type of Pump	Centrifugal Pump
Discharge Pressure (kPa)	506.6
Suction Pressure (kPa)	283.71
Power Required (kW)	57.41
Net Positive Suction Head (m)	4.35

Table 19. Design specifications of pump

4.4 Heat Exchanger

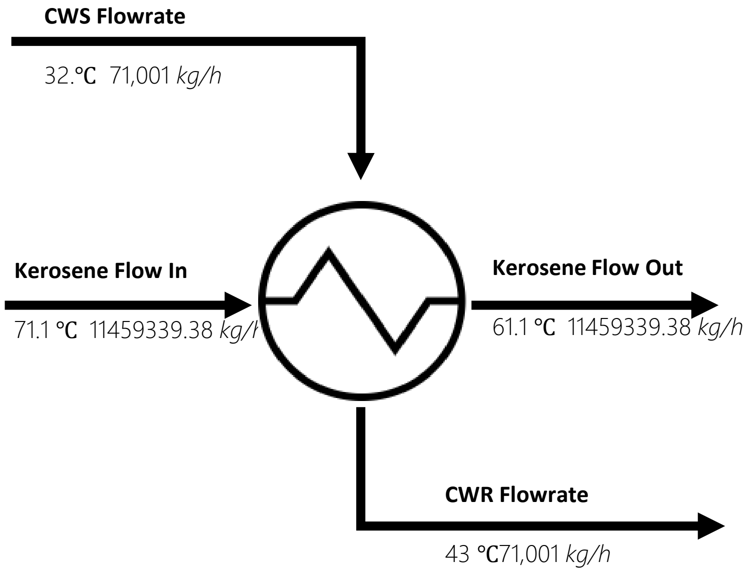
One of the heat exchangers from HBU-I was designed. All the other exchangers from rest of the plants have the same design procedure. The process stream used is kerosene and the calculations were carried out using Kern method where initial assumptions were made and calculations were carried out to determine the dirt factor and pressure drop within the required range.

4.4.1 Type

A 1-2 shell and tube exchanger was selected because:

- Shell and tube is the most common type used in refineries and has easier maintenance
- It is more efficient as compared to double pipe due to higher heat transfer area
- A familiar system which is widely used as compared to other types
- 1-2 type shell and tube has easier construction

4.4.2 Design specifications



Tube Side	**ID (m)**	0.0169
	OD (m)	0.75
	Number	248
	Length(m)	4.879
	Type of Pitch	Square
	Pitch (m)	0.0254
	Passes	2
Shell Side	**ID (m)**	0.5334
	Baffle Spacing (m)	0.2197
	Passes	1

Table 20. Assumptions of heat exchanger

4.4.3 Log-mean temperature difference

LMTD was calculated assuming a counter-flow exchanger configuration and then later corrected using F_T factor specifically for shell and tube.

LMTD

$$\Delta T_{LM} = \frac{\Delta T_2 - \Delta T_1}{ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$$

$$\Delta T_{LM} = \frac{(61.1 - 32) - (71.1 - 43)}{ln\left(\frac{61.1 - 32}{71.1 - 43}\right)}$$

$$\Delta T_{LM} = 28.60°\mathrm{C}$$

F_T Factor

$$R = \frac{71.1 - 61.1}{43 - 32} = 0.909$$

$$S = \frac{t_2 - t_1}{T_1 - t_1} = \frac{43 - 32}{61.1 - 32} = 0.378$$

$$S = \frac{43 - 32}{61.1 - 32} = 0.378$$

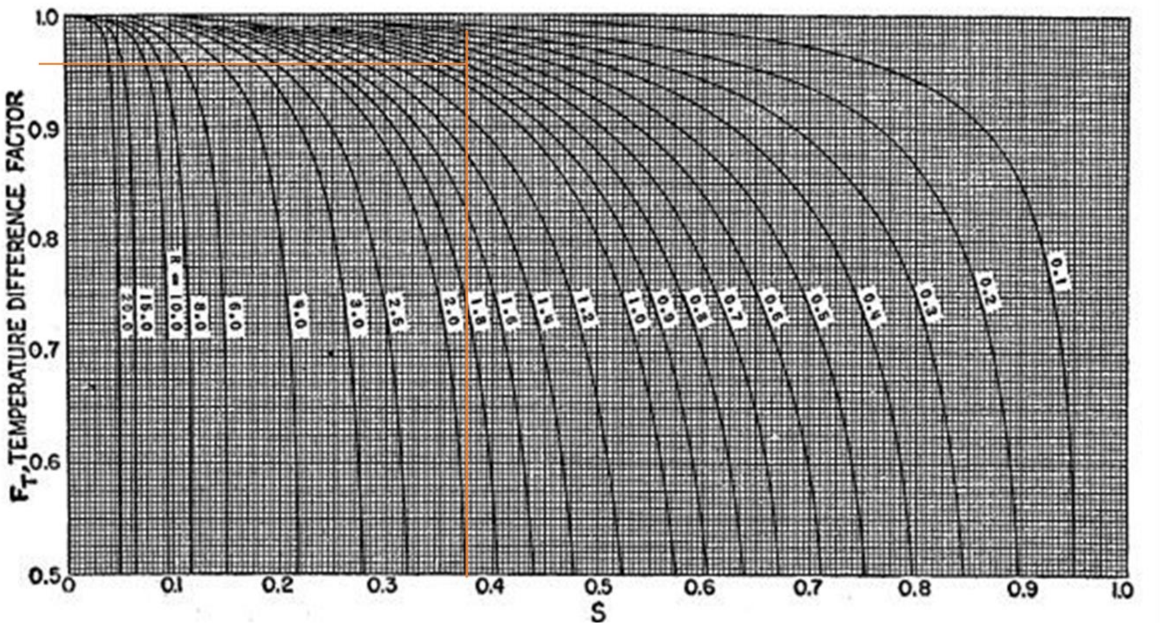


Figure 16. FT Factor for 1-2 Shell and Tube Exchanger

$$F_T = 0.96$$

Corrected LMTD

$$\Delta T_{LM(corrected)} = \Delta T_{LM} \text{ x } F_T$$

$$\Delta T_{LM(corrected)} = 28.60 \text{ x } 0.96$$

$$\Delta T_{LM(corrected)} = 27.456℃$$

4.4.4 Shell side calculations

Flow Area

Flow area on shell side depends upon the internal diameter, pitch and clearance between the tubes and also baffle spacing as it quantifies the area through which the fluid on shell side actually passes through.

$$a_S = ID \text{ x } \frac{C'B}{P_T}$$

$$a_S = 0.5334 \text{ x } \frac{(0.0254 - 0.01905)(0.2197)}{(0.0254)}$$

$$a_S = 0.0293m^2$$

Mass Velocity

Mass velocity or mass flux is the mass flow rate which passes through a unit area.

$$\dot{G}_s = \frac{\dot{m}_s}{a_S}$$

$$\dot{G}_s = \frac{3183.15(\frac{\text{kg}}{\text{s}})}{0.0293m^2}$$

$$\dot{G}_s = 1.086 \text{ x } 10^5 \left(\frac{kg}{m^2 s}\right)$$

Reynold’s Number

$$Re = \frac{D_e \dot{G}_s}{\mu}$$

$$Re = \frac{(0.02413m)\left(1.086\, x\, 10^5 \left(\frac{kg}{m^2 s}\right)\right)}{6.39 \text{ x } 10^{-4} Pa.s}$$

$$Re = 4.10 \text{ x } 10^6$$

4.4.5 Tube side calculations

Flow Area

Flow area on tube side depends upon number and passes of tubes incorporated with the designated flow area on the specific type of tube used.

$$a_t = \frac{No.of\ tubes\ \mathrm{x}\ Flow\ Area/Tube}{No.of\ passes}$$

$$a_t = \frac{248\ \mathrm{x}\ 0.000173}{2}$$

$$a_t = 0.02145m^2$$

Mass Velocity

$$\dot{G}_t = \frac{\dot{m}_t}{a_t}$$

$$\dot{G}_t = \frac{19.722(\frac{\mathrm{kg}}{\mathrm{s}})}{0.02145m^2}$$

$$\dot{G}_t = 9.915\ \mathrm{x}\ 10^2\left(\frac{kg}{m^2s}\right)$$

Reynold’s Number

$$Re = \frac{D\dot{G}_t}{\mu}$$

$$Re = \frac{(0.0148)\left(9.915\ x\ 10^2\left(\frac{kg}{m^2s}\right)\right)}{0.7\ x\ 10^{-3}}$$

$$Re = 2.10\ \mathrm{x}\ 10^4$$

4.4.6 Heat transfer co-efficient on shell side

Reynold's number calculated previously is used to find Chilton and Colburn factor from the extrapolation of the given graph which is further used in an equation along with Nusselt and Prandtl number to calculate the convective heat transfer co-efficient.

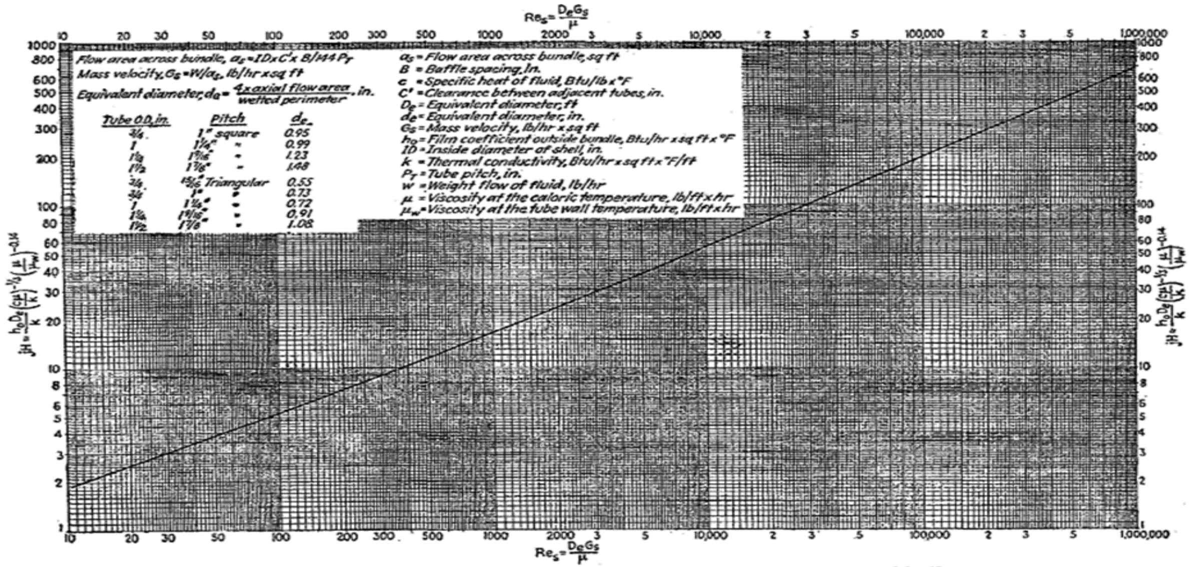


Figure 17. JH Factor on Shell Side

$$J_H = 1400$$

$$h_o = j_H \frac{k}{D_e}\left(\frac{C_p \mu}{k}\right)^{\frac{1}{3}}$$

$$h_o = (1400)\left(\frac{1.33\frac{x\,10^{-4} kW}{m}{}^{\circ}\mathrm{C}}{0.02413m}\right)$$

$$\left[\frac{(2.202kJ/kg{}^{\circ}\mathrm{C})(6.39\,x\,10^{-4} Pa.s)}{1.33\ \mathrm{x}\ 10^{-4} kW/m{}^{\circ}\mathrm{C}}\right]^{\frac{1}{3}}$$

$$h_o = 16.94\frac{kW}{m^2{}^{\circ}\mathrm{C}}$$

4.4.7 Heat transfer co-efficient on tube side

To calculate the heat transfer co-efficient on tube side, another graph was used which is specific for water. Velocity on the tube side was calculated and the value of the co-efficient at the caloric temperature was read off. This was further multiplied for the given internal diameter of the tube.

Velocity

$$v = \frac{\dot{G}_t}{\rho}$$

$$v = \frac{9.915\ x\ 10^2 \left(\frac{kg}{m^2 s}\right)}{1000\,\frac{kg}{m^3}}$$

$$v = 0.9915\,\frac{m}{s} = 3.253\,\frac{ft}{s}$$

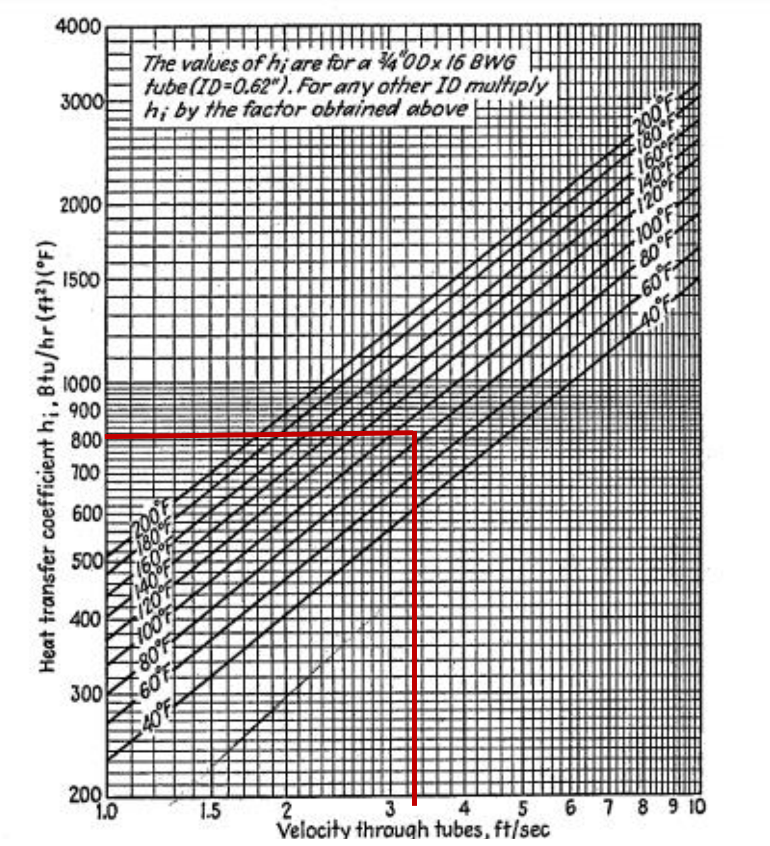


Figure 18. Heat transfer co-efficient on inside the tube for water as fluid

$$h_i = 810 \frac{Btu}{hr(ft)^2 °F}$$

$$h_i = 1.4235 \frac{kW}{m^2 °C}$$

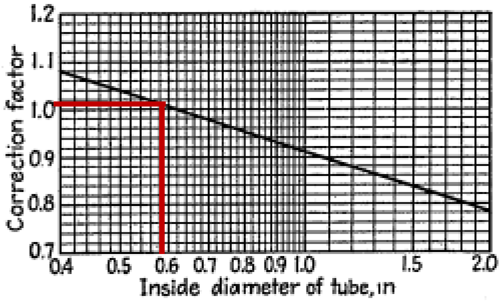


Figure 19. Correction factor for the heat transfer co-efficient

$$Correction\ factor = 1.02$$

Heat transfer co-efficient on the inner side of tube was

$$h_i = 1.02 \text{ x } 4.599 \frac{kW}{m^2 °C}$$

$$h_i = 1.452 \frac{kW}{m^2 °C}$$

Inner side co-efficient was used to find the co-efficient on the outer side of tubes due to the heat transfer from the tube using a ration of the diameters.

$$h_{io} = h_i \text{ x } \frac{ID}{OD}$$

$$h_{io} = \left(1.452 \frac{kW}{m^2 °C}\right) \text{ x } \frac{0.0148m}{0.01905m}$$

$$h_{io} = 1.128 \frac{kW}{m^2 °C}$$

4.4.8 Clean heat transfer co-efficient

Using both the co-efficients on shell and tube side, clean heat transfer co-efficient along the whole exchanger was found.

$$U_c = \frac{h_{io} h_o}{h_{io} + h_o}$$

$$U_c = \frac{(1.128)(16.94)}{1.128 + 16.94}$$

$$U_c = 1.923 \frac{kW}{m^2 °\mathrm{C}}$$

4.4.9 Heat Transfer Area

Overall heat transfer area comprised of the outside area of all the tubes.

$$External\ Surface, a'' = 0.0142 m^2/m$$

$$A = No. of\ tubes \text{ x } Length\ of\ tuibe \text{ x } External\ Surface$$

$$A = 248 \text{ x } 4.879 m \text{ x } 0.0142 m^2/m$$

$$A = 17.18 m^2$$

4.4.10 Design Co-efficient

Using the heat load equation for the whole exchanger, design heat transfer co-efficient was calculated.

$$Q = U_D A \Delta T_{LM(corrected)}$$

$$906.84 \frac{kJ}{s} = U_D (17.18 m^2)(27.456 °\mathrm{C})$$

$$U_D = 1.922 \frac{kW}{m^2 °\mathrm{C}}$$

4.4.11 Dirt Factor

Inverse of the clean and design co-efficients gives the overall resistance to heat transfer. Using the principle of resistors connected in parallel the dirt factor was calculated which came out to be within the allowable range.

$$R_D = \frac{U_C - U_D}{U_C U_D}$$

$$R_D = \frac{1.923 - 1.922}{(1.923)(1.922)}$$

$$R_D = 0.000275$$

4.4.12 Pressure drop on shell side

Pressure drop calculations were carried out on both shell and tube side to determine whether the pressure drop due to flow or heat transfer was within the allowable range of 10psi.

- **Friction Factor**

The following graph was extrapolated to find the friction factor on shell side.

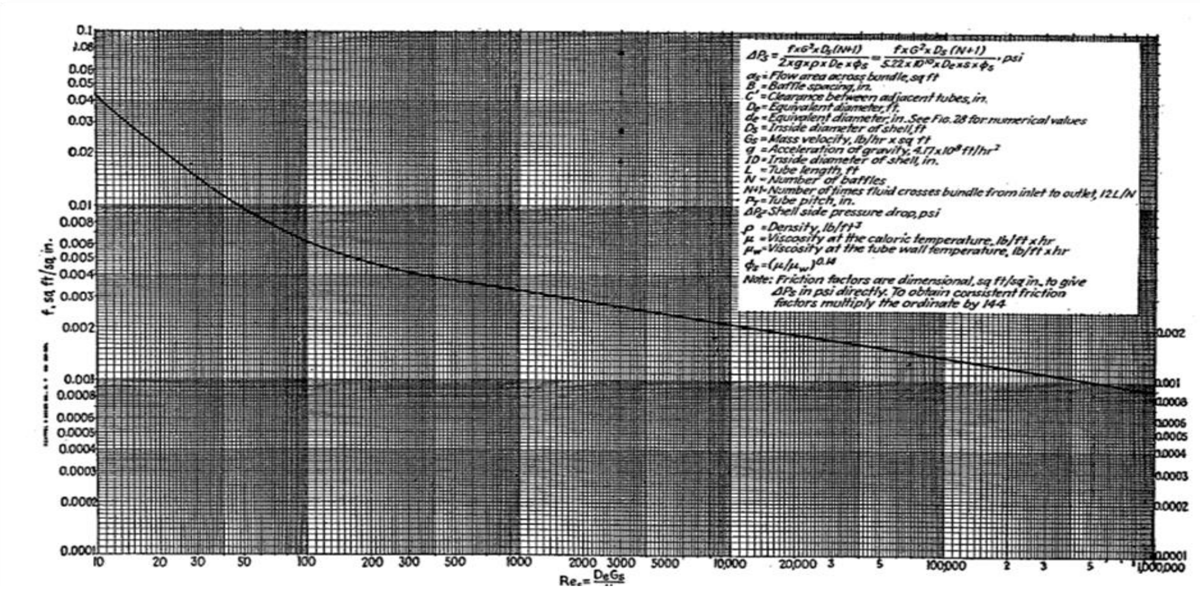


Figure 20. Friction factor on shell side

$$f = 0.0004\frac{ft^2}{in^2}$$

- **Number of crosses**

Number of crosses quantities the number of times the fluid on shell side changes direction due to the installation of baffles.

$$N + 1 = 12\frac{L}{B}$$

$$N + 1 = 12\left(\frac{16}{8.66}\right)$$

$$N + 1 = 22$$

- **Pressure drop**

$$\Delta P_S = \frac{fG_s^2D(N+1)}{5.22 \text{ x } 10^{10}D_e s\emptyset_s}$$

$$\Delta P_S = \frac{(0.0004)(1437475.913)^2(1.75)(22)}{5.22\, x\, 10^{10}(0.07917)(1.0)(1.0)}$$

$$\Delta P_S = 7.7\, psi$$

4.4. 13 Pressure drop on tube side

- **Friction Factor**

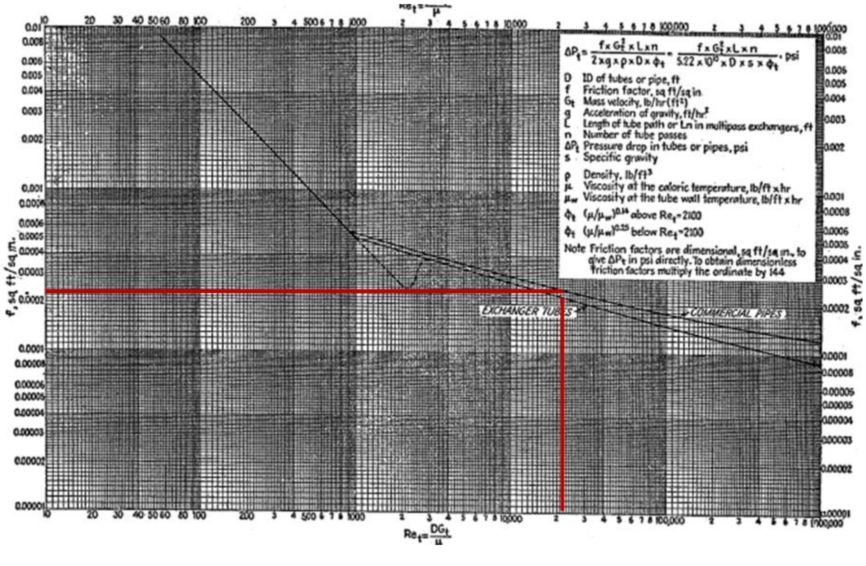


Figure 21. Friction factor on tube side

$$f = 0.00022\frac{ft^2}{in^2}$$

- **Pressure drop due to tubes**

$$\Delta P_t = \frac{fG_t^2Ln}{5.22\text{ x }10^{10}Ds\ \emptyset_s}$$

$$\Delta P_t = \frac{(0.00022)(731070.2304)^2(16)(2)}{5.22\ x\ 10^{10}(0.04856)(1.0)(1.0)}$$

$$\Delta P_t = 1.48psi$$

- **Pressure drop due to flow**

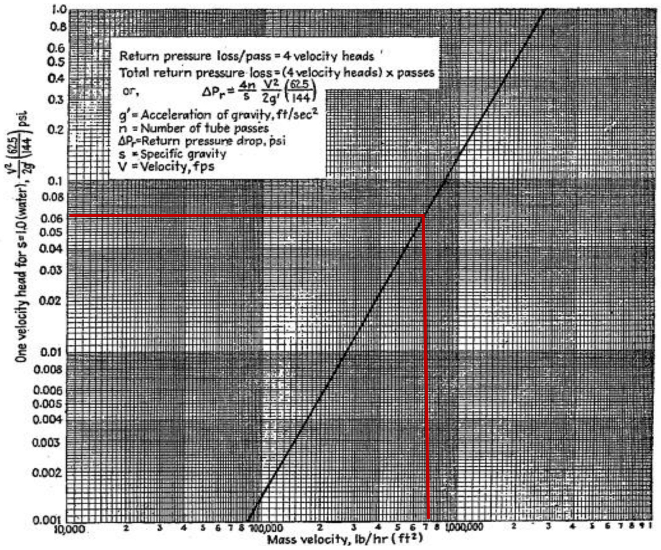


Figure 22. Pressure drop due to flow

$$\Delta P_r = \frac{4n}{s}\left(\frac{V^2}{2g}\right)$$

$$\Delta P_r = \frac{4\text{ x }2}{1}(0.06)$$

$$\Delta P_r = 0.48psi$$

- **Total ΔP**

Total pressure drop is a summation of the drop due to tubes and flow.

$$\Delta P = 1.96psi$$

CHAPTER 5

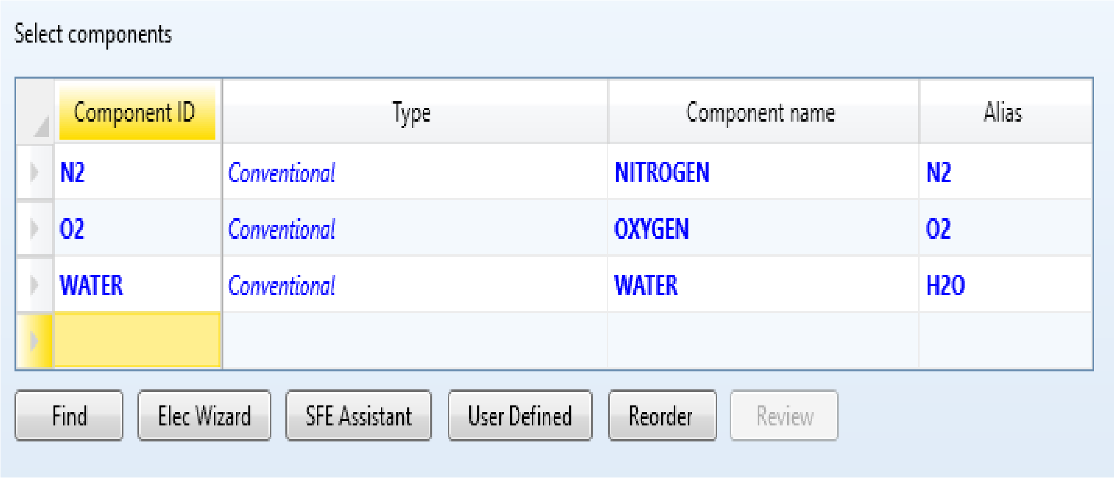
Process Modelling and Simulation

5.1 Cooling Tower Simulation

Simulation of our project was done using two softwares. The cooling tower was simulated on Aspen Plus while the exchanger networks of each plant were simulated using Aspen Energy Analyzer. The results obtained were in accordance with the values calculated by performing design as well as material and energy balance calculations.

5.1.1 Selection of components

The components were selected from the Aspen Plus library. The air stream was added in the form of O_2 and N_2 components, the composition of which was specified later in the simulation stage.



Component ID	Type	Component name	Alias
N2	Conventional	NITROGEN	N2
O2	Conventional	OXYGEN	O2
WATER	Conventional	WATER	H2O

Figure 23. Component Lists

5.1.2 Selecting the Henry components

The gas components are selected as henry components which further plays a part in specifying the property method.

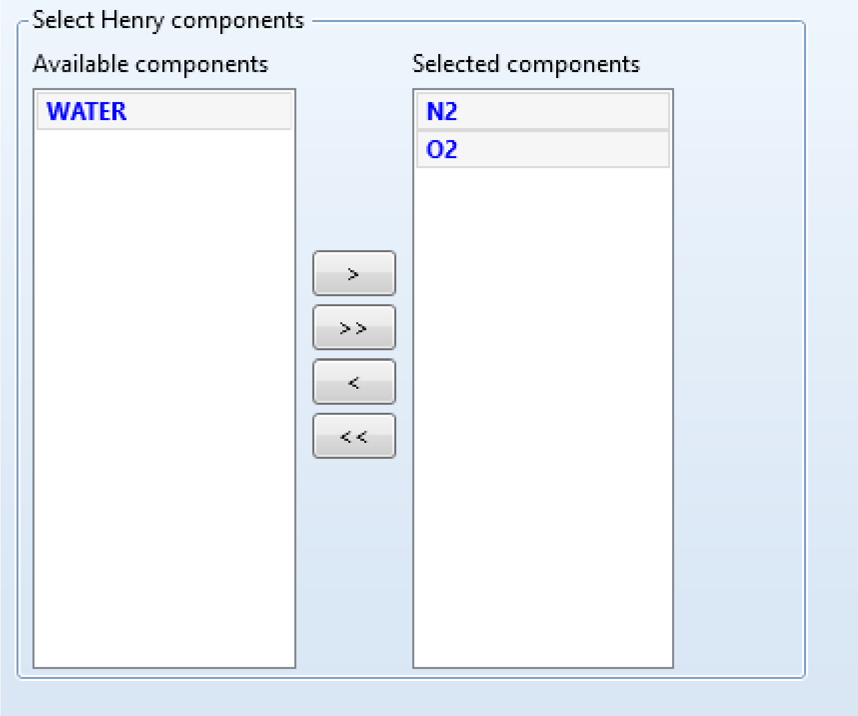
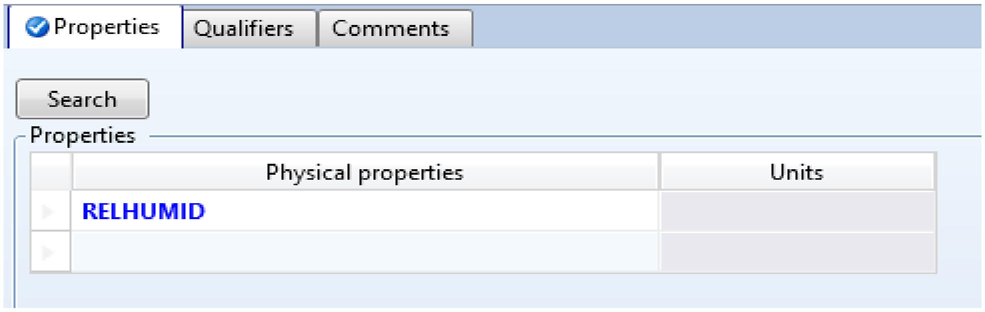


Figure 24. Henry Components

5.1.3 Adding the property set

From a set of different properties relative humidity is chosen which plays a role as the design basis of the simulation of our cooling tower.

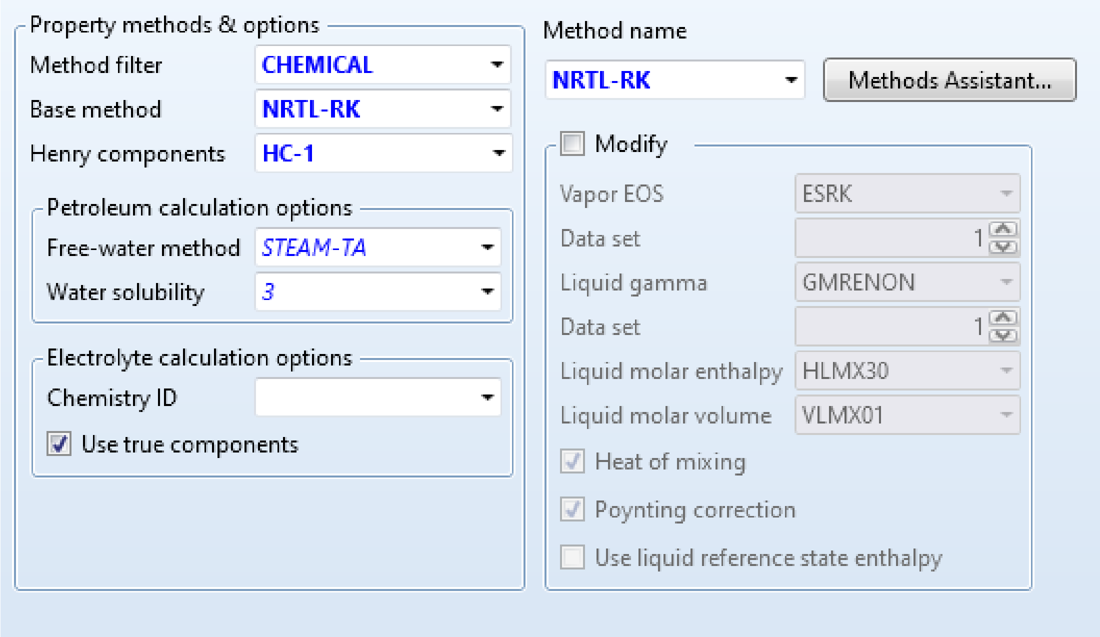


Physical properties	Units
RELHUMID	

Figure 25. Property Set

5.1.4 Adding the property method

Selecting the suitable property method is often the important decision in deciding the accuracy of your simulation results. The fluid package selected was NRTL-RK, because it was compatible with the selection of components as well as the range of the pressure used which was less than 10 bar.



Property methods & options
Method filter: CHEMICAL
Base method: NRTL-RK
Henry components: HC-1

Petroleum calculation options
Free-water method: STEAM-TA
Water solubility: 3

Electrolyte calculation options
Chemistry ID:
☑ Use true components

Method name: NRTL-RK

☐ Modify
Vapor EOS: ESRK
Data set: 1
Liquid gamma: GMRENON
Data set: 1
Liquid molar enthalpy: HLMX30
Liquid molar volume: VLMX01
☑ Heat of mixing
☑ Poynting correction
☐ Use liquid reference state enthalpy

Figure 26. Property Method

5.1.5 Process Flowsheet Modelling and Simulation

The Rad-frac column was simulated as cooling tower as the equipment required for our system was not directly available in the model palette. The design and working conditions were fed and the cooling tower system was simulated.

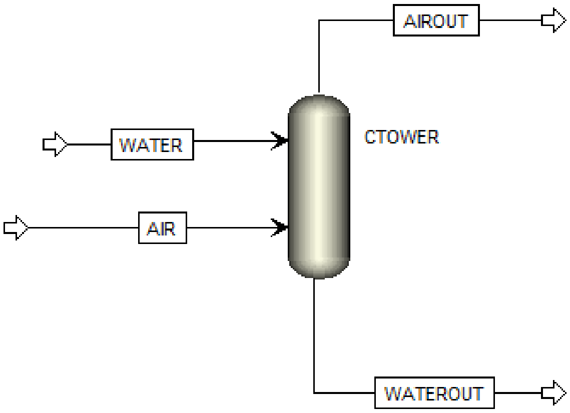
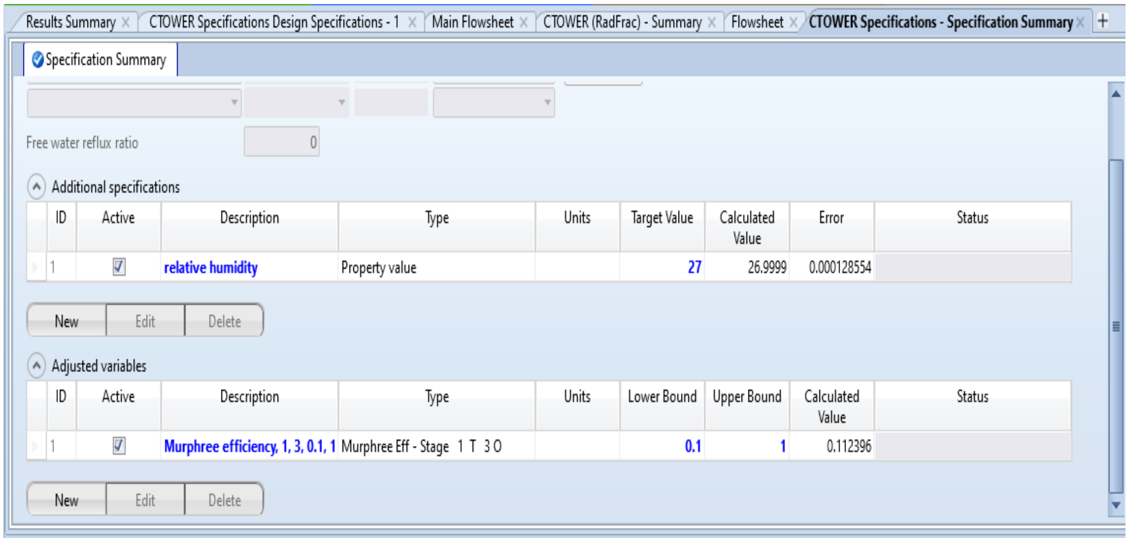


Figure 27. Process Flowsheet

5.1.6 Results

The cooling tower was simulated for the desired value of Relative Humidity vale, which was obtained at our cooling tower operation conditions. The relative humidity value was found using the psychometric charts which was 27%. The cooling tower was simulated for this value of relative humidity; The simulated value calculated by Aspen Plus at our design conditions was 26.999% giving an error of 0.000128 only.



Free water reflux ratio 0

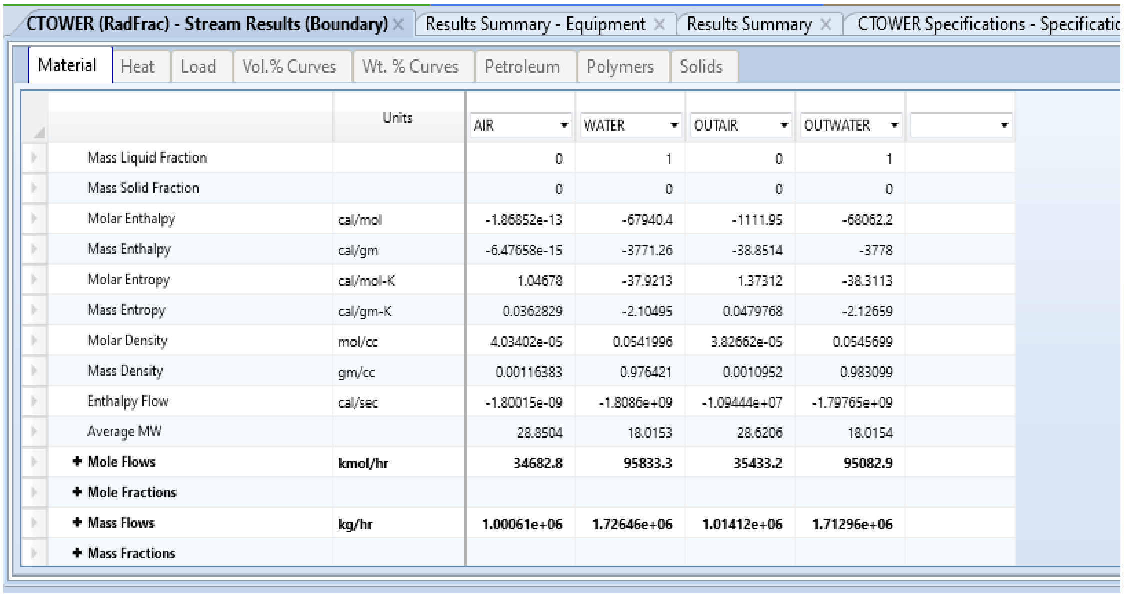
Additional specifications

ID	Active	Description	Type	Units	Target Value	Calculated Value	Error	Status
1	☑	relative humidity	Property value		27	26.9999	0.000128554	

Adjusted variables

ID	Active	Description	Type	Units	Lower Bound	Upper Bound	Calculated Value	Status
1	☑	Murphree efficiency, 1, 3, 0.1, 1	Murphree Eff - Stage 1 T 3 O		0.1	1	0.112396	

Figure 28. Specifications Summary



	Units	AIR	WATER	OUTAIR	OUTWATER	
Mass Liquid Fraction		0	1	0	1	
Mass Solid Fraction		0	0	0	0	
Molar Enthalpy	cal/mol	-1.86852e-13	-67940.4	-1111.95	-68062.2	
Mass Enthalpy	cal/gm	-6.47658e-15	-3771.26	-38.8514	-3778	
Molar Entropy	cal/mol-K	1.04678	-37.9213	1.37312	-38.3113	
Mass Entropy	cal/gm-K	0.0362829	-2.10495	0.0479768	-2.12659	
Molar Density	mol/cc	4.03402e-05	0.0541996	3.82662e-05	0.0545699	
Mass Density	gm/cc	0.00116383	0.976421	0.0010952	0.983099	
Enthalpy Flow	cal/sec	-1.80015e-09	-1.8086e+09	-1.09444e+07	-1.79765e+09	
Average MW		28.8504	18.0153	28.6206	18.0154	
+ Mole Flows	**kmol/hr**	**34682.8**	**95833.3**	**35433.2**	**95082.9**	
+ Mole Fractions						
+ Mass Flows	**kg/hr**	**1.00061e+06**	**1.72646e+06**	**1.01412e+06**	**1.71296e+06**	
+ Mass Fractions						

Figure 29. Streams results

5.2 Heat Exchangers Simulation

Aspen Energy Analyzer was used to simulate heat exchanger networks to find out the optimized design configurations with increased heat integration projects while significantly decreasing design, operating, and capital costs, and minimizing energy-related emissions. The section below covers the simulation of all exchanger networks supplying cooling water to five process plants. The process stream of within each plant is sown by the red lines and the blue lines configuration represents the cooling water streams with heat exchanger connecting the hot and cold streams.

5.2.1 Reformer

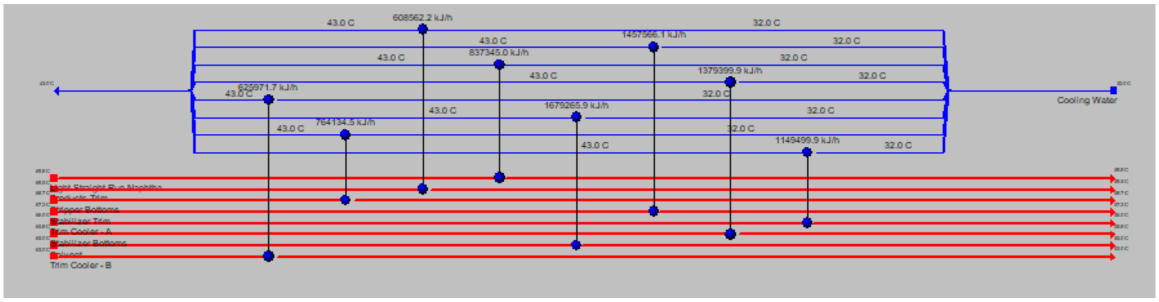
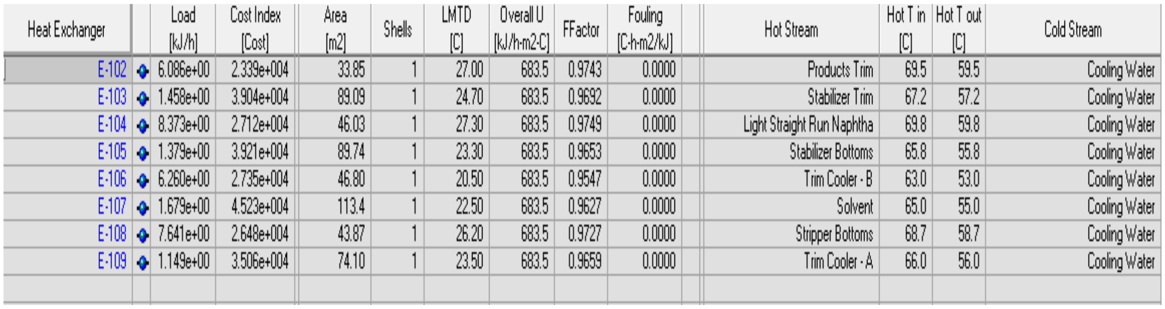


Figure 30. Recommended exchanger network for reformer

The recommended exchanger design for reformer on Aspen energy analyzer included eights heat exchangers with total heat transfer area of 274572.9429 m^2 the simulation also included the load of each exchanger which was in accordance with the manual calculation done in the material and energy balance section.



Heat Exchanger		Load [kJ/h]	Cost Index [Cost]	Area [m2]	Shells	LMTD [C]	Overall U [kJ/h-m2-C]	FFactor	Fouling [C-h-m2/kJ]	Hot Stream	Hot T in [C]	Hot T out [C]	Cold Stream
E-102	◆	6.086e+00	2.339e+004	33.85	1	27.00	683.5	0.9743	0.0000	Products Trim	69.5	59.5	Cooling Water
E-103	◆	1.458e+00	3.904e+004	89.09	1	24.70	683.5	0.9692	0.0000	Stabilizer Trim	67.2	57.2	Cooling Water
E-104	◆	8.373e+00	2.712e+004	46.03	1	27.30	683.5	0.9749	0.0000	Light Straight Run Naphtha	69.8	59.8	Cooling Water
E-105	◆	1.379e+00	3.921e+004	89.74	1	23.30	683.5	0.9653	0.0000	Stabilizer Bottoms	65.8	55.8	Cooling Water
E-106	◆	6.260e+00	2.735e+004	46.80	1	20.50	683.5	0.9547	0.0000	Trim Cooler - B	63.0	53.0	Cooling Water
E-107	◆	1.679e+00	4.523e+004	113.4	1	22.50	683.5	0.9627	0.0000	Solvent	65.0	55.0	Cooling Water
E-108	◆	7.641e+00	2.648e+004	43.87	1	26.20	683.5	0.9727	0.0000	Stripper Bottoms	68.7	58.7	Cooling Water
E-109	◆	1.149e+00	3.506e+004	74.10	1	23.50	683.5	0.9659	0.0000	Trim Cooler - A	66.0	56.0	Cooling Water

Figure 31. Exchanger design specifications for reformer

5.2.2 Hydro Cracking Unit

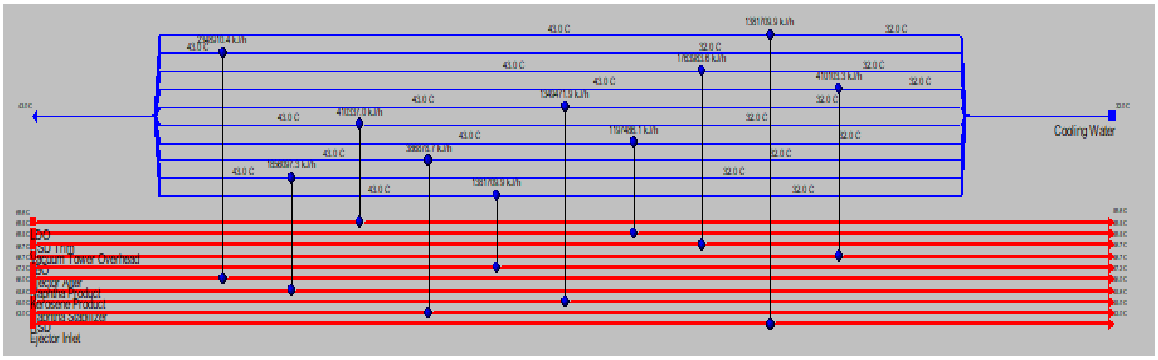
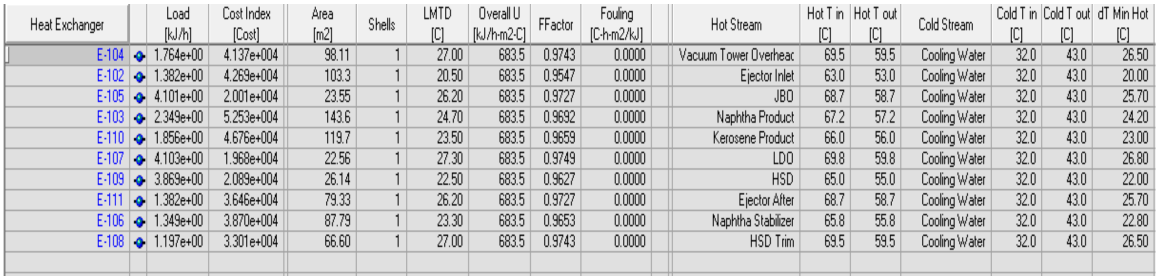


Figure 32. Recommended exchanger network for HCU

The recommended exchanger design for reformer on Aspen energy analyzer included eights heat exchangers with total heat transfer area of 376629.4286 m^2 the simulation also included the load of each exchanger which was in accordance with the manual calculation done in the material and energy balance section.



Heat Exchanger		Load [kJ/h]	Cost Index [Cost]	Area [m2]	Shells	LMTD [C]	Overall U [kJ/h-m2-C]	FFactor	Fouling [C-h-m2/kJ]	Hot Stream	Hot T in [C]	Hot T out [C]	Cold Stream	Cold T in [C]	Cold T out [C]	dT Min Hot [C]
E-104	◆	1.764e+00	4.137e+004	98.11	1	27.00	683.5	0.9743	0.0000	Vacuum Tower Overheac	69.5	59.5	Cooling Water	32.0	43.0	26.50
E-102	◆	1.382e+00	4.269e+004	103.3	1	20.50	683.5	0.9547	0.0000	Ejector Inlet	63.0	53.0	Cooling Water	32.0	43.0	20.00
E-105	◆	4.101e+00	2.001e+004	23.55	1	26.20	683.5	0.9727	0.0000	JBO	68.7	58.7	Cooling Water	32.0	43.0	25.70
E-103	◆	2.349e+00	5.253e+004	143.6	1	24.70	683.5	0.9692	0.0000	Naphtha Product	67.2	57.2	Cooling Water	32.0	43.0	24.20
E-110	◆	1.856e+00	4.676e+004	119.7	1	23.50	683.5	0.9659	0.0000	Kerosene Product	66.0	56.0	Cooling Water	32.0	43.0	23.00
E-107	◆	4.103e+00	1.968e+004	22.56	1	27.30	683.5	0.9749	0.0000	LDO	69.8	59.8	Cooling Water	32.0	43.0	26.80
E-109	◆	3.869e+00	2.089e+004	26.14	1	22.50	683.5	0.9627	0.0000	HSD	65.0	55.0	Cooling Water	32.0	43.0	22.00
E-111	◆	1.382e+00	3.646e+004	79.33	1	26.20	683.5	0.9727	0.0000	Ejector After	68.7	58.7	Cooling Water	32.0	43.0	25.70
E-106	◆	1.349e+00	3.870e+004	87.79	1	23.30	683.5	0.9653	0.0000	Naphtha Stabilizer	65.8	55.8	Cooling Water	32.0	43.0	22.80
E-108	◆	1.197e+00	3.301e+004	66.60	1	27.00	683.5	0.9743	0.0000	HSD Trim	69.5	59.5	Cooling Water	32.0	43.0	26.50

Figure 33. Exchanger design specifications for HCU

5.2.3 LUMMUS

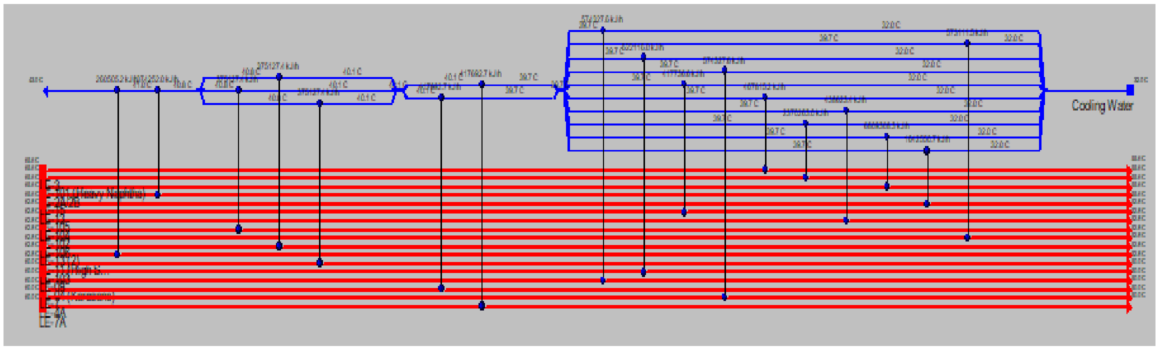


Figure 34. Recommended exchanger network for LUMMUS

The recommended exchanger design for reformer on Aspen energy analyzer included eights heat exchangers with total heat transfer area of 556834.2857 m^2 the simulation also included the load of each exchanger which was in accordance with the manual calculation done in the material and energy balance section.

Heat Exchanger		Load [kJ/h]	Cost Index [Cost]	Area [m2]	Shells	LMTD [C]	Overall U [kJ/h-m2-C]	FFactor	Fouling [C-h-m2/kJ]	Hot Stream	Hot T in [C]	Hot T out [C]	Cold Stream	Cold T in [C]	Cold T out [C]	dT Min Hot [C]	dT Min Cold [C]
E-109	◆	3.751e+00	2.298e+004	32.57	1	16.91	683.5	0.9964	0.0000	LE-102	62.8	52.8	Cooling Water	40.1	40.8	22.03	12.65
E-107	◆	3.743e+00	2.162e+004	28.37	1	19.32	683.5	0.9991	0.0000	LE-15	65.6	55.6	Cooling Water	40.8	41.0	24.60	14.85
E-122	◆	1.643e+00	4.169e+004	99.37	1	24.71	683.5	0.9787	0.0000	LE-13	65.6	55.6	Cooling Water	32.0	39.7	25.85	23.60
E-112	◆	4.177e+00	2.595e+004	42.13	1	14.56	683.5	0.9964	0.0000	LE-7	60.0	50.0	Cooling Water	39.7	40.1	19.85	10.30
E-114	◆	5.731e+00	2.509e+004	39.33	1	21.92	683.5	0.9727	0.0000	LE-106	62.8	52.8	Cooling Water	32.0	39.7	23.08	20.80
E-108	◆	3.751e+00	2.298e+004	32.57	1	16.91	683.5	0.9964	0.0000	LE-13 (2)	62.8	52.8	Cooling Water	40.1	40.8	22.03	12.65
E-110	◆	3.751e+00	2.298e+004	32.57	1	16.91	683.5	0.9964	0.0000	LE-103	62.8	52.8	Cooling Water	40.1	40.8	22.03	12.65
E-113	◆	5.743e+00	2.699e+004	45.58	1	19.13	683.5	0.9638	0.0000	LE-04 (Kerosene)	60.0	50.0	Cooling Water	32.0	39.7	20.30	18.00
E-115	◆	5.221e+00	2.574e+004	41.44	1	19.13	683.5	0.9638	0.0000	LE-09	60.0	50.0	Cooling Water	32.0	39.7	20.30	18.00
E-117	◆	4.177e+00	2.172e+004	28.65	1	21.93	683.5	0.9727	0.0000	LE-105	62.8	52.8	Cooling Water	32.0	39.7	23.10	20.80
E-116	◆	5.743e+00	2.699e+004	45.58	1	19.13	683.5	0.9638	0.0000	LE-4A	60.0	50.0	Cooling Water	32.0	39.7	20.30	18.00
E-118	◆	4.678e+00	2.160e+004	28.30	1	24.71	683.5	0.9787	0.0000	LE-3	65.6	55.6	Cooling Water	32.0	39.7	25.85	23.60
E-120	◆	2.370e+00	5.249e+004	143.4	1	24.71	683.5	0.9787	0.0000	LE-101 (Heavy Naphtha)	65.6	55.6	Cooling Water	32.0	39.7	25.85	23.60
E-106	◆	2.605e+00	1.998e+004	23.44	1	16.28	683.5	0.9991	0.0000	LE-11 (High Speed Diese	62.8	52.8	Cooling Water	41.0	41.1	21.69	11.85
E-111	◆	4.177e+00	2.595e+004	42.13	1	14.56	683.5	0.9964	0.0000	LE-7A	60.0	50.0	Cooling Water	39.7	40.1	19.85	10.30
E-119	◆	4.386e+00	2.218e+004	30.08	1	21.93	683.5	0.9727	0.0000	LE-104	62.8	52.8	Cooling Water	32.0	39.7	23.10	20.80
E-121	◆	6.809e+00	1.088e+005	411.9	1	24.71	683.5	0.9787	0.0000	LE-2A/2B	65.6	55.6	Cooling Water	32.0	39.7	25.85	23.60

Figure 35. Exchanger design specifications for LUMMUS

5.2.4 HBU – I

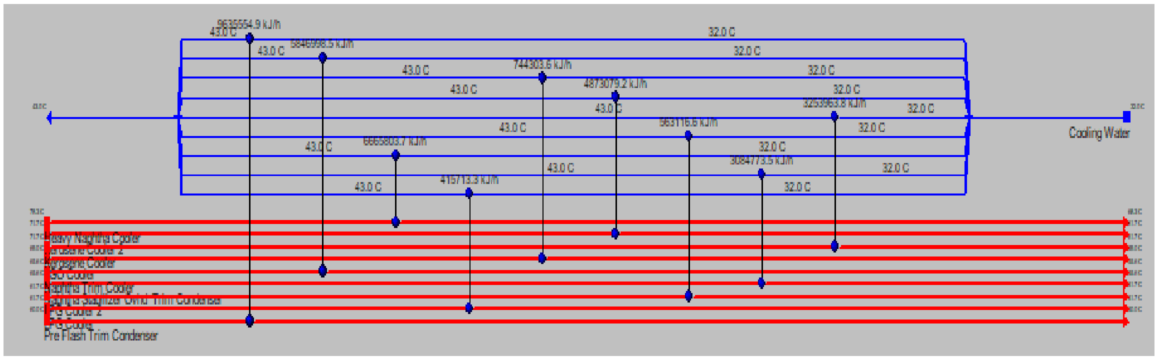


Figure 36. Recommended exchanger network for HBU-I

The recommended exchanger design for reformer on Aspen energy analyzer included eights heat exchangers with total heat transfer area of 591317.1429 m^2 the simulation also included the load of each exchanger which was in accordance with the manual calculation done in the material and energy balance section.

Heat Exchanger		Load [kJ/h]	Cost Index [Cost]	Area [m2]	Shells	LMTD [C]	Overall U [kJ/h-m2-C]	FFactor	Fouling [C-h-m2/kJ]	Hot Stream	Hot T in [C]	Hot T out [C]	Cold Stream	Cold T in [C]	Cold T out [C]	dT Min Hot [C]
E-102	◆	9.636e+00	2.146e+005	860.0	2	17.50	683.5	0.9369	0.0000	Pre Flash Trim Condenser	60.0	50.0	Cooling Water	32.0	43.0	17.00
E-103	◆	5.847e+00	1.035e+005	384.3	1	23.07	683.5	0.9647	0.0000	Naphtha Trim Cooler	65.6	55.6	Cooling Water	32.0	43.0	22.56
E-108	◆	6.666e+00	8.185e+004	276.5	1	35.79	683.5	0.9855	0.0000	Heavy Naphtha Cooler	78.3	68.3	Cooling Water	32.0	43.0	35.28
E-110	◆	4.157e+00	2.326e+004	33.44	1	19.18	683.5	0.9482	0.0000	LPG Cooler	61.7	51.7	Cooling Water	32.0	43.0	18.67
E-104	◆	7.443e+00	2.598e+004	42.22	1	26.50	683.5	0.9733	0.0000	LGO Cooler	69.0	59.0	Cooling Water	32.0	43.0	26.00
E-105	◆	4.873e+00	7.624e+004	249.8	1	29.18	683.5	0.9782	0.0000	Kerosene Cooler 2	71.7	61.7	Cooling Water	32.0	43.0	28.67
E-107	◆	5.631e+00	2.689e+004	45.27	1	19.20	683.5	0.9481	0.0000	LPG Cooler 2	61.7	51.7	Cooling Water	32.0	43.0	18.70
E-109	◆	3.085e+00	6.606e+004	202.7	1	23.07	683.5	0.9647	0.0000	Naphtha Stabilizer Ovhd Trim Cond	65.6	55.6	Cooling Water	32.0	43.0	22.56
E-106	◆	3.254e+00	5.795e+004	166.8	1	29.18	683.5	0.9782	0.0000	Kerosene Cooler	71.7	61.7	Cooling Water	32.0	43.0	28.67

Figure 37. Exchanger design specifications for HBU-I

5.2.5 HBU – II

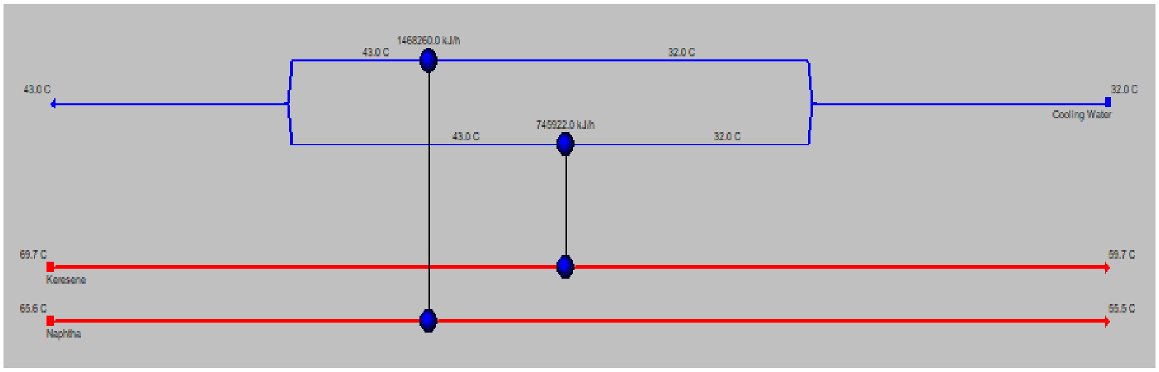
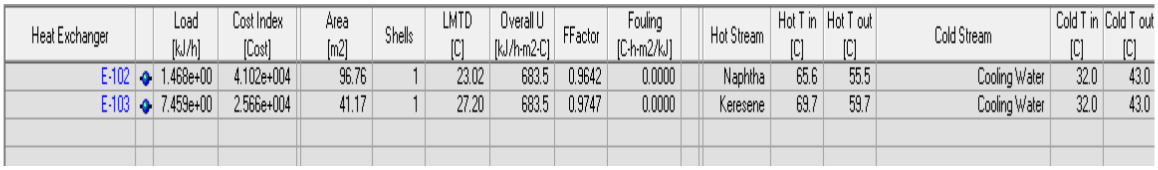


Figure 38. Recommended exchanger network for HBU-II

The recommended exchanger design for reformer on Aspen energy analyzer included eights heat exchangers with total heat transfer area of 71520 m^2 the simulation also included the load of each exchanger which was in accordance with the manual calculation done in the material and energy balance section.



Heat Exchanger		Load [kJ/h]	Cost Index [Cost]	Area [m2]	Shells	LMTD [C]	Overall U [kJ/h-m2-C]	FFactor	Fouling [C-h-m2/kJ]		Hot Stream	Hot T in [C]	Hot T out [C]	Cold Stream	Cold T in [C]	Cold T out [C]
E-102	◆	1.468e+00	4.102e+004	96.76	1	23.02	683.5	0.9642	0.0000		Naphtha	65.6	55.5	Cooling Water	32.0	43.0
E-103	◆	7.459e+00	2.566e+004	41.17	1	27.20	683.5	0.9747	0.0000		Keresene	69.7	59.7	Cooling Water	32.0	43.0

Figure 39. Exchanger design specifications for HBU-II

CHAPTER 6

Instrumentation and Process Control

6.1 Introduction

The significance of process control and instrumentation and how this is used in the cooling water network system is described in this chapter. The instrumentation ensures that the process remains safe.

6.2 Objective of Process Controls

One of the main objectives to employ controls and instrumentation in our system is to achieve the desired operating conditions of different equipments and the improving the lifetime of a particular equipment by counteracting the chances of equipment malfunction by providing safety measures through it.

Different controlling parameters are adjusted (manipulated) to keep the control system running smoothly, which are as follows:

1. Temperature
2. Pressure
3. Level
4. Flowrate

The above parameters can be controlled through an equipment like alarms, indicators or any controlling valves or through different mechanisms which can be used to detect any deviations and so that the necessary actions can be done in order to maintain the desired value within the required limit. Properly engineered cooling tower, heat exchangers, and pumps piping, and controls will improve heat transfer and avoid problems such as losing priming in pumps and slugging of air.

6.3 Implementation of Control Systems

6.3.1 Cooling tower controls

Optimum working of cooling water systems includes minimum consumption of water while maintaining desired temperatures to restrict algae growth and cool all equipment properly. One way to help reach these goals while considerably reducing the consumption of energy is to install control valves for cooling water.

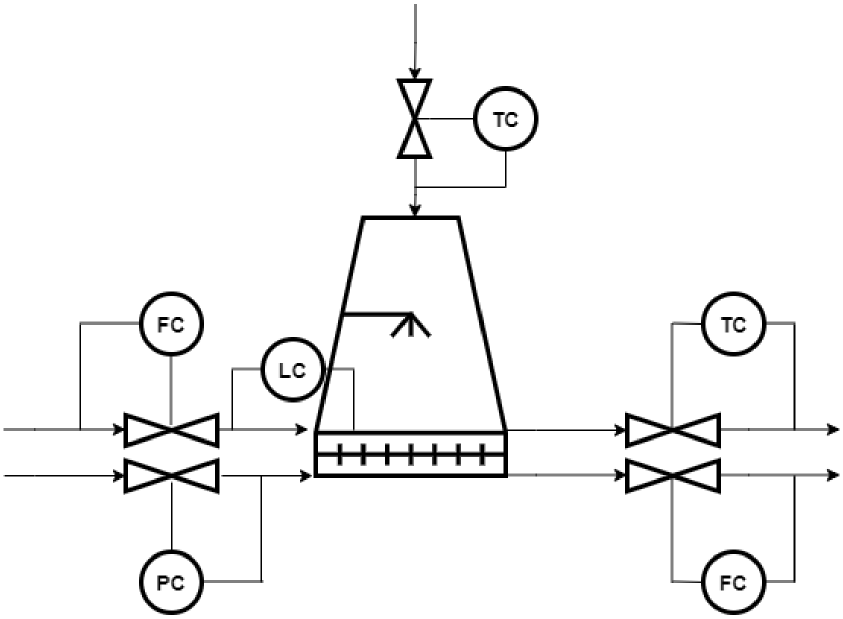


Figure 40. Control system for cooling tower

Name of Controller	Type of Controller	Manipulated Variable	Controlled Variable
LC	PID	Flow of Make-up Water	Level of CW in basin
PC	PID	Flowrate	Pressure
TC	PID	Flowrate of Return Header	Temperature of Water
TC	PID	Flowrate of Supply Header	Temperature of Water
FC	PID	Valve Opening	Make-up line flowrate
FC	PID	Valve Opening	Blow-down line flowrate

Table 21 Controllers of cooling tower

Flow Control

The flow of water through the cooling tower is controlled by incorporating a valve and a pump (non-controlled). The valve opening increase as cooling water flowrate in the blowdown stream decreases and vise versa.

Level Control

The level control works in the form of two basic control systems, one to add liquid into the basin, and one to send back the water recirculation system on or off. The key requirement for this application is to observe the liquid level, automatically refill the basin, and stop the system from running dry.

Temperature control

The valve controls the water flow rate which is in in direct proportion to the outlet temperature, positioned as close to the cooler as possible. When the cooling water is cold, the valve lowers the flow rate to a minor bleed. As the temperature of the outlets stream increases, the valve opens and adjusts the flow to keep a constant discharge temperature.

6.3.2 Make-up water tank controls

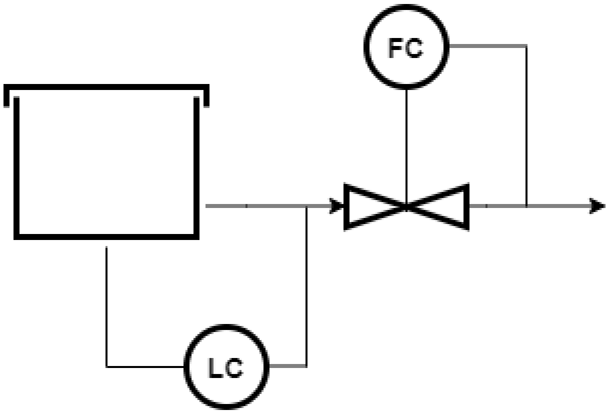


Figure 41.Control system for make-up water tank

Name of Controller	Type of Controller	Manipulated Variable	Controlled Variable
LC	PID	Makeup water Stream Flowrate	Level of water in makeup water tank
FC	PID	Valve Opening	Outlet Stream Flowrate

Table 22. Controllers of make-up water tank

6.3.3 Heat exchanger controls

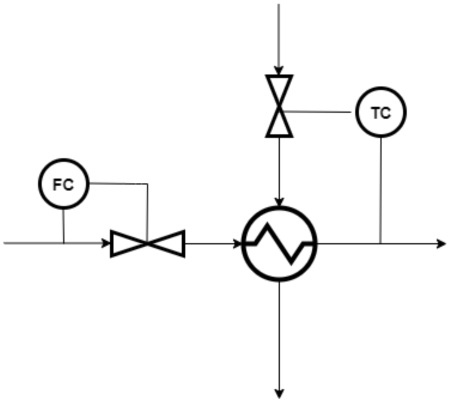


Figure 42. Control system for heat exchanger

Name of Controller	Type of Controller	Manipulated Variable	Controlled Variable
TC	PID	Flowrate of water	Temperature of Outlet Stream
FC	PID	Valve Opening	Flowrate of Outlet Stream

Table 23. Controllers of heat exchanger

6.3.4 Pump controls

One method is to confirm that the pump always provides its minimum flow is by configuring a recirculation loop from the reservoir. When the process requirement is low, the pump output will still fulfil the minimum flow requirements. The valve employed in the process may also be described as a sustaining valve for pump pressure.

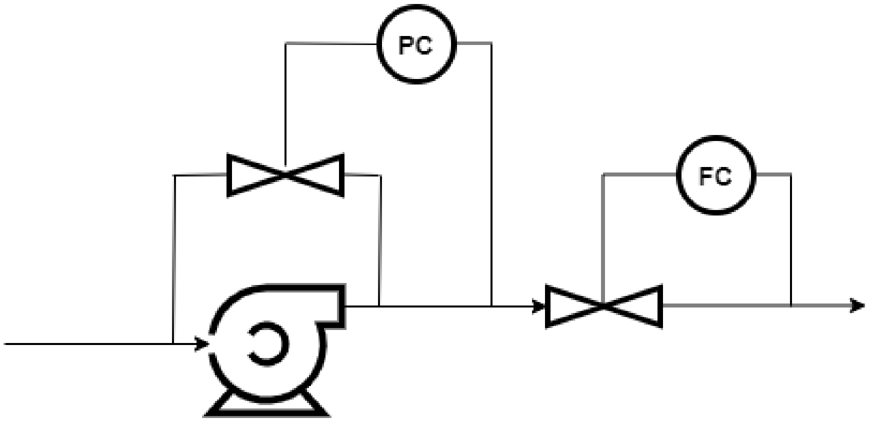


Figure 43. Control system for pump

Name of Controller	Type of Controller	Manipulated Variable	Controlled Variable
PC	PID	Flowrate	Pressure
FC	PID	Valve Opening	Flowrate

Table 24. Controllers of pump

6.3.5 Filter Controls

If backwash rates are very large values, considerably more media could vanish, affecting the filter performance. Therefore, controlling the flowrate is very essential which is carried out by changing the opening of the valve installed.

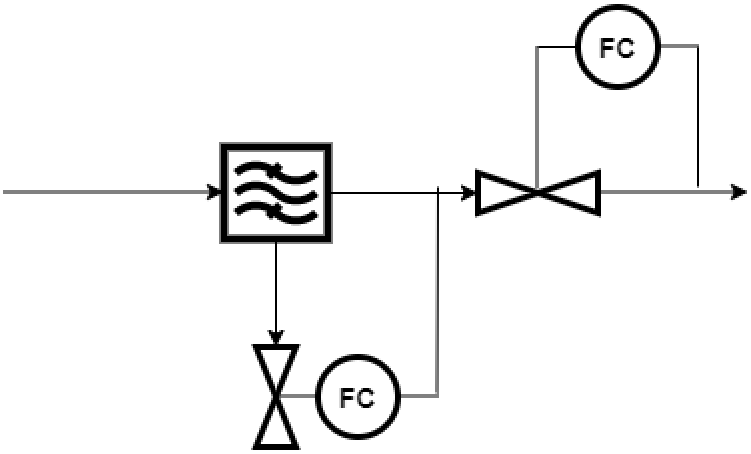


Figure 44. Control system for filter

Name of Controller	Type of Controller	Manipulated Variable	Controlled Variable
FC	PID	Valve Opening	Flowrate

Table 25. Controllers of filter

CHAPTER 7

Economic Analysis

7.1 Purchase Cost of Equipment

The purchase cost each equipment in year 2004 was calculated using using graphs given and relevant tables given in Richardson and Coulson Vol 6. The values obtained were inflation adjusted using the following formula:

$$Cost\ in\ year\ 2021 = Cost\ in\ year\ 2004 \times \left(\frac{Cost\ index\ in\ year\ 2021}{Cost\ index\ in\ year\ 2004}\right)$$

7.1.1 Cooling Tower

Property	Value
Range (°F)	51.8
Approach (°F)	37.4
Wet Bulb Temperature (°F)	84.2
Constant C	271.94

Table 26. Parameters for cost estimation of cooling tower

Value of Constant

$$C = \frac{279}{[1 + 0.0335(85 - t_{wb})^{1.143}]}$$

$$C = \frac{279}{[1 + 0.0335(85 - 84.2)^{1.143}]}$$

$$C = 271.94$$

Cost in 2004

$$\$_{2004} = \frac{Q}{C \text{ x } A + 39.2R\text{-}586} \text{ x } 2.7 \text{ x } (1.08)^{13}$$

$$\$_{2004} = \frac{75308013.128}{271.94 \text{ x } 37.4 + 39.2(51.8)\text{-}586} \text{ x } 2.7 \text{ x } (1.08)^{13}$$

$$\$_{2004} = \$47608.99$$

Cost in 2021

Cost in year A = Cost in year B x (Cost index in year A/Cost index in year B)

$$\textbf{Cost in 2021} = \$\mathbf{128803.98}$$

7.1.2 Filter

The cost of filter was calculated using the following formula, which depends on the design parameter raised to the respective index value obtained from the table on the next page.

$$C_e = CS^n$$

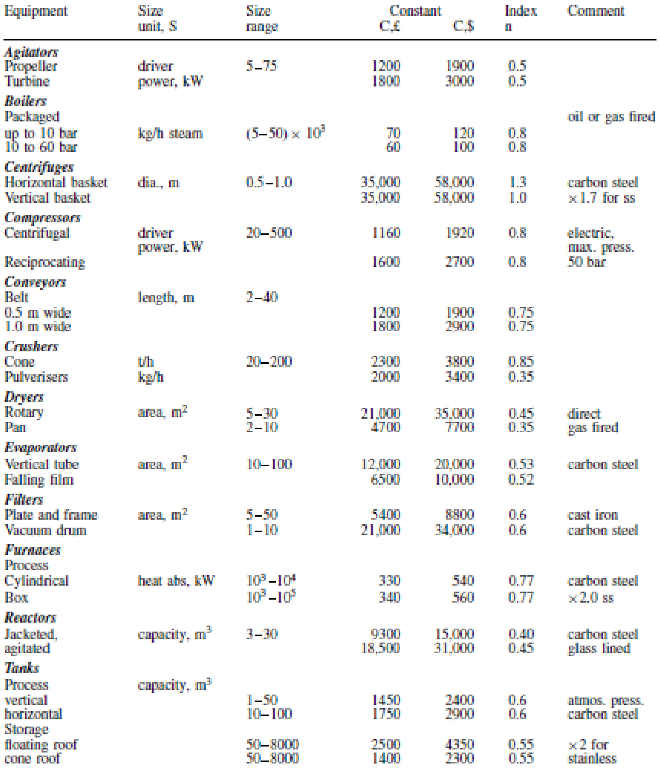
Where,

Ce = purchased equipment cost

S = characteristic size parameter

C = cost constant

n = index for that type of equipment.



Equipment	Size unit, S	Size range	Constant C,£	C,$	Index n	Comment
Agitators						
Propeller	driver	5–75	1200	1900	0.5	
Turbine	power, kW		1800	3000	0.5	
Boilers						
Packaged						oil or gas fired
up to 10 bar	kg/h steam	$(5–50) \times 10^3$	70	120	0.8	
10 to 60 bar			60	100	0.8	
Centrifuges						
Horizontal basket	dia., m	0.5–1.0	35,000	58,000	1.3	carbon steel
Vertical basket			35,000	58,000	1.0	× 1.7 for ss
Compressors						
Centrifugal	driver	20–500	1160	1920	0.8	electric,
	power, kW					max. press.
Reciprocating			1600	2700	0.8	50 bar
Conveyors						
Belt	length, m	2–40				
0.5 m wide			1200	1900	0.75	
1.0 m wide			1800	2900	0.75	
Crushers						
Cone	t/h	20–200	2300	3800	0.85	
Pulverisers	kg/h		2000	3400	0.35	
Dryers						
Rotary	area, m^2	5–30	21,000	35,000	0.45	direct
Pan		2–10	4700	7700	0.35	gas fired
Evaporators						
Vertical tube	area, m^2	10–100	12,000	20,000	0.53	carbon steel
Falling film			6500	10,000	0.52	
Filters						
Plate and frame	area, m^2	5–50	5400	8800	0.6	cast iron
Vacuum drum		1–10	21,000	34,000	0.6	carbon steel
Furnaces						
Process						
Cylindrical	heat abs, kW	$10^3–10^4$	330	540	0.77	carbon steel
Box		$10^3–10^5$	340	560	0.77	× 2.0 ss
Reactors						
Jacketed,	capacity, m^3	3–30	9300	15,000	0.40	carbon steel
agitated			18,500	31,000	0.45	glass lined
Tanks						
Process	capacity, m^3					
vertical		1–50	1450	2400	0.6	atmos. press.
horizontal		10–100	1750	2900	0.6	carbon steel
Storage						
floating roof		50–8000	2500	4350	0.55	× 2 for
cone roof		50–8000	1400	2300	0.55	stainless

Figure 45. Purchase cost of miscellaneous equipment

$$C = \$\ 8800, n = 0.6, S = 12.5$$

$$Ce = CS^n$$

$$Ce = (8800)(12.5)^{0.6}$$

$$Ce = \$40052.41$$

$$\text{Cost in } 2021 = \$63940.8$$

7.1.3 Make-Up Water Tank

$$C = \$\ 2900, n = 0.6, S = 75$$

$$Ce = CS^{n}$$

$$Ce = (2900)(75)^{0.6}$$

$$Ce = \$\ 38675.39$$

$$\text{Cost in 2021} = \$61742.5$$

7.1.4 Heat Exchangers

Area = 74.1 m^2

Carbon steel shell and carbon steel tubes from Figure

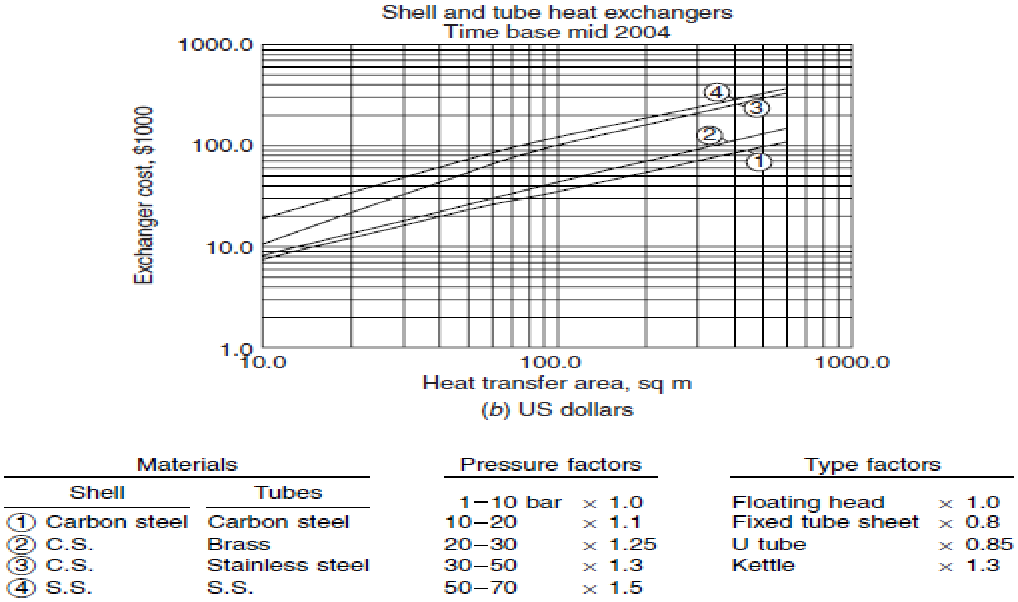


Figure 46. Cost of shell and tube heat exchangers

Cost in 2004 = (Bare cost from figure) x (Pres. Factor) x (T.F)

Cost in 2004= (29000) x (0.8) x (1.0) = $23,200

Cost in 2021 = $ 37,037.14

Unit	**Total Cost ($)**
Reformer	274572.9429

HCU	376629.4286
HBU-I	591317.1429
HBU-II	71520
LUMMUS	556834.2857
Total	1870873.8

Table 27. PCE of heat exchangers

7.1.5 Total Purchase Cost of Equipment (PCE)

PCE = 61742.5 + 30000 + 128803.98 + 1870873.8 + 63940.8

PCE = $ 2155361.08

7.2 Physical Plant Cost (PPC)

Typical factors for estimation of project fixed capital cost (for fluids type) from table 6.1 (R&C Vol.6) are as follows:

f_1 Equipment erection	0.40
f_2 Piping	0.70
f_3 Instrumentation	0.20
f_4 Electrical	0.10
f_5 Buildings, process	0.15
f_6 Utilities	0.50
f_7 Storage	0.15
f_8 Site development	0.05
f_9 Ancillary buildings	0.15

Table 28. Factors for PPC

Total physical plant cost (PPC) = $PCE(1+f_1+f_2 \ldots f_9)$

$$= PCE\ (1 + 0.4 + 0.7 + 0.2 + 0.1 + 0.5 + 0.15)$$

$$PPC = \$\ 6573851.294$$

7.3 Fixed Capital Cost

f_{10} design & Engineering	0.30
f_{11} Contractor’s fee	0.05
f_{12} Contingency	0.1

Table 29. Factors for fixed capital cost

Fixed Capital (FC) = PPC $(1+f_{10}+f_{11}+f_{12})$

$$= (PPC) * (1 + 0.3 + 0.05 + 0.1)$$

$$FC = \$\ 9532084.376$$

7.4 Working Capital Cost

Working Capital = 5% of FC = $ 476604.2188

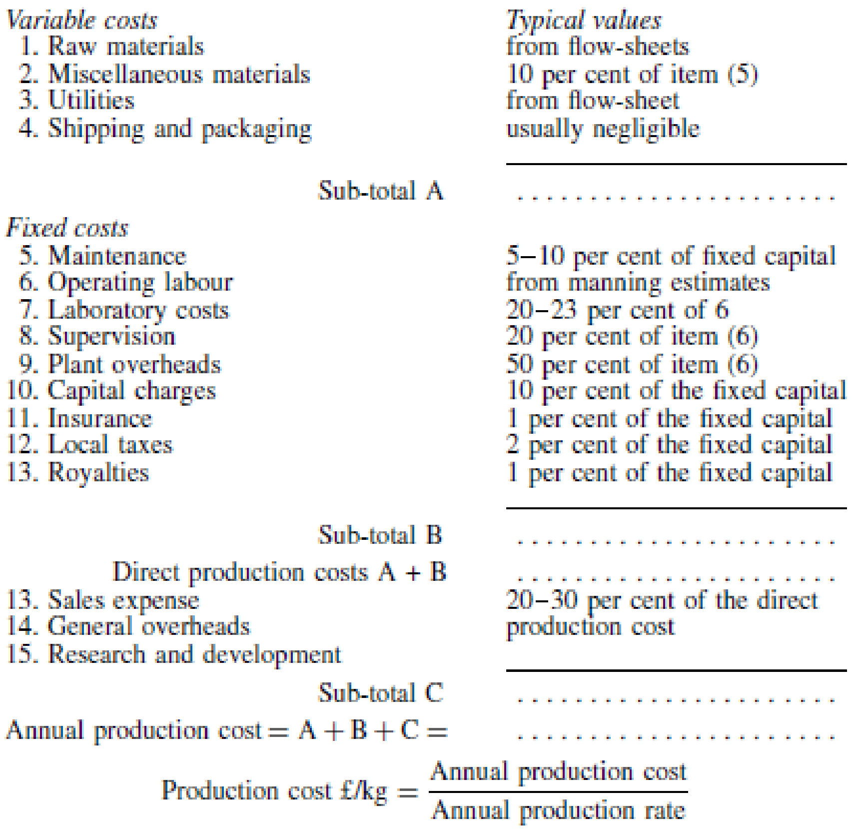
7.5 Total Investment

Total investment required = Fixed capital + working capital

= $ 10008688.6

7.6 Annual Production Cost

The cost of operation of the cooling water system was found over the course of a year. It was divided into variable and fixed cost. The following table along with the previously calculated fixed capital cost was used to calculate the annual production cost.



Variable costs	*Typical values*
1. Raw materials	from flow-sheets
2. Miscellaneous materials	10 per cent of item (5)
3. Utilities	from flow-sheet
4. Shipping and packaging	usually negligible
Sub-total A	....
Fixed costs	
5. Maintenance	5–10 per cent of fixed capital
6. Operating labour	from manning estimates
7. Laboratory costs	20–23 per cent of 6
8. Supervision	20 per cent of item (6)
9. Plant overheads	50 per cent of item (6)
10. Capital charges	10 per cent of the fixed capital
11. Insurance	1 per cent of the fixed capital
12. Local taxes	2 per cent of the fixed capital
13. Royalties	1 per cent of the fixed capital
Sub-total B	....
Direct production costs A + B	....
13. Sales expense	20–30 per cent of the direct production cost
14. General overheads	
15. Research and development	
Sub-total C	....
Annual production cost = A + B + C =	....

$$\text{Production cost £/kg} = \frac{\text{Annual production cost}}{\text{Annual production rate}}$$

Figure 47. Annual Production Cost

7.6.1 Variable operating cost

The variable cost included the cost of raw materials which was make-up water in our case while the cost of utilities covered the water circulation rate of the cooling tower. There was no bagging and shipping cost involved in our project as there was no product being manufactured.

Raw material	$ 433360
Miscellaneous materials	$ 47660.42188
Utilities	$ 151110
Shipping and packaging	Not applicable

Table 30. Variable costs

Total Variable Operating Cost = \$ 632130.4219

7.6.2 Fixed Operating Cost

The fixed operating cost consisted of maintenance cost which included the cleaning and backwashing of our fills and filter, respectively. Operating labor, supervision and plant overheads consisted of all the man force employed on the plant.

Maintenance	\$ 476604.2188
Operating Labor	\$ 1564.56
Supervision	\$ 312.912
Plant overheads	\$ 782.28
Laboratory	\$ 312.912
Capital Charges	\$ 95320.84376
Insurance	Not applicable
Local taxes	\$19810.51
Royalty payments	Not applicable

Table 31. Fixed costs

Fixed Operating Cost = \$ 765539.4141

7.6.3 Annual Production Cost

Annual Production cost = 632130.4219 + 765539.4141

= \$ 1397669.836

CHAPTER 8

Hazard and Operability (HAZOP) Analysis

Process safety is of paramount importance in all chemical plants. One mistake or oversight can lead to a disaster. Hence, it’s important to carry out risk assessment to avoid loss of personnel or equipment. Hazard and Operability study is a systemic risk assessment to review, identify and evaluate problems in the process design, facilities, equipment and operation that may qualify as a risk or hazard to personnel or equipment. It is assumed that problems occur when the process deviates from set operational parameters.

In order to carry out this study, the complex process is broken down into smaller processes called “nodes” which are then individually evaluated. It is carried out by experienced professionals who are expected to use good intuition and judgement to come up with all possible hazards, emergencies and risks at each individual node. Guide-word prompts are used to mark each node. The following table explains the guide words:

Guide Word	Meaning
NO OR NOT	Complete negation of the design intent
MORE	Quantitative increase
LESS	Quantitative decrease
AS WELL AS	Qualitative modification/increase
PART OF	Qualitative modification/decrease
REVERSE	Logical opposite of the design intent
OTHER THAN / INSTEAD	Complete substitution
EARLY	Relative to the clock time

LATE	Relative to the clock time
BEFORE	Relating to order or sequence
AFTER	Relating to order or sequence

Table 32. Guide words for Hazop

For each node, the deviation from design intent is identified along with its consequences and troubleshooting mechanism. It is further decided whether an additional safeguard measure needs to be installed or not. The team will suggest measures to minimize the chances of deviation from design intent, before moving on to the next node.

The following standard steps are used to do HAZOP analysis:

1. Definition

2. Preparation

3. Examination

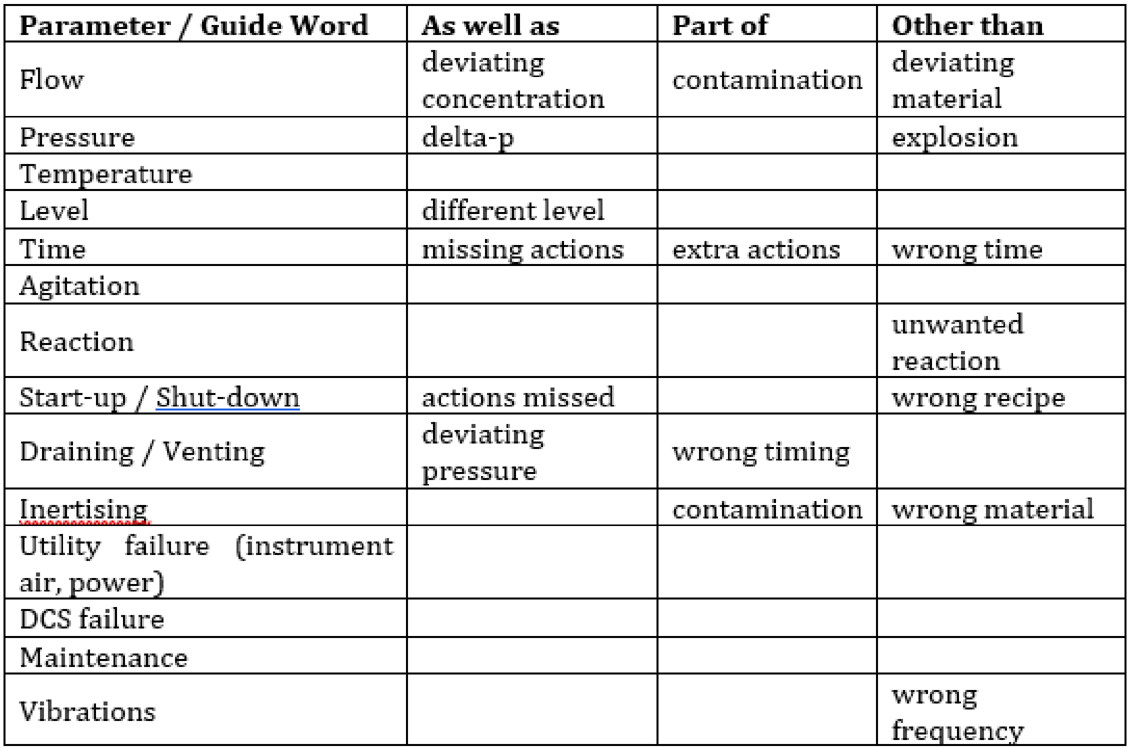
4. Documentation and Follow-up

Apart from guide-word prompts mentioned above, guide-words can be used for process parameter as well.

Parameter / Guide Word	**More**	**Less**	**None**	**More**
Flow	high flow	low flow	no flow	high flow
Pressure	high pressure	low pressure	vacuum	high pressure
Temperature	high temperature	low temperature		high temperature
Level	high level	low level	no level	high level
Time	too long / too late	too short / too soon	sequence step skipped	too long / too late
Agitation	fast mixing	slow mixing	no mixing	fast mixing
Reaction	fast reaction / runaway	slow reaction	no reaction	fast reaction / runaway
Start-up / Shut-down	too fast	too slow		too fast
Draining / Venting	too long	too short	none	too long

Inertising	high pressure	low pressure	none	high pressure
Utility failure (instrument air, power)			failure	
DCS failure			failure	
Maintenance			none	
Vibrations	too low	too high	none	too low

Table 33. Hazop study



Parameter / Guide Word	As well as	Part of	Other than
Flow	deviating concentration	contamination	deviating material
Pressure	delta-p		explosion
Temperature			
Level	different level		
Time	missing actions	extra actions	wrong time
Agitation			
Reaction			unwanted reaction
Start-up / Shut-down	actions missed		wrong recipe
Draining / Venting	deviating pressure	wrong timing	
Inertising		contamination	wrong material
Utility failure (instrument air, power)			
DCS failure			
Maintenance			
Vibrations			wrong frequency

Table 34. Hazop study

We performed HAZOP analysis of cooling tower and heat exchanger networks. It has been summarized in the tables below:

8.1 Hazop Analysis on Cooling Tower

Guide Word	**Deviation**	**Causes**	**Consequences**	**Action**
More	More Chlorides > 300 ppm	High cycles of Concentration	Corrosive to most metals	Open CBD@100 m3/h or more if possible
	More pH>8.5	Evaporation of Water	Scale Formation	Shock dose extra 40kg Bulab7041 (Polymer)
	More suspended solids>20ppm	Water evaporates leaving behind dissolved or suspended solids	Blockage or corrosion to the cooling water system	Shock dose extra 40kg bio-dispersant Bulaab8006
Less	Less pH 5.0-6.0	High acid concentration	Corrosive to most metals	Stop acid dosing and isolate leaked exchanger. Maintain molybdate between 4-5ppm and zinc between 2-3ppm for three days

Table 35. Hazop analysis on cooling tower

8.2 Hazop Analysis on Heat Exchangers

Guide Word	**Deviation**	**Causes**	**Consequences**	**Action**
None	No cooling water flow	Failure of inlet cooling water valve to open	Process fluid temperature is not lowered accordingly	Install temperature indicator before and after the process fluid
More	More cooling water flow	Failure of inlet cooling water valve to close	Output of process fluid temperature too low	Install temperature indicator before and after the process fluid line.
Less	Less cooling water flow	Pipe leakage	Process fluid temperature too low	Installation of flow meter
More of	More pressure on tube side	Failure of process fluid valve	Bursting of tube	Install high pressure alarm
Reverse	Reverse process fluid flow	Failure of process fluid inlet valve	Product offset	Install check valve
Contamination	Process flow contamination	Contamination in cooling water	Outlet temperature too low	Proper maintenance and operator alert
Corrosion	Corrosion of pipe	Hardness of cooling water	Less cooling and crack of pipe	Proper maintenance

Table 36. Hazop analysis on heat exchanger

CONCLUSION

After successful completion of our project, we were to achieve our project deliverables. From design calculations, the height of the cooling tower was found to be 11.1 m for a water circulation rate of 1,725 m^3/hr. We managed to replace three existing cooling towers with one and calculated a lesser area and height for the same flow rate. The losses through blowdown were minimized by incorporating a packed bed sand filter of area 12.5 m^2 which managed to reduce make-up water consumption. Heat exchanger networks were simulated on Aspen Energy Analyzer, to find the minimum heat transfer area which came out to be 4,853.1 m^2.

REFERENCES

[1] Wang, Yufei, Xiao Feng, and Jiaze Ma. "Sustainable design of cooling water system." *Towards Sustainable Chemical Processes*. Elsevier, 2020. 241-274.

[2] Kloppers, Johannes C., and Detlev G. Kröger. "A critical investigation into the heat and mass transfer analysis of counterflow wet-cooling towers." *International journal of heat and mass transfer* 48.3-4 (2005): 765-777.

[3] Zou, Zheng, Zhiqiang Guan, and Hal Gurgenci. "Optimization design of solar enhanced natural draft dry cooling tower." Energy conversion and management 76 (2013): 945-955.

[4] Kim, Jin-Kuk, and Robin Smith. "Cooling water system design." *Chemical Engineering Science* 56.12 (2001): 3641-3658

[5] Balaji, D., et al. "Experimental and comparative study of a sea water-cooled surface condenser of LTTD plant with HTRI and Kern method." *Desalination and Water Treatment* 57.41 (2016): 19540-19556.

[6] Serna-Gonzalez, Medardo, José M. Ponce-Ortega, and Arturo Jiménez-Gutiérrez. "MINLP optimization of mechanical draft counter flow wet-cooling towers." *Chemical Engineering Research and Design* 88.5-6 (2010): 614-625.

[7] Zakaria, Zaki Yamani, and Chikezie Nwaoha. "Cooling Towers." *Process Plant Equipment: Operation, Control, and Reliability* (2012): 63-79.

[8] Coulson, John Metcalfe, et al. *Chemical Engineering: Fluid flow, heat transfer and mass transfer*. Pergamon press, 1954.

[9] Leeper, Stephen A. Wet cooling towers: rule-of-thumb design and simulation. No. EGG-GTH-5775. EG and G Idaho, Inc., Idaho Falls, ID (United States), 1981.

[10] Rezaei, Ebrahim, Sirous Shafiei, and Aydin Abdollahnezhad. "Reducing water consumption of an industrial plant cooling unit using hybrid cooling tower." *Energy Conversion and Management* 51.2 (2010): 311-319.

[11] Bahadori, Alireza. *Hazardous Area Classification in Petroleum and Chemical Plants: A Guide to Mitigating Risk*. CRC Press, 2019.

[12] Kloppers, Johannes C., and Detlev G. Kröger. "A critical investigation into the heat and mass transfer analysis of counterflow wet-cooling towers." *International journal of heat and mass transfer* 48.3-4 (2005): 765-777.

[13] Ma, Peizheng, Lin-Shu Wang, and Nianhua Guo. "Modeling of hydronic radiant cooling of a thermally homeostatic building using a parametric cooling tower." *Applied energy* 127 (2014): 172-181.

[14] Mohiuddin, A. K. M., Keshav Kant, and Rajeev Sangal. "ESTOWER: an expert system for the thermal design of wet cooling towers." *Engineering Applications of Artificial Intelligence* 9.2 (1996): 185-194.

[15] Rubio-Castro, Eusiel, et al. "Optimization of mechanical draft counter flow wet-cooling towers using a rigorous model." *Applied Thermal Engineering* 31.16 (2011): 3615-3628.

[16] Sinnott, Ray. *Chemical Engineering Design: Chemical Engineering Volume 6*. Elsevier, 2005.

[17] Sun, Jin, Xiao Feng, and Yufei Wang. "Cooling-water system optimisation with a novel two-step sequential method." *Applied Thermal Engineering* 89 (2015): 1006-1013.

[18] Rezaei, Ebrahim, Sirous Shafiei, and Aydin Abdollahnezhad. "Reducing water consumption of an industrial plant cooling unit using hybrid cooling tower." *Energy Conversion and Management* 51.2 (2010): 311-319.