A TWO STEP APPROACH TO OPTIMIZATION OF RECIRCULATING COOLING TOWER SYSTEM

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JANUARY 2012

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COOLING TOWER SYSTEM

By

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A TWO STEP APPROACH TO OPTIMIZATION OF RECIRCULATING COOLING TOWER SYSTEM

by

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A Thesis

Submitted to the Post Graduated Studies Programme

as a Requirement for the Degree of

MASTER OF SCIENCE

DEPARTMENT OF CHEMICAL ENGINEERING

UNIVERSITI TEKNOLOGI PETRONAS

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To my beloved parents,

Jalani Simun and Marmi Md Pandi,

For their prayers and relentless support

ACKNOWLEDGEMENT

In the name of Allah, most gracious, most merciful. First and foremost, I would like to thank Allah the Almighty for His blessings and guidance in allowing me to complete this thesis as required.

I would like to express my gratitude to all those who gave me the possibility to complete this thesis. My heart goes to UTP for giving me this opportunity to thrive in my journey of pursuing knowledge.

The greatest appreciation must go to my parents and siblings for their love, support and understanding while I spent most of my time trying to complete my Masters. I would like to acknowledge the former Director of Postgraduate Studies, Prof. Ir. Dr. Ahmad Fadzil Mohamad, for allowing me to pursue my dream to do my Masters Programme in UTP. My appreciation also goes to the current Director of Postgraduate Studies, Associate Professor Dr Mohd Noh Karsiti, and also other former and current Postgraduate Programme staffs for giving my colleagues and I the support that we needed during the duration of our studies.

I am deeply indebted to my supervisor, Dr Shuhaimi Mahadzir and my former supervisor, Ir Dr. Kamarul Ariffin Amminudin whose help, stimulating suggestions and encouragement helped me in all the time of research for and writing of this thesis. His trust in me has also allowed me to join Water Team from PRSS, En Ahmad Nazrene and Puan Mardhiyah for Cooling Tower Audit Programme at Petronas OPU's in Kerteh, Terengganu.

Specials thanks go to Research Enterprise Office especially to Associate Professor Mohamed Ibrahim Abdul Mutalib, En Zamri, and Puan Hafizah for their support andunderstanding. I have furthermore thanked to staff of UTP especially the lecturers and technicians of Chemical Engineering Department and also to MOSTI for funding this research under IRPA grant.

A special acknowledgement goes to friends; Kak Sarah, Yati, Ira, Wan Zai, Aida, Azah, Lin, Linda and Diana. Many thanks to Kak Aniza for putting up with me throughout the duration of my research, who guided me in writing, who was there all the way to support me and share my views. My thanks also go to my fellow postgraduate colleagues. Their support and friendship are unforgettable and will be cherished.

I would like to thank also to those whose names I have not mentioned. My sincere thanks goes to all those who had helped me whether directly or indirectly. May Allah bless all those who have touched my heart in so many ways.

ABSTRACT

Cooling tower is one of the unit that is involved with water network system and it can contribute to higher water savings for a plant if maximum attention is given to it. Much of the works only concentrate on individual cooling tower unit, especially in improving the performance of the internals. Nonetheless, work on the total cooling water system, which addresses the issues of interactions between the cooling tower and its associated heat exchangers or coolers, has received lesser attention. The objective of this study is to develop a systematic method for optimization strategy to improve efficiency of the existing cooling tower system, based on the established empirical model. A well-known Merkel's Equation (Perry and Green, 1997) is used to predict the cooling tower performance. The basic idea in this optimization strategy is to minimize cooling water circulation in cooling tower through water reuse so as to maximize cooling tower return temperature. A two-stage approach is adopted in the optimization procedure. The first stage is to address the cooling tower performance itself. This effort takes into account the minimum approach temperature, pressure drop and fouling issues so that any modification of process parameters are within the acceptable limits of the cooling tower. In the second stage, cooling water composite curve, which is similar to a conventional water pinch technology, is proposed to identify water reuse opportunities. Further design of water reuse is carried out by mathematical approach using General Algebraic Modelling System (GAMS) mainly when composite curve unable to identify water reuse opportunity. Finally, the economics of the proposed improvement are then presented to demonstrate its cost effectiveness. Based on the case studies, application of water reuse enables the total operating cost of the cooling water systems to be reduced up to 27% for case study 1 and 28% for case study 2. While for case study 3, the additional product capacity could be obtained up to 15%. These findings show a great promise for industrial application as the methodology developed in this thesis can be used to improve the performance of the cooling water system.

ABSTRAK

Menara penyejuk adalah sebuah unit yang melibatkan system jaringan air dan boleh memberikan lebih banyak keuntungan untuk sesebuah loji jika tumpuan yang lebih diberikan kepada sistem tersebut. Kebanyakan kerja-kerja pembaikan yang dilakukan ke atas menara penyejuk hanyalah menumpukan ianya secara individu seperti pengubahsuaian sistem dalaman. Bagaimanapun, kerja-kerja yang melibat interaksi keseluruhan sistem tidak begitu mendapat perhatian. Objektif kajian ini adalah untuk menghasilkan metodologi yang sistematik sebagai strategi supaya menara penyejuk beroperasi secara optimum dan lebih efisyen dengan menggunakan model empirikal yang telah diperkenalkan sebelum ini. Persamaan Merkel's (Perry dan Green, 1997) telah digunakan untuk menganggarkan parameter menara penyejuk yang baru. Idea asas dalam kajian ini adalah dengan mengurangkan penggunaan air di dalam sistem ini melalui "guna semula" air dan juga dengan memaksimakan suhu air panas yang kembali ke menara penyejuk. Prosedur kajian telah dibahagikan kepada dua tahap. Tahap pertama adalah untuk meningkatkan prestasi menara penyejuk. Tahap ini mengambilkira tentang beza minimum antara suhu udara lembab dan suhu air sejuk, beza tekanan dan pembentukan lapisan (fouling) di dalam sistem, dengan yang demikian sebarang pengubahsuaian parameter sentiasa berada di dalam had yang dibenarkan oleh sistem. Pada tahap kedua, "Graf Komposit Air Penyejuk" yang menyamai "Teknologi Titik Pertemuan Air" yang konvensional, telah diperkenalkan. Kemudian, rekabentuk ini diteruskan dengan menggunakan persamaan matematik menggunakan program *GAMS* terutamanya apabila graf komposit tidak dapat mengenalpasti peluang 'guna semula' air. Akhir sekali, analisis ekonomi dilakukan untuk menunjukkan kos bagi kajian ini adalah efektif. Beberapa kajian kes yang disertakan di dalam kajian ini menunjukkan aplikasi guna semula air telah mengurangkan jumlah kos operasi sistem penyejuk air sehingga 27 peratus untuk kes 1 dan 28 peratus untuk kes 2. Bagi kes 3 pula, penghasilan tambahan produk diperolehi sehingga 15%. Penemuan ini menjanjikan kepada industri bahawa metodologi yang diperkenalkan boleh digunakan untuk meningkatkan mutu operasi sistem penyejuk air.

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ABBREVIATIONS

UA	overall heat transfer coefficient x heat transfer area
HVAC	heating, ventilating and air conditioning
DOS	Disk operating system
NTU	number of transfer units
MINLP	Mixed integer nonlinear programming
ppm	part per millions
GPM	gallon per minute

NOMENCLATURE

E	Evaporation rate (m^3/hr)
B	Blowdown rate (m^3/hr)
M	Make-up water rate (m^3/hr)
F_1	Cooling water supply flowrate (m^3/hr)
F_o	Total cooling water inlet into heat exchanger (m^3/hr)
F_2	Cooling water return flowrate (m^3/hr)
T_1	Supply temperature (^oC)
T_M	Make-up temperature (^oC)
To	Inlet to heat exchanger temperature (^oC)
T_2	Return temperature (^oC)
Q_{HEN}	Heat load of heat exchanger network (MW)
G	Dry air flowrate (kg/s m^2)
H	Enthalpy (kJ/kg)
h	Enthalpy (kJ/kg)
W	Air Humidity (kg water / kg air)
T	Temperature (^oC)
Z	Height of cooling tower (m^3)
dH	Differential element of enthalpy
dL	Differential element of water flowrate (kg/s m^2)
dT	Differential element of temperature (^oC)
dW	Differential element of air humidity
dZ	Differential element of cooling tower height (m^2)
ε	Effectiveness of cooling tower
R'	Ratio of heat capacity rates of air to water (kg_w / kg_{da})
$C_{in,p}$	Inlet concentration of process stream
$C_{in,w}$	Inlet concentration of water stream
$C_{out,p}$	Outlet concentration of process stream
$C_{out,w}$	Outlet concentration of water stream
F_p	Process stream flowrate

F_w	Water stream flowrate
Q	Heat load (BTU/min or kW)
R	Range (^oF or ^oC)
L	Cooling water circulation rate (GPM or m^3/hr or ib/min)
L`	New cooling water circulation rate (GPM or m^3/hr or ib/min)
G	Air flowrate (ib/min or cfm or m^3/hr)
L/G	Water to air mass ratio
T_{cw}	Cold water/supply temperature (^oF or ^oC)
T_{hw}	Hot water/return temperature (^oF or ^oC)
T_{wb}	Wet-bulb temperature (^oF or ^oC)
KaV/L	Tower characteristic
K	Mass transfer coefficient (lb water/h ft2)
a	Contact area/tower volume
V	Active cooling volume/plan area
hw	Enthalpy of air-water vapor mixture at bulk water temperature (J/kg dry air or Btu/lb dry air)
ha	Enthalpy of air-water vapor mixture at wet bulb temperature (J/kg dry air or Btu/lb dry air)
Δh1	Value of hw-ha at $T_{cw} + 0.1(T_{hw} - T_{cw})$
Δh2	Value of hw-ha at $T_{cw} + 0.4(T_{hw} - T_{cw})$
Δh3	Value of hw-ha at $T_{hw} - 0.4(T_{hw} - T_{cw})$
Δh4	Value of hw-ha at $T_{hw} - 0.1(T_{hw} - T_{cw})$
kW	Kilowatt
RT	Refrigerant tone
F_{cw} (i)	Flowrate of cooling water at heat exchanger i
T_{ref}	Reference temperature
F_{cwsink} (i)	Total flowrate of cooling water in mixing point i
C_{pw}	Heat capacity of cooling water
T_{sink}	Sink temperature
F_{out}	Flowrate of cooling water return
z	Objective function
x	Amount of cooling water reuse
y	Fresh cooling water supply for heat exchanger i

B(i)	Cooling water inlet to heat exchanger i
C(i)	Cooling water outlet from heat exchanger j

CHAPTER 1

INTRODUCTION

1.1 Background

The cooling tower unit is always been ignored in plants as compared to any other plant utilities such as boilers and steam turbines. This is partly due to its less problematic operation and relatively cheaper maintenance. Nonetheless, the perception of that cooling tower is just “the box in the back where we send the hot water and it comes back cold” is no longer taken for granted. In fact, it is found that improvement in the cooling tower operations could generate a source of revenue in plant operation in the form of both energy and water savings. Cooling water is largely used as a cooler in processing plant due to its ease of availability and low cost. Cooling water demands have been estimated to account for up to 70 percent of water use in commercial buildings (Burger, 1995). Cooling water supply can be obtained through various systems such as once-through, closed recirculating and open-recirculating cooling water systems

In a once-through cooling system, high volume of hot water discharged could pose a severe environmental problem to aquatic system. Kairouani et al., (2004) has reported that the optimal water loss quantity from once-through cooling tower model has been determined at 10 million m^3 per year. In contrast, converting once-through to a closed loop or recirculating system can reduce water usage by 20% to 95% (deMonsabert and Liner, 1996). This shows that, a single cycle cooling tower system could produce larger reduction of water consumption as compared to once-through system and thus reducing cooling tower operating cost.

Problems in cooling tower operation include the inadequate thermal performance of cooling towers that contributes to large electricity cost for more than $25 million per year. Inefficient thermal performance also leads to high back pressure on turbine and thus, increasing fuel cost and decreasing its cycle efficiency (Burger, 1995). Bad maintenance practice also leads to cooling tower inefficiency. For example, untreated cooling water will cause fouling inside condensers and this in turn reduces heat transfer area. Since product quality must be maintained to fulfill customer's demand, more cooling water is needed to meet cooling requirement in condenser unit.

By improving the performance of the cooling tower system, the outlet temperature return to the heat exchanger should be colder. Burger (1995) stated that a 1^{o}F (0.6^{o}C) colder water returns to the compressors and condensers in air-conditioning and refrigeration equipment results in a 3% savings in electrical energy input to these machines. Therefore, 2^{o}C colder water off the tower can be expected to yield approximate 10% savings in electrical energy.

Generally, optimization of cooling tower is done on its individual unit such as improving the cooling tower treatment program, adding new cells, increasing air flowrate by increasing fan power and replacing the packing. Those improvements can only produces colder cooling water supply temperature, while the energy and water consumptions remained the same.

1.2 Problem Statement

Recently, researchers started to carry out system-wide optimization in which the interaction between cooling tower and its associated components is investigated (Kim and Smith, 2001). Modification of the cooling water user network is then performed so that the cooling water consumption can be reduced and optimized. However, cooling tower is then modified so that the cooling tower can operate according to the parameters that are specified by optimized cooling water network. The drawbacks of this is that the problems may arise if the existing cooling tower cannot suit with the new parameters given by cooling water network and this may require new cooling tower. In this study, alternative procedure in optimizing cooling tower, especially for recirculating cooling water system is proposed. This method is basically to compliment the previous work so that systematic procedure can be applied in improving cooling tower efficiency.

1.3 Objective of Research

The objectives of this study are:

1. To increase the efficiency of cooling tower operation by reducing cooling water supply temperature through lower cooling water circulation rate inside cooling tower system.
2. To exploit the use of graphical visualization and mathematical programming to identify the water re-use, regeneration and recycling in order to compensate the reduction in cooling water flow supply to the system.
3. To determine the plant revenue obtained from the cooling tower optimization.

1.4 Scope of Research

The scope of this research focuses on a development of a systematic procedure to optimize recirculating cooling water system including cooling tower optimization, cooling water reuse, regeneration and recycle in the process operations.

Previously, cooling tower optimization is more on improving or upgrading cooling tower internals. However, this study focuses only on modification of cooling tower operating parameters such as cooling water circulation rate inside the tower. In addition, this study will provide the extra revenue that is able to be obtained from the cooling tower optimization in terms of reduction of cooling tower operating cost and also the additional product capacity from the plants.

The two-step optimization will be introduced in this study to ensure that all constraints and limitations in cooling tower and heat exchanger is clearly defined before go for water reuse design and thus, the design is more practicable to the existing systems.

The principle of heat and mass transfer will be used in this study. The heat balance around cooling tower can be analyzed by indicating the inlet and outlet temperature of cooling water, cooling water and air flowrate as well as inlet and outlet temperature of air. Physchrometric analysis will be used in determining the properties of the air. Basically, psychrometrics deals with thermodynamic properties of moist air in and from the charts, the enthalpy value can be determined. The factors that are affected the enthalpy value are humidity ratio, wet and drybulb temperature as well as the barometric pressure. In this study, the wetbulb temperature and the humidity ratio are assumed to be constant by considering that the ambient condition in Malaysia is not much vary as compared to other seasonal countries.

Meanwhile, heat and mass balance principle is carefully evaluated in cooling water reuse design. This is to ensure that the performance of cooling water user will not be disturbed. Since the stream mixing assume that the heat balance is involving only sensible heat, the calculation is simpler as compared to the heat balance around the cooling tower. The parameters that should be considered are the flowrates and temperatures for respective cooling water streams that going to be mixed.

CHAPTER 2

LITERATURE REVIEW

2.1 Cooling Water System

2.1.1 Types Of Cooling Water System

There are many types of cooling water systems for industrial cooling. It includes once through cooling water system, open recirculating cooling water and closed recirculating cooling water system.

Figure 2.1 shows a typical once through cooling water system. The cooling media or cooling water is used on a once-through basis. Cooling water is pumped from a water source where it absorbs heat from the process side of the heat exchanger, and then discharged to the environment. If required, the cooling water is cooled by means of spray pond or lagoon before being discharged to the environment. Generally water extracted from lakes or rivers is screened to remove large contaminants to prevent damages to pumps and clogging of heat exchanger equipment. Typical water source for once-through cooling system are seawater or freshwater from lakes, rivers or underground water source. A once through system requires a large amount of water, thus typically used by plants located where abundant water source is available and accessible.

The advantages of using the once through system include:

a. No cooling tower system thus low capital cost
b. In some cases no water treatment is required thus reducing operating cost

The disadvantages of this system are:

a. Plant must be located near the water source
b. Only operate at small temperature rise, between 1°C to 2°C to limit environmental effect
c. Since this system usually use large amount of water quantity, it requires large pump and pipe work and thus increasing electricity cost
d. This system also poses a high risk of fouling on the heat exchangers from suspended material in water.

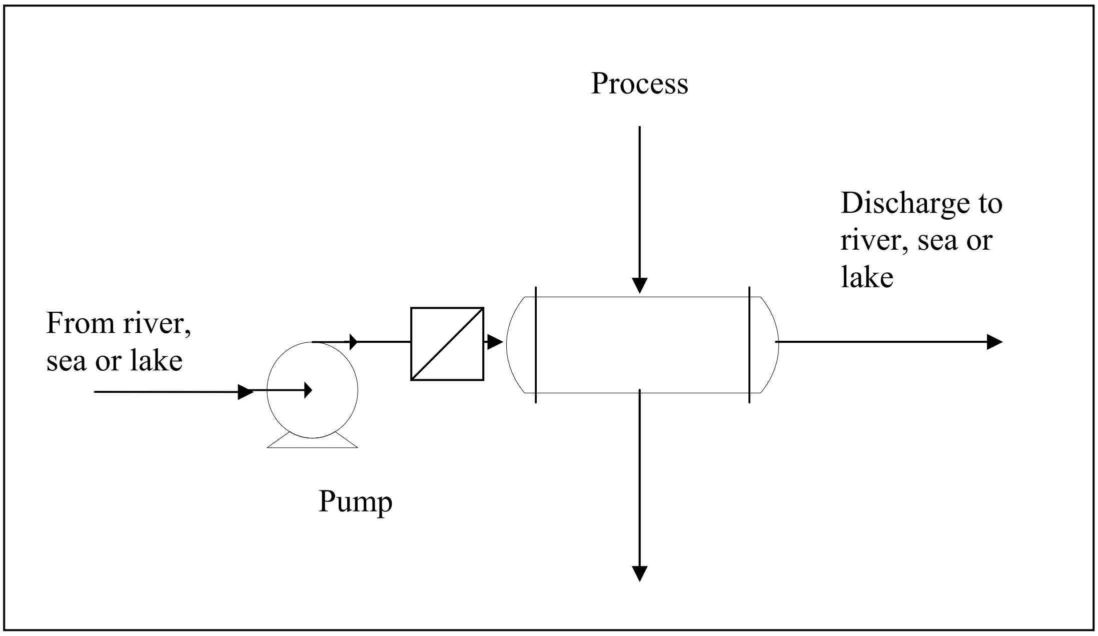

Figure 2.1: Once Through Cooling Tower System

For closed recirculating cooling water system as shown in Figure 2.2, heat is transferred from the process into the recirculating cooling water. The heat is then removed from the cooling water into another medium which acts as heat sink. Possible heat sinks include once-through seawater cooling, air cooling and open recirculating evaporative cooling.

The obvious advantage of the system is its ability to operate at low water usage or even stagnant flow. Consequently, the requirement for lower chemical treatment is also lower. A closed system is designed to be filled with water, and run continuously for long periods without significant amount of make-up water. In addition, the system can operate at higher temperatures since scale-forming constituents in a truly closed cooling system are low (PRSS, 2005).

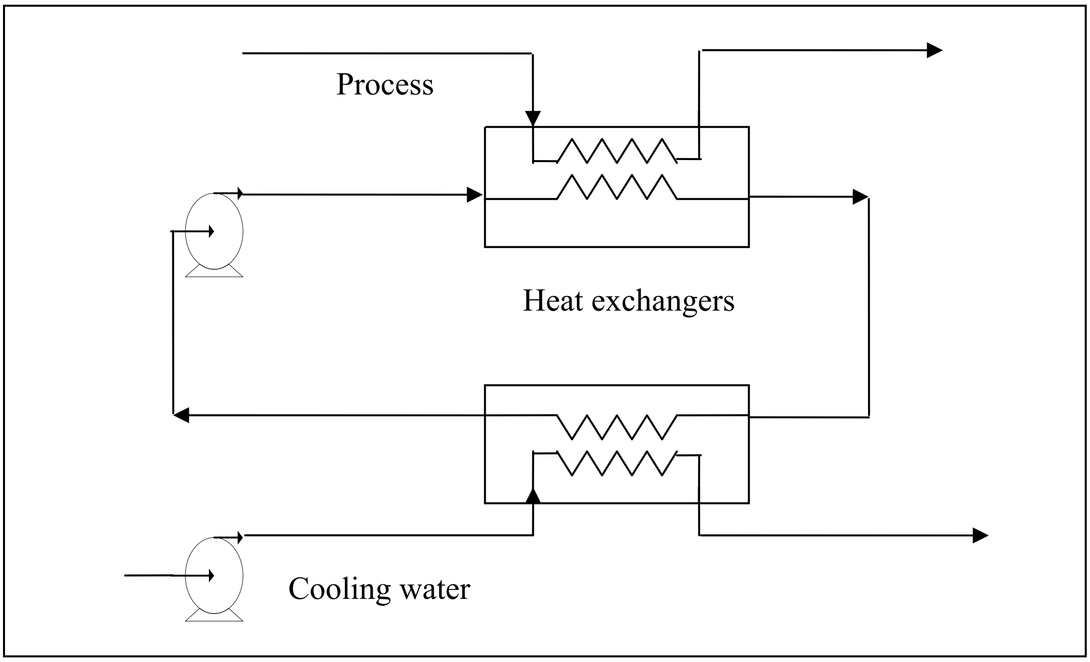

Figure 2.2: Closed Recirculating Cooling Water System

While, the disadvantages of this system include:

a. Closed systems, which are essentially two cooling systems in one, may require higher capital investment compared with other systems due to their greater requirement for equipment and pipework.
b. Closed re-circulating systems are less efficient than once-through or open evaporative systems as they have to rely on two heat transfer stages rather than just one. Thus, the cooled water temperature for open or once through system can get closer to the approach temperature or wet bulb temperature.

The commonly used cooling water system is open recirculating cooling water system. This system is described further in next section.

2.1.2 Open Recirculating Cooling Water Systems

Open recirculating cooling water system is the most widely used system in industries. The basic configuration of this system is shown in Figure 2.3. Open re-circulating cooling system is also known as open evaporative cooling system. The system is characterized by the presence of a cooling tower that is used to cool the cooling water. The cooling water, supplied by tower basin, absorbs heat from the process side through heat exchanger, thus raising its outlet temperature to a few degrees higher. The cooling water then returns to the tower. The return point is located just above the tower packing or fill. As the water flows down into the basin, the water is cooled by evaporative action of air and the process is repeated. Addition of fresh makeup water is required to replace water loss from evaporation and blowdown.

This system has few advantages and one of them is reducing the environmental problem (Lenntech, 2006). Cooling water that is used to cool process fluid will be circulated back to cooling tower. Only small portion of this water will be discharged as blowdown. It is different with once through cooling system in which all of cooling water is discharge after cooling process. In case of heat exchangers' leak, once it goes back to cooling tower basin, proper cooling tower treatment is required to control the contaminant level. Besides, the side stream filter is also used to remove suspended solids from cooling water. Thus, the cooling water blowdown is relatively clean compared to once through system.

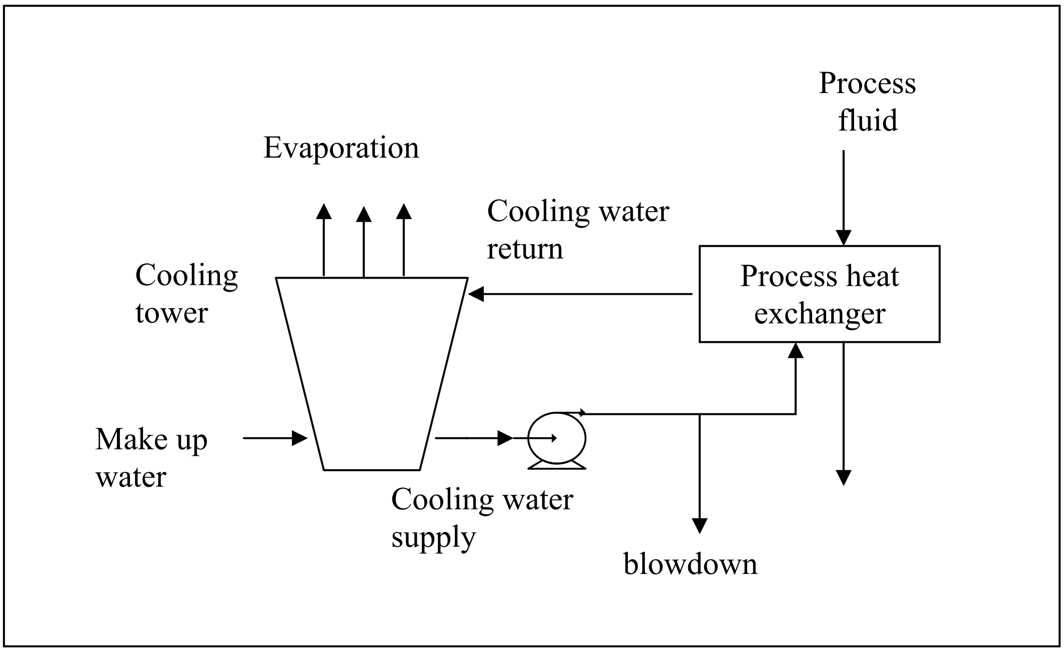

Figure 2.3: Open Recirculating Cooling Tower System (PRSS, 2005)

As cooling water is recycled within the cooling system, the water consumption is reduced compared to once through system. It is because; all water that is used for cooling is returned back to be cooled by cooling tower. Make-up water is only added to recover water loss by evaporation, blowdown and drift losses. Smaller amount of water quantity also reduces pump and piping capacity as well as electricity consumption compared to once through system.

2.1.3 Component of Cooling Water System

Generally, cooling water systems include cooling tower, chiller and several heat exchangers such as shell and tube heat exchanger and condenser for distillation column. The component in this system is important to be considered in the optimization studies, since this study will look at overall system. The interaction of these components will add value on quantifying the economic savings.

2.1.3.1 Chiller

A chiller can be generally classified as a refrigeration system that cools water (FEMP, 2006). Similar to an air conditioner, a chiller uses either a vapor-compression or absorption cycle to cool. Once cooled, chilled water has a variety of applications from space cooling to process uses.

The refrigeration cycle of a simple mechanical compression system is shown in Figure 2.4. The mechanical compression cycle has four basic components through which the refrigerant passes. The first component is evaporator, a component in which liquid refrigerant flows over a tube bundle and evaporates, absorbing heat from the chilled water return line that is circulating through the tube bundle. Then, the compressor is functioning to compress the refrigerant vapor to the condenser by raising the refrigerant pressure and consequently increasing temperature. In addition, condenser is a component in which refrigerant condenses on a set of cooling water coils giving up its heat to the cooling water. Finally, the high-pressure liquid refrigerant coming from the condenser passes through this expansion device, reducing the refrigerant's pressure and temperature to that of the evaporator.

The cycle begins in the evaporator where the liquid refrigerant flows over the evaporator tube bundle and evaporates, absorbing heat from the chilled water circulating through the tube bundle. The refrigerant vapor, which is somewhat cooler than the chilled water temperature, is drawn out of the evaporator by the compressor. The compressor "pumps" the refrigerant vapor to the condenser by raising the refrigerant pressure and thus, the temperature. The refrigerant condenses on the cooling water coils of the condenser giving up its heat to the cooling water. The high-pressure liquid refrigerant from the condenser then passes through the expansion device that reduces the refrigerant pressure and temperature to that of the evaporator. The refrigerant again flows over the chilled water coils absorbing more heat and completing the cycle.

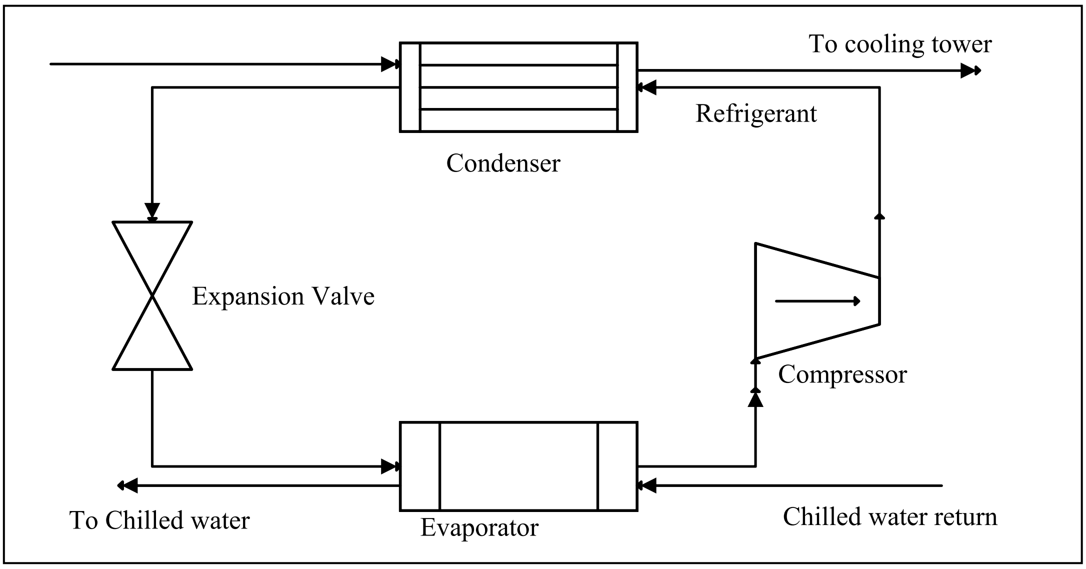

Figure 2.4: Mechanical Compression Chiller System (GDC, 2002)

While, for absorption chiller (Figure 2.5), the components are evaporator, absorber, generator and condenser. In a compression cycle chiller, cold water is produced in the evaporator where the refrigerant or working medium is vaporized and heat is rejected in the condenser where the refrigerant is condensed. In an absorption cycle chiller, compressing the refrigerant vapor is effected by the absorber, the solution pump and the generator in combination, instead of a mechanical vapor compressor. Vapor generated in the evaporator is absorbed into a liquid absorbent in the absorber. The absorbent that has taken up refrigerant, spent or weak absorbent, is pumped to the generator where the refrigerant is released as a vapor, which vapor is to be condensed in the condenser. The regenerated or strong absorbent is then returned to the absorber to pick up refrigerant vapor.

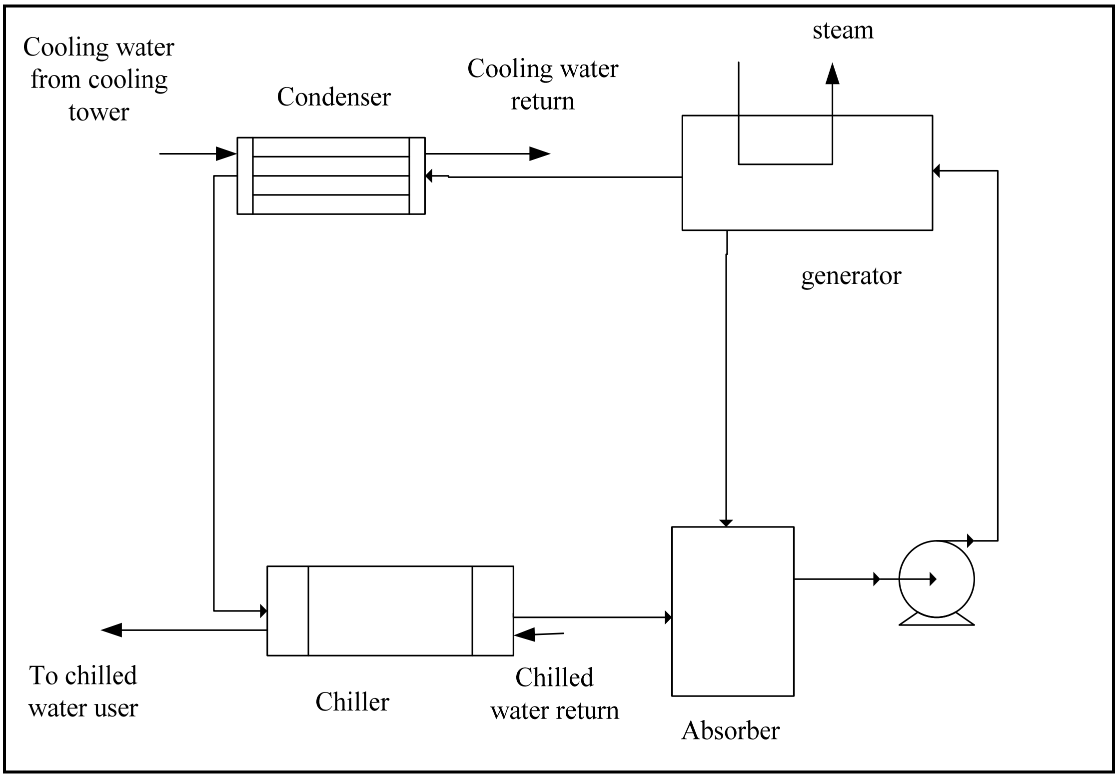

Figure 2.5: Steam Absorption Chiller (Perry and Green, 1997)

In both type of chillers, it will use cooling water that is supplied by cooling tower. Thus, any changes in cooling water will affect the chiller or refrigerant cycle. Burger (1995) stated that compression work will be saved by 3% for every 1°F (0.6°C) cooling water temperature reduction. Otherwise, FEMP (2006) stated that for every 5 °F to 10°F rise in cooling water temperature, \$2.5K to \$7K have to be paid for additional electricity cost in chiller operation.

2.1.3.2 Condenser for distillation column

Distillation column is one of main equipment in processing plant. It used for product separation where mixture with binary or multicomponents liquid is fed to the tower and it is separated by the difference of its boiling point. The lighter component will vaporize to overhead of the column and will be recovered as liquid. Condenser is used to convert vapor product to liquid product through condensation by cooling water.

Cooling water flow for condenser is one of the important parameter in controlling pressure in distillation column as shown in Figure 2.6. The cooling water flow is regulated in order to get the suitable overhead pressure, so that the desired amount of the product can be achieved. In this case if the cooling water flow is increased then more vapors are condensed and the vapor pressure is reduced and vice versa.

2.1.3.3 Process cooling

In a processing plant, cooling water is mostly used (Wurtz, 2000) for process cooling such as to cool final product before storage or going into other equipments, as compressor intercooler or use to control reactor temperature that results from an exothermic reaction.

For a reactor, a cooling jacket (Figure 2.7) is needed for controlling the temperature inside the reactors. It is required to prevent the temperature rising especially for exothermic reaction and to avoid material deterioration for reactors and heat exchangers and both reactant and product depreciation. Cooling water temperature and flowrate must be suitable for respective reactors to control the product quality and equipment efficiency. From Figure 1.8, it also can be seen that heat exchangers are using water as service fluid to cool the product from reactor before going for separation or storage.

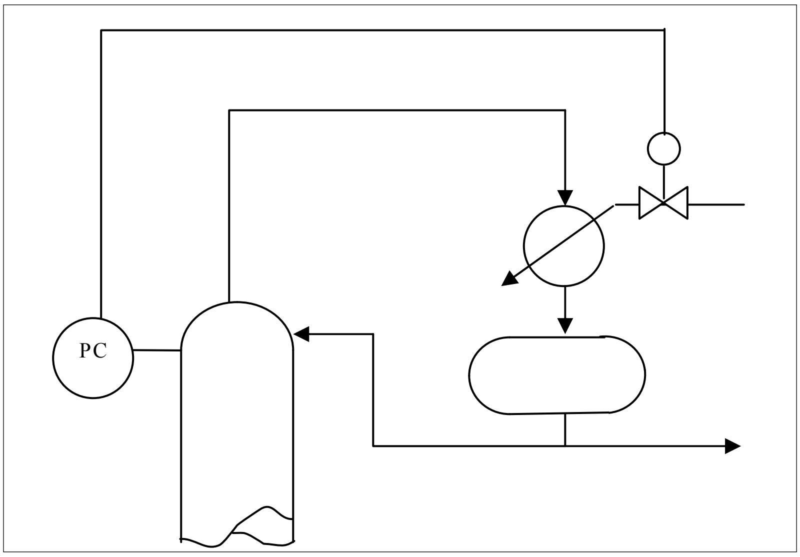

Figure 2.6: Controlling Column Pressure by Adjustment of Cooling Water Flow (Perry and Green 1997)

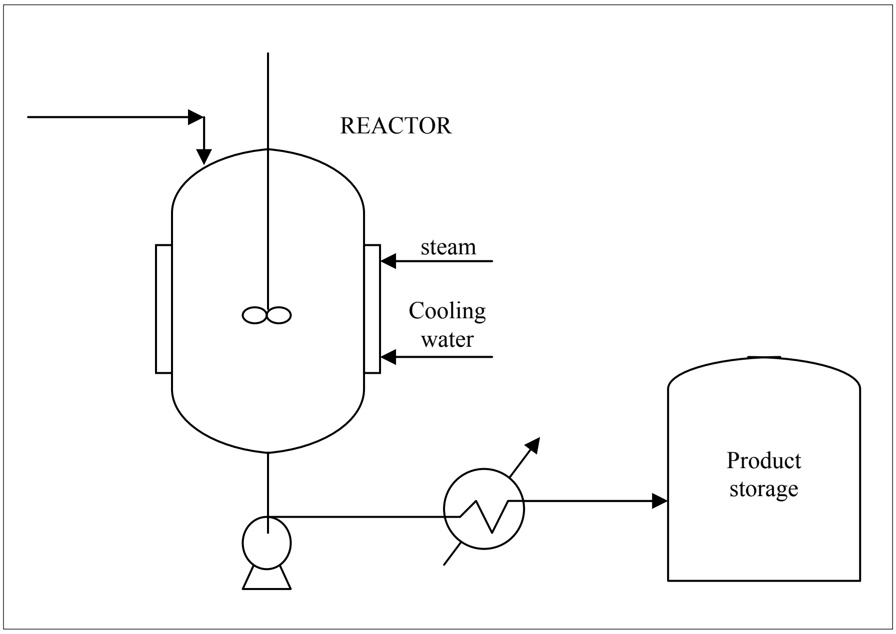

Figure 2.7: Reactor with Cooling Water Jacket and Cooling Water Heat Exchanger

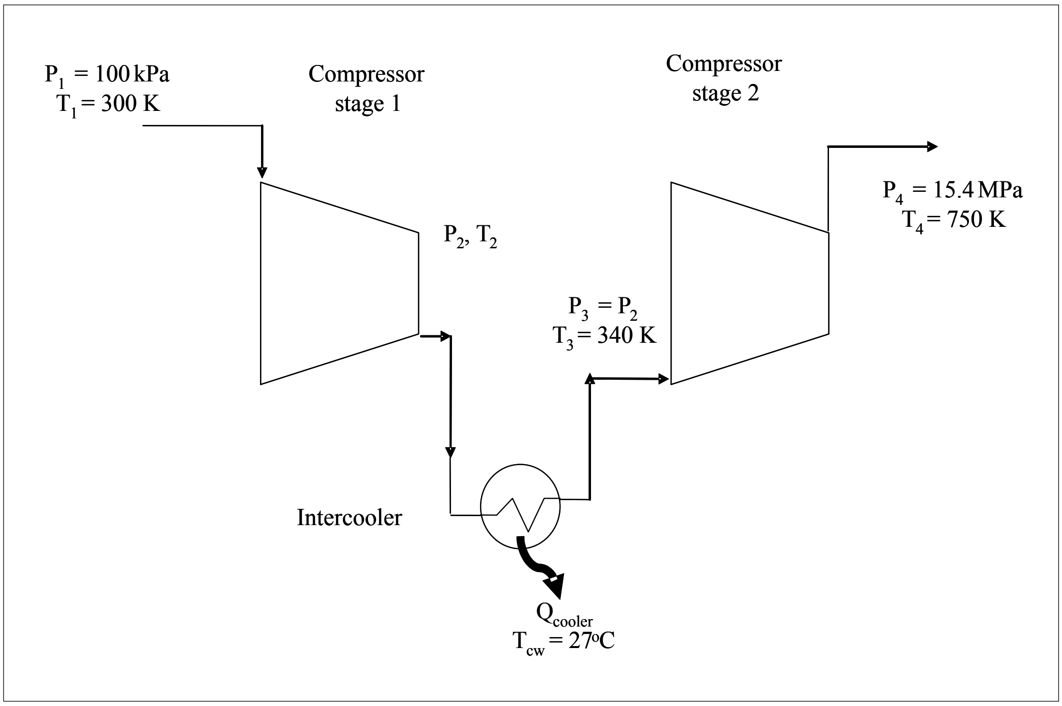

Figure 2.8: Cooling Water as Cooling Medium in Stage-Compressor Intercooler

2.2 Cooling Water System Model

Kim and Smith (2001) carried out the optimization of cooling tower by looking into interactions of cooling tower and its associated heat exchangers. Systematic approach to optimize the system has been outlined in their study. Mathematical modeling was formulated to investigate the interaction between cooling tower and its heat exchangers based on system shown in Figure 2.9. A one-dimensional steady-state model is developed to illustrate the working principles of cooling towers and cooling tower efficiency.

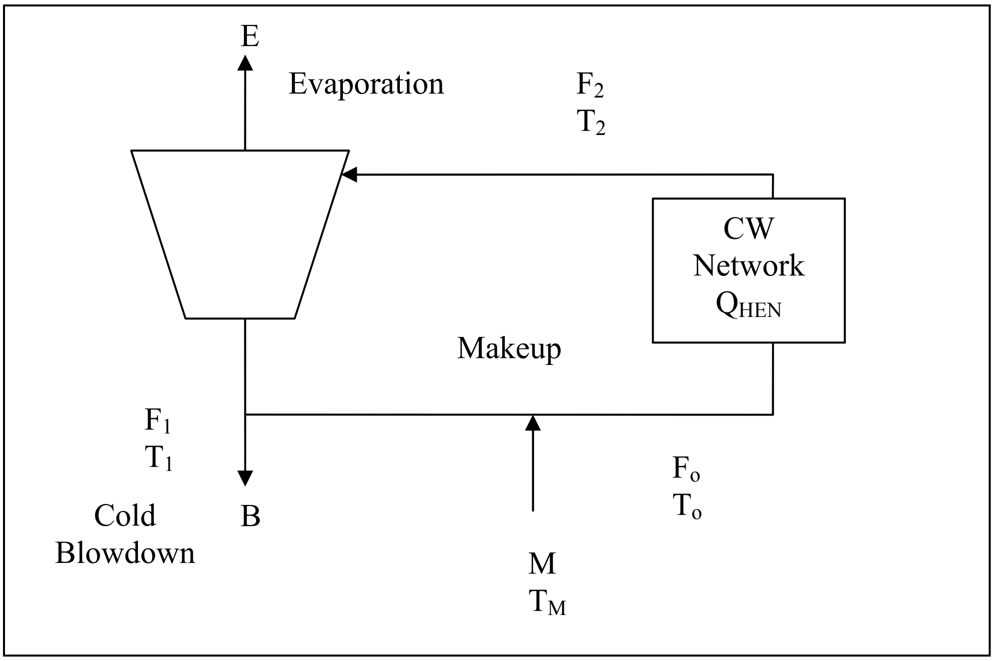

Figure 2.9: Cooling Water System (Kim and Smith, 2001)

The schematic for mass and energy balance for cooling tower system shown in Figure 2.10 is usually used in deriving the model.

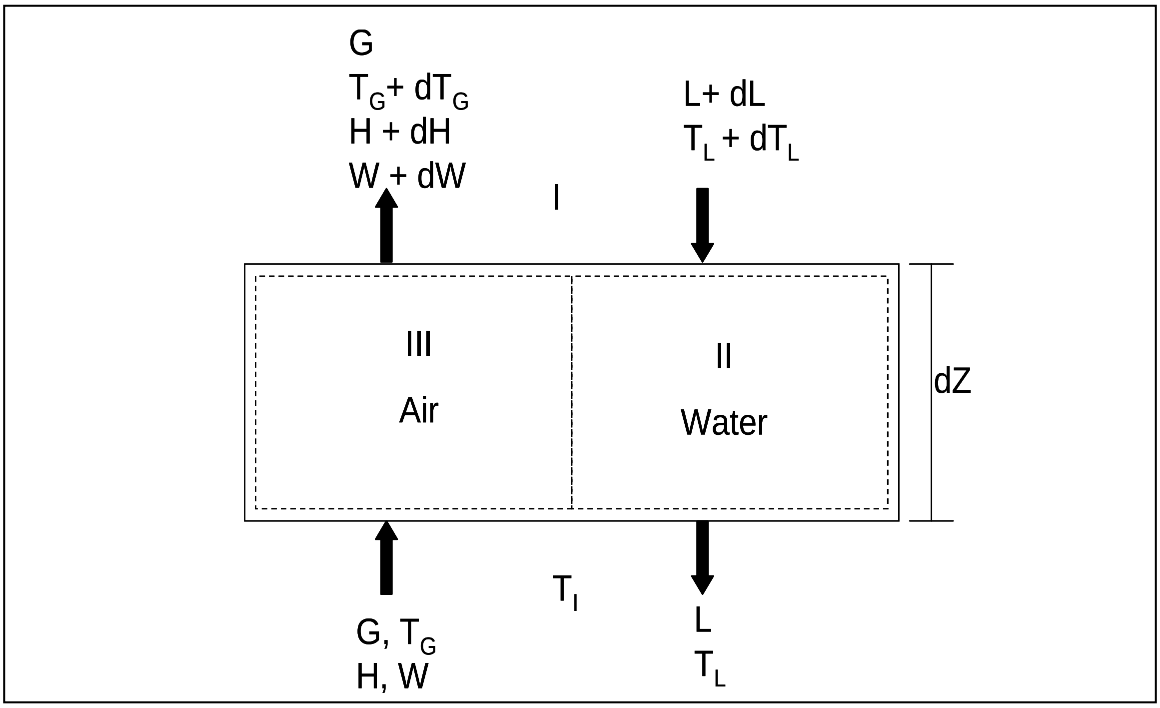

Figure 2.10: Schematic Figure for Mass and Energy Balance for Cooling Tower System (Kim and Smith, 2001)

Khan et al., (2004) proposed a model that present a risk based approach to the analysis of fouling models and to describe its impact on the thermal performance in cooling tower. This model assumed constant specific heat of water and dry air and also constant heat and mass transfer coefficient and Lewis number throughout the tower. In addition, heat transfer from the tower fans to air or water stream and also heat and mass transfer through the tower walls to the environment are negligible. The temperature is also assumed to be uniformed throughout the water stream at any cross section as well as the cross-sectional area of the tower.

This model is used to study the sensitivity analysis of various cooling tower parameters during the design calculation of a cooling tower. The sensitivity analysis includes the sensitivity of cooling tower volume with respects to cooling water outlet temperature, cooling water inlet temperature and wet-bulb temperature. Besides, the sensitivity of the effectiveness and water outlet temperature could be analyzed by using various mass to air ratio. Furthermore, the effect of atmospheric pressure of tower performance can also be studied by using this model.

While, a mathematical model for the numerical prediction of the performance of a crossflow cooling towers was presented by Kairouani et al., (2004). His model was based on the heat and mass transfer equations in which Lewis number, number of transfer unit, the percentage of water evaporation, water losses and cooling tower efficiency became its leading parameters. This model has been used to predict the performance of thermal behavior of six cooling towers that located in South of Tunisia as well as to determine the optimal of water loss quantity in cooling tower operation.

In addition, Söylemez (2004) presented a model that combining the thermal and hydraulic performance analysis of cooling towers in order to determine the optimum ratio of the mass rate of circulating water flow to the mass rate dry air flow. This optimum ratio can be investigated by varying the cooling water mean temperature at fixed ambient pressure or by varying the ambient pressure at fixed cooling water mean temperature. This model seems to be helpful for cooling tower designers, manufactures and users.

Furthermore, Cortinovis et al., (2009) has also built a model that considers the hydraulic, thermal and cooling water interactions in the overall process. A fundamental model is developed to obtain the performance of cooling tower, based on characterization of mass transfer coefficient, as a function of air and water flow rates that is obtained from the experimental design in the pilot plant. Due to the complex surface geometries of the cooling tower fills, the mass transfer coefficient is more precisely determined by the experiments.

2.3 Cooling Tower Performance

The effectiveness of cooling tower can be investigated through experimental work or modeling. From heat and mass balance model for cooling tower system, Kim and Smith (2001), it showed that when the inlet cooling water has high temperature and low flowrate, the effectiveness of cooling tower is high when the cooling tower removes heat from hot water. Kim (2001) compared the previous experimental data with his model, and both results agreed that the performance of cooling towers increases with a decrease in the L/G ratio. Maintaining high temperature and low flowrate of inlet cooling tower is important in order to keep the driving force high.

Fouling in cooling tower system can be described as the deposition of foreign matters, including bio growth on the water film area. This is usually true in cooling tower fills. Cooling tower model that was proposed by Khan et al., (2004) showed that fouling factors may reduced cooling tower effectiveness to approximately 6% and this reduces heat removal and in turn, increases 1.2% of water outlet temperature.

Marley (1983) reported two primary external factors, which are wind and air obstructions that influence the performance of cooling tower. The speed and direction of wind tends to cause part discharge air recirculate into the entering air stream. Then, the system begins to experience problems associated with elevated water temperatures such as an unexpected rise in wet-bulb temperature of the air entering the cooling tower. Higher cold water temperature is produced and consequently higher fan horsepower is needed and also increasing electrical consumption.

2.4 Cooling Tower Issues

Cooling tower design and operations as well as control system are main contributors for problems that are experienced by cooling tower internals and cooling water circulate in the system. Recirculating cooling water system use the same water repeatedly and the stagnant water in cooling tower basin result into water issues. The four fundamentals problems in cooling tower consist of scaling, corrosion, deposition fouling and microbiological growth. These water issues become worst when a problem becomes complex as depicted in Figure 2.11.

2.4.1 Fouling

Fouling in cooling systems may lead to corrosion. Fouling is mainly caused by the presence of insoluble suspended solids entrained into the system. The solids are deposited and accumulated onto surfaces of equipment of the water circulation. For instance, the particles of dust and dirt that presents in air will contaminate recirculating cooling water through the water make-up. It can create fouling on the inside surfaces of the condenser system which can lead to under-deposit corrosion and loss of heat-transfer efficiency. In addition, air dissolved in the water making it saturated with corrosive oxygen. This happens at all times during cooling tower operation and also creates ideal condition for corrosion.

Fouling can also be caused by microbiological growth. For open evaporative system, the presence of warm water and open sunlight is conducive for variety of life forms and nutrient sources. Thus, they are perfect breeding conditions for algae, fungi and bacteria. Microbiological growth can lead to corrosion as a result of under-deposit corrosion or direct attack from species that consume iron in order to propagate (PACE, 2006)

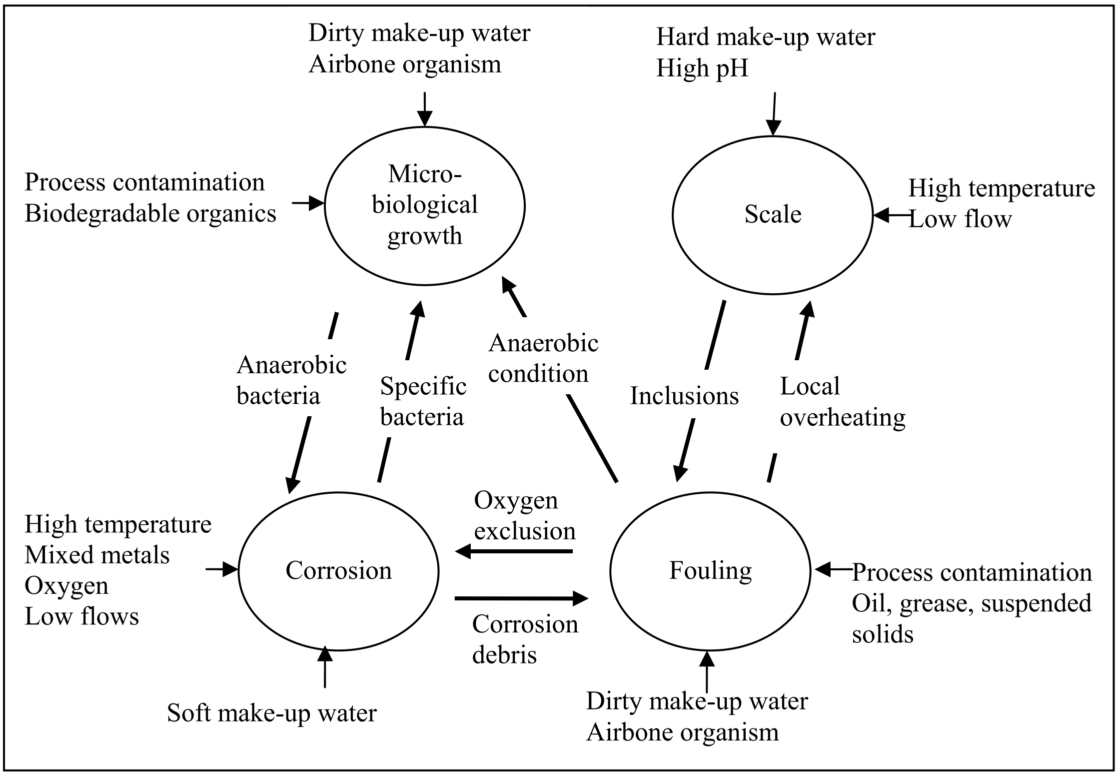

Figure 2.11: Water Issues in Cooling Tower (PRSS, 2005)

2.4.2 Scaling

Scaling is the crystalline deposition on the metal surfaces of inorganic materials from supersaturated solutions. Scaling occurs typically when the make up water has high hardness and alkalinity and the pH of the recirculating water is high. The main problem of scale is that it forms on heated surface of heat exchanger and consequently reduces heat transfer efficiency.

2.4.3 Corrosion

In addition to scaling problem, corrosion can occur through an electrochemical reaction in the presence of oxygen and water. It may cause equipment failures and can reduce the cooling tower performance. As opposed to scaling problem, water with low hardness concentration and low pH are more corrosive. Proper hardness and pH control must be established to minimize such problem.

Decreasing heat transfer efficiency will translate directly into increased cooling cost. The cooling tower problem affects not only the cooling tower performance, but also the component in recirculating cooling tower system such as condensers and heat exchangers. Thus, proper maintenance and treatment program must be implemented.

2.4.4 Chemical Treatment

PACE (2006) has suggested the following ways to minimize these problems. One of that is to implement a properly designed chemical treatment. It involves in maintaining adequate levels of corrosion inhibitor, scale inhibitors and biocide in the cooling tower system. These agents should be carefully chosen to suit the local conditions under which the tower operates, for instance, raw water quality, air quality and material constructions. Chemical for treatment must be fed properly to ensure it works efficiently. The corrosion and scale inhibitors should be maintained in constant level at all times, while biocides are most effective when applied in slug doses on a product-alternate basis.

Proper implementation of an appropriate chemical treatment program will eliminate metal corrosion and scale deposits; reduce water usage and discharge; and allow running at higher cycles of concentration. Furthermore, the installation and proper maintenance of a filter for the water to condenser/cooling tower user can also help to minimize the needs of cooling tower treatment. Sand filter can be installed on a sidestream of cooling water and it will greatly assist in controlling the buildup of solids in the circulating water and on internal surfaces. Regular testing of the cooling water and observation of the equipment is also necessary to maintain adequate chemical levels and to ensure prompt action in the case of sudden system disruptions.

2.5 Cooling Tower Heat Transfer

The water and air relationship is illustrated in Figure 2.12. This illustration is only applicable for counterflow tower. This diagram is used in understanding cooling tower process.

The water operating line is shown by line AB and is fixed by the inlet and outlet tower water temperatures. Meanwhile, line CD representing air operating line which starts at point C, vertically below point B. The liquid-gas ratio, L/G is the slope of the operating line. The cooling range is equal to the differences of cold water and wet bulb temperature and approach is the differences between cold water and hot water temperature.

Basically, cooling tower process heat balance can be used to predict cooling tower performance. As shown by Equation 2.3, by finding the area between ABCD in Figure 2.12, one can find the tower characteristic. An increase in heat load would have the following effects on the diagram in Figure 2.12 in which as increase in the length of line CD, and a CD line shift to the right. It also will increases in hot and cold water temperatures as well as increases in range and approach areas.

The increased heat load causes the hot water temperature to increase considerably faster than does the cold water temperature. Although the area ABCD should remain constant, it actually decreases about 2% for every 10^{o}F increase in hot water temperature above 100^{o}F (Cheresources, 2005).

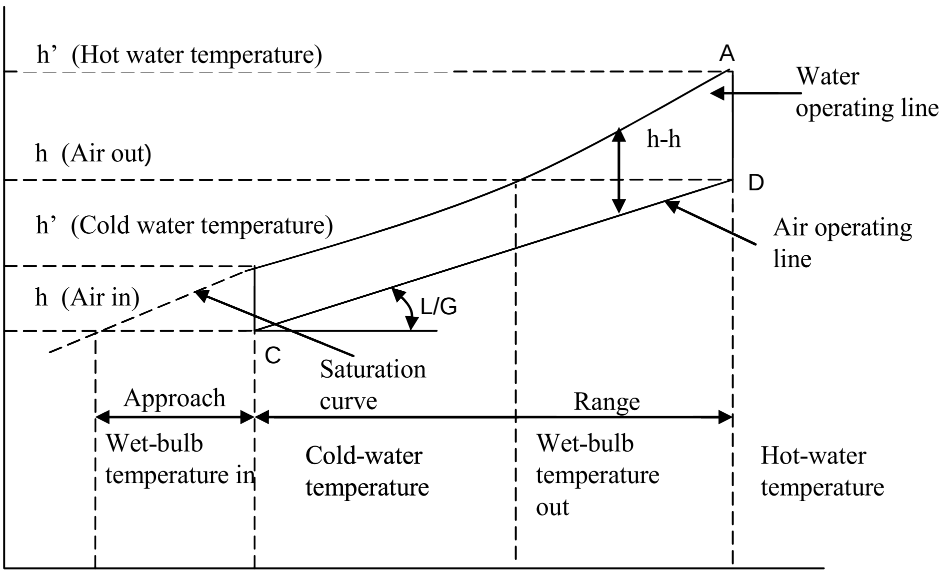

Figure 2.12: Cooling Tower Process Heat Balance (Perry and Green, 1997)

2.5.1 Cooling Tower Characteristic Curve

Usually, cooling tower manufacturer will provide cooling tower characteristic curve (Figure 2.13). This curve is used for cooling tower testing. This curve contains data on cooling tower characteristic value, KaV/L and water/air ratio, L/G. According to Cooling Tower Institute (CTI), the curves should be based on constant fan pitch angle. The straight line shown in Figure 2.13 is a plot of L/G vs KaV/L at a constant airflow. The slope of this line is dependent on the tower packing, but can often be assumed to be -0.60. From thus curve, it can be concluded that:

1. A change in wet bulb temperature (due to atmospheric conditions) will not change KaV/L
2. A change in the cooling range will not change KaV/L
3. Only a change in the L/G ratio will change KaV/L

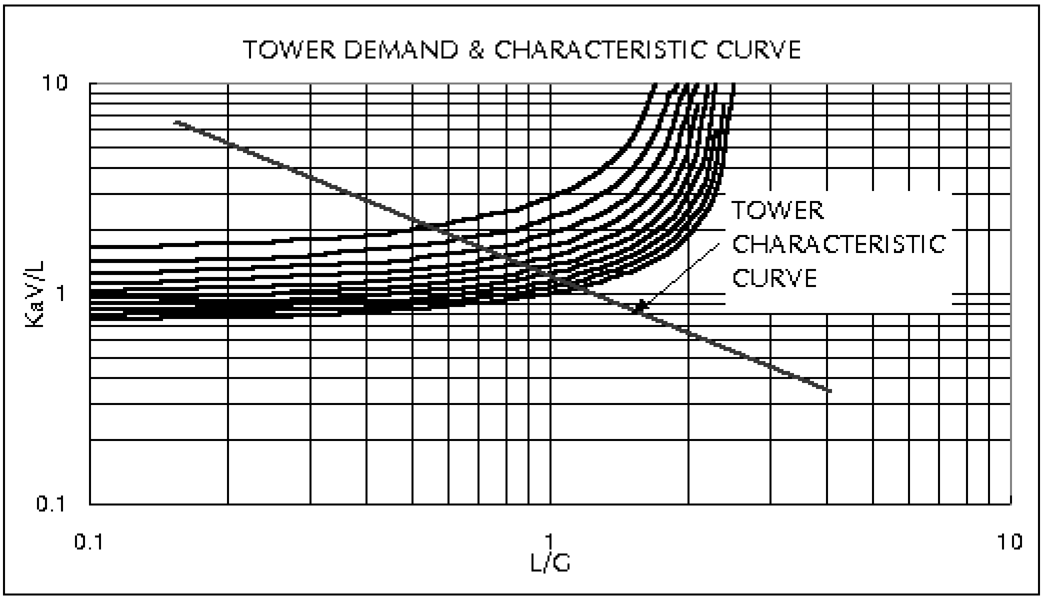

Figure 2.13: A Typical Set of Tower Characteristic Curves (Burger, 1995)

2.5.2 Merkel's Equation

An alternative approach of estimating cooling tower performance is by using Merkel's Equation. Merkel's model was developed by Merkel in 1925 (Burger, 1995). His analysis and Equations include the sensible and latent heat transfer into and overall heat and mass transfer process based on enthalpy difference as the basic driving force.

$$\frac{KaV}{L} = \int_{TW2}^{TW1} \frac{dT}{h_w - h_a} \tag{2.1}$$

Cooling tower performance can be evaluated by using Merkel's Equation (Perry and Green, 1984) as in Equation 2.1. Similar to cooling tower characteristic curve, the terms KaV/L is used to describe the amount of heat transfer by the cooling tower or also known as tower characteristic curve. This theory is generally accepted by the industries due to its simplicity.

This model is basically derived by assuming that heat is transferred from water drops to the surrounding air by the transfer of sensible and latent heat as illustrated in Figure 2.14. Temperature of air, T_A is lower than bulk water temperature, $T_{B,}$ and so as the enthalpy for the respective temperature. This enthalpy difference will create driving force and thus, heat will remove from water to the wet air.

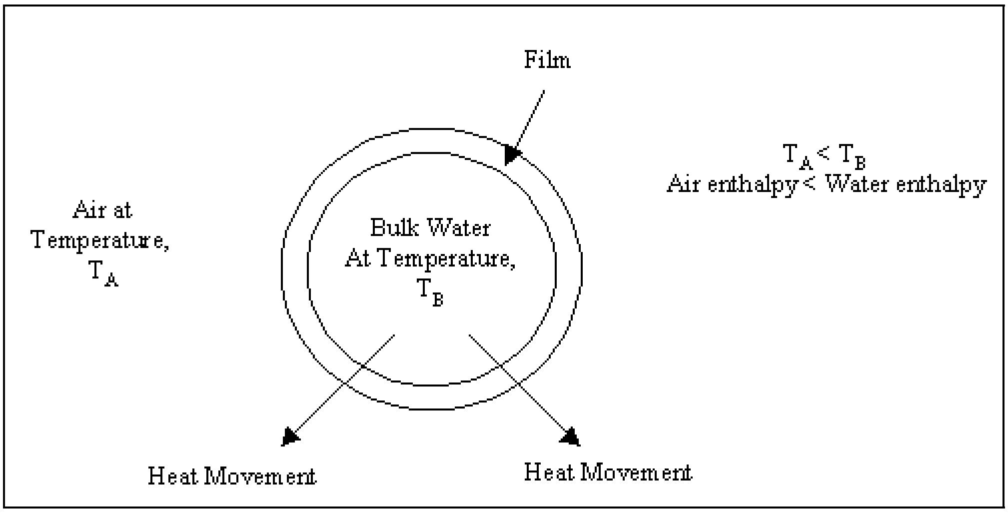

Figure 2.14: Water Drop with Interfacial Film (Cheresources, 2005)

Thermodynamics also dictate that the heat removed from water must be equal to the heat absorbed by the surrounding air:

$$L(T_{hw} - T_{cw}) = G(h_2 - h_1) \tag{2.2}$$

$$\frac{L}{G} = \frac{h_2 - h_1}{T_{hw} - T_{cw}} \tag{2.3}$$

The terms KaV/L in Equation 3.3 can be solve used Chebyshev method:

$$\frac{KaV}{L} = \int_{T_{cw}}^{T_{hw}} \frac{dT}{h_w - h_a} = \frac{T_{hw} - T_{cw}}{4}\left(\frac{1}{\Delta h1} + \frac{1}{\Delta h2} + \frac{1}{\Delta h3} + \frac{1}{\Delta h4}\right) \tag{2.4}$$

2.6 Operational Constraint on Cooling Tower Performance

Prior to any parameter changes in cooling tower operation, the constraint and limitations of the existing cooling tower must be made known. This will determine the number of degree of freedom exist in the optimization process.

2.6.1 Constant Wet-bulb Temperature

Marley (1986) stated the performance of cooling tower is affected by wet-bulb temperature, hot water temperature, and ratio of water to air flowrate (L/G). The heat load of the cooling tower is directly proportional to cooling water flow and cooling water range, which are the difference of hot and cold water.

While, the wet-bulb temperature depends on ambient temperature as well as the humidity or moisture content in air. In a seasonal country, the wet bulb temperature will change due to the ambient temperature change. Tower size factor varies inversely with wet-bulb temperature. When heat load, range, and approach values are fixed, reducing the design wet-bulb temperature increases the cooling tower characteristic or cooling tower size factor. This is because most of the heat transfer in a cooling tower occurs by means of evaporation and air's ability to absorb moisture reduces with temperature However, in Malaysia, the ambient temperature and air humidity is constant throughout the year. As such, the moisture content change can be neglected.

2.6.2 Approach, L/G and KaV/L

Ideally, wet-bulb temperature is the lowest theoretical temperature to which the water can be cooled. However, in practical, the cooling water temperature cannot meet the air wet-bulb temperature because it is impossible to contact all water with fresh air as water drops through cooling water fills. In actual practice, cooling tower is seldom designed for approaches lower than 2.8^{o}C.

Water to air ratio, L/G can be set as low as possible, by decreasing water circulation rate or increasing fan power. However, smaller water flowrate will affect the cooling water user demand. In addition, high fan power will increase energy usage and hence cooling tower operating cost. Thus, before changing cooling tower parameters, there is a boundary limit for L/G value and also tower characteristic, KaV/L. Mechanical-draft cooling towers normally are designed for L/G ratios ranging from 0.75 to 1.5, and KaV/L ranging from 0.5 to 2.5.

2.6.3 Water losses

Meanwhile, Perry and Green (1997) gave some factors that could be use in quantifying the water lost from the cooling tower system such includes evaporation, drift and blowdown. Evaporation loss quantity can be calculated by adding factors of 0.00085 to the total heat load of the cooling tower. This occurs when hot water is exposed to cooling air streams, hot water turns to vapor and heat from hot water is removed during this process.

Moreover, the drift loss is caused by water entrained in discharge vapor. Usually, drift eliminator is installed to prevent water being carried upwards by air. However, of course there will still small quantities that can be escaped from the eliminator which usually about 0.2% of water circulation rate. Besides, a blowdown is needed to prevent salt and chemical treatment buildup in cooling tower system. Unfortunately, a blowdown will make the circulated water reduced. Generally, 3% of water circulation rate will be discarded, or it can be more or less depending on cycle of concentration (CC) required for treatment system.

Those water losses must be quantified properly. The quantity of water make-up required is equal to total water losses through blowdown, drift and evaporation losses. This is important to replace it and maintain the cooling water circulation in the system and thus, the performance of heat exchanger in process side is also maintained.

2.6.4 Maximum hot water temperature

In addition, the maximum hot water temperature must be identified so that the cooling tower internal including fills would not be destroyed. Spxcooling (2006) stated that, as general rule, the hot water temperature must be maintained below $60^{o}C$. Besides destroying cooling tower internals, high water temperature could affect the chemical treatment program and lead to corrosion and scaling. Scaling will reduce cooling tower efficiency since it will reduce heat transfer area.

2.7 Optimization of Cooling Tower System

2.7.1 Mechanical Modifications

The optimization of cooling tower can be carried out by changing the mechanical parts, the existing configuration or by changing the operating condition at process side that using cooling water as a cooling medium to the process fluid. Mechanical modification of cooling tower involves change or addition of new cooling tower equipment such as new piping, adding new cell, installing new pump or change cooling tower fill.

Goshayshi et al., (1999) studied the cooling tower optimization through evaluating the effects of various cooling tower fills. Basically, changing new cooling tower fills will improve cooling tower performance by improving the cooling ability. Since the cost of packing contributing 20 to 25% of total cooling tower cost, the selection of the best packing should be made to minimize the investment cost as well as to improve cooling tower efficiency.

The study concluded that overall mass transfer coefficient and pressure drops of ribbed corrugated packing increase considerably compared with smooth packing and also affected by spacing of the packing as well as the distance between the ribs. It also found that the packing with high air turbulence in combination with relatively low fluid velocity is more economic than a fairly smooth and straight packing in combination with high liquid velocity.

Stanford (2003) proposed to change the tower configuration can be change by reconfiguring a forced draft tower as an induced draft tower or the small fans of a forced draft tower can be replaced with ducted air delivered from much larger fans. However, this type modification is not always cost effective and it is more economically attractive by replacing it with a new one.

Gañán et al.,(2004) is also proposed a new cooling tower configuration that combines a present cooling system (Lake Arrocampo) with natural convection cooling tower in parallel in order to improve the performance of cooling tower system for the

Nuclear power plant. The newly installed cooling tower is designed by using Merkel's Equation in which the water to air mass flowrate ratio comprised between 1 to 1.5.

During the coldest months, the temperature of the water cooled by the towers would be too low for the condenser operation. Thus, the specific volume of the vapour would increase excessively. This would lead to a growth in its outlet rate from the low pressure turbine. In such case, the efficiency of the thermodynamic cycle would not be increased. Thus, the three-ways valve system is also installed in this system together with the appropriate connections. It would be possible to operate with the cooling towers during the unfavourable months. This would lower the circulation water temperature, thus increasing the condenser vacuum and consequently improving the efficiency of the system.

2.7.2 Process Modifications

Optimization of the operating conditions for cooling tower applications in cooling water is extremely significant in order to get the most energy efficient operating point for this system. Cooling tower optimization through process modification is carried out through changing the cooling tower operating parameters.

Crozier et al., (1977) proposed an approach that generates savings in both capital costs of the cooling water system and the energy required for pumping. In his guidelines, two constraints must be satisfied that are closer approach to the wet-bulb temperature could increases the cooling tower investment and closer approach to the limiting process temperature will increases the exchanger area.

Furthermore, the cooling water temperature rise is assumed to be 20^{o}F unless temperature crosses is resulted, in which case a 10^{o}F approach to the process outlet was used. In addition, the "guideline" approach set the cooling water temperature outlet temperature equal to the process outlet temperature. For heat exchanger that having LMTD less than 30^{o}F, a real optimum could be determined by plotting capital and operating cost against cooling water temperature rise.

Based on this approach, the cooling water operating cost is saved due to less cooling water flowrate and less power using for pumping work. However, the water treatment program cost is increased since the lesser cooling water flow inside the cooling tower will make the water more concentrate and need more chemical dosing. This study will become good guidelines for designing cooling water reuse where the LMTD can be used as a constraint.

In addition, Hoots et al., (2001) improving the cooling tower performance by modifying the cooling tower parameters in which the high cycles of concentration is applied in cooling tower operation. By recirculating cooling tower system at higher concentration provides many economic and environmental benefits. Higher cycles of concentration will reduce water and chemical discharge and thus reducing cooling tower operating cost. But operation at high cycle of concentration should consider the few considerations such as hydraulic factors, time-related factors and water chemistry factors.

The study also looks at the effects of high cycle of concentration in heat exchanger network. The minimum flowrate is measured to determine heat exchanger performance in order to ensure that the performance is not being limited by insufficient cooling water flowrate. Fouling inside the heat exchanger is also monitored in case of the excessive throttling of cooling water flowrate or incorrect heat exchanger design. Finally, the efficiency is also determined by measuring cooling tower flowrate, process fluid flowrate and temperature drops.

Their results showed that at maximum concentration cycles setting, operating cost reduces up to $135,000. However, overall treatment cost increased due to the increase need of more-aggressive bio-control approach and the installation of side-stream filters.

Meanwhile, Söylemez (2004) carried out an optimization of cooling tower by considering two important parameters, the ratio of heat capacity flowrates and the number of transfer units and it is done in thermo-hydraulic manner. The optimum ratio of mass flowrate of circulating water to the mass flowrate of dry air, $M_{opt,}$ can be determined by combining the thermal and hydraulic performance analyses of cooling tower.

This study was found that the optimum values of M are varies with different mean water temperature and pressure. The relationship is presented in linear curve in which at constant cooling water mean temperature, the optimum M will decreasing as the ambient pressure is increasing. However, at constant ambient pressure, the optimum M is proportional to cooling water mean temperature. The optimum M value is increased as the average water temperature increases or the ambient temperature decreases. The water mass flowrate must be increased for a location that has lower ambient pressure and for higher average tower water temperature for the given air flowrate. The correct selection of M will lead to increase cooling tower efficiency.

NCDENR (2005) gave several options in improving the cooling tower efficiency in terms of water management including blowdown and cooling tower water treatment program. In blowdown optimization option, water consumption can be reduced by minimizing blowdown in conjunction with an integrated and maintenance program. Besides, this paper also presented few treatment programs options in order to maintain a clean heat transfer surface while minimizing water consumption and meeting discharge limits.

Several guidelines are suggested by Nesta and Bennet (2006) in order to minimize fouling effect in cooling water system. During system design, all items in cooling water loop should be designed to use the maximum allowable pressure rather than fixing the temperature rise and set the least amount of cooling water and then maximizing allowable pressure drop where it possible. Water flowrate is then adjusted to get the same pressure drop, more or less. However, the critical tube wall temperature also must be monitored because it may lead to corrosion and fouling. Thus, the cooling water flowrate is based on equal pressure drop by distributing itself to equalize the system pressure drop from inlet to outlet header.

In contrast, if design pressure drop varies from exchanger to exchanger, the resulting cooling water flow to a given item may not be that required on the data sheet; some coolers may get more or less. A large cooling water user with low design pressure drop may rob cooling water from other users. Equal pressure drop may prevent this problem.

2.8 Water and Wastewater Minimization

Besides being used as cooling fluid in heat exchangers, water is consumed for separation process in extraction, absorption, stripping, scrubbing operation, such as product quenching, equipment washing and steam generation.

Previously, the industries always think that water is a very cheap utility. However, the prevailing shortage of water in some parts of the world, together with the increase environmental concerns on water pollution has made the job to conserve water become necessary.

Conventionally, the engineers reduce freshwater consumption by changing the process for individual units. For instance, they increase number of mass transfer plates such as extraction and scrubbing, introduce local recycle, implement better control scheme or upgrade water washing equipment system.

There were different approaches that are used by researchers in water minimization technique. Wang and Smith (1994) specifically addressed the water minimization problem by considering it as a contamination-transfer problem from process streams to water streams. This approach has served as the pioneering tool for water minimization technique.

The study have adopted mass transfer concept to explain the concept of the creation of liquid wastes as a migration of contaminants from a plant's process streams to its water streams. It can also be represented as a plot of concentration versus mass or also called as limiting water profile.

The concept of limiting water profile enables different water-using operations to be treated on a uniform basis and allows the design procedure to proceed without concern about the specific nature of the process stream or particular operating pattern. As this profile defines a boundary between feasible and infeasible region, any supply water line below or at the limiting profile would satisfy the process requirements.

Linnhoff (1997) was introduced a systematic approach based on water reuse between processes in his case study for Mosanto plc. Based on this case study, the benefits that identified by this systematic approach include reducing the volume of water used in the sytem, save raw materials and energy, reduce chemical oxygen demand (COD) and finally save of capital expenditure of centralized effluent treatment plant. Water pinch analysis also showed how Mosanto could improve effluent handling. Instead of all effluent being discharged centrally, it was far more efficient to segregate and treat different effluent streams. Adopting this measure meant only 25% of the site's effluent need secondary treatment.

Moreover, Isahak (2004) study was developed a systematic methodology to minimize freshwater consumption and hence wastewater based on the process integration techniques. In this work, the water -source and -demand plot was explored further to look at the application of the Water Composite Curve (WCC) and Water Grand Composite Curve (WGCC). A new methodology was also produced to develop the WGCC. There are some new findings that were looked into such as process modification, water bypass and mixing, and pseudo pinch, which are used to explore new applications of these plots.

Three case studies were presented to illustrate the application of the methodology developed for single contaminant, which has been extended for multiple contaminants using an example to show how the WCC is plotted. From these examples, not only an average of 34% fresh water savings can be achieved, but at the same time, several options were able to be generated by this procedure. The best option or design can be screened out without going into the detail design of the plant.

Furthermore, Foo et al., (2002) was applied water cascade analysis (WCA) by using tabular and numerical approach to eliminate the tedious iterative steps of the water surplus diagram. By applying WCA, the accurate water targeting and pinch point location can be quickly yield. This method is not just limited to mass transfer-based operations but can be applied in wide range of water using operation. Various options involving process changes, including water regeneration and mechanical modification can easily assessed using this method.

This study also showed that WCA can be used to handle multiple streams operation in very efficient and accurate way as well as with much less effort. The systematic procedure of this method is also can easily translated into any computer language for the software development.

Less work has been done on water minimization problem for batch processes and this lead Tan et al., (2003) to develop the systematic that involving two key steps for water minimization, namely water targeting and network design have been conceived for batch processes. For water targeting, a new procedure which employs the water cascade table (WCT) has been developed to establish the minimum water requirement for maximum water recovery and minimum wastewater generated. This table has been adapted from water surplus diagram for continuous processes. The WCT is a tabulated approach that avoids the tedious graphical drawings of water surplus diagram.

In addition, a systematic procedure for water networks design for batch processes, which include a recent developed graphical tool called the time-water network, has been introduced to allow designers to achieve the utility targets established for the problem.

2.9 Design of Cooling Water Network

During plant design stage, the cooling water network is usually designed in parallel configurations. In which, the cooling water supply from cooling tower divided into heat exchangers correspond to the flow needed by those units. Every unit will receive fresh cooling water from the tower and after it has been used, hot water will return to heat exchanger.

2.9.1 Cooling Water Pinch Analysis

Kim (2001) adapted the limiting water profile concept into cooling water system pinch analysis in order to develop ‘limiting cooling water profile’. In cooling network analysis, it is assumed that any cooling water-using operation can be represented as a counter-current heat exchange operation with a minimum temperature difference. Maximum inlet and outlet temperatures of cooling water stream are limited by the minimum temperature differences (ΔT_{min}).

The limiting profile is used to identify between feasible and infeasible region. In constructing limiting cooling water profile, the data of hot stream is extracted. The data was including inlet temperature of hot stream, outlet temperature of heat stream, heat capacity of the stream and also the heat load for the heat exchangers. Then, the curve of temperature versus heat load is drawn together with maximum cooling water stream outlet and inlet temperature. From this curve, the feasible region of cooling process can be determined.

Then, the cooling water composite curve is constructed by combining all individual profiles into single curve within temperature intervals. From this curve, the cooling water network can be designedThe maximum reuse can be determined by maximizing outlet temperature and minimizing the cooling water flowrate. Each point where the supply line touches the composite curve creates a pinch in the design. In heat transfer, the pinch does not imply zero driving force but a minimum driving force.

2.9.2 Cooling Water Network with intermediate mains

Cooling water mains are also included in cooling water network design in which they are conceptualized in cooling water design grid. In the network, an intermediate cooling-water main is positioned between the cooling-water supply main and the cooling-water return main, with the temperature usually at the pinch.

The intermediate main receives recirculating cooling water from some coolers at temperatures less than or equal to its temperature and provides cooling water to some other coolers, which can use cooling water at temperatures higher than or equal to its temperature. In this way, the recirculating cooling water into or out of each cooler will be coming from or going into one of the three mains.

Kim and Smith (2001) shows example of cooling water design grid with cooling water main using limiting cooling water data that extracted earlier. Three cooling water mains are created in three different temperatures, at supply temperature, pinch temperature and maximum temperature allowable in the system. All streams are connected by cooling water mains at respective temperatures and thus satisfying the individual cooling requirement.

The method is carried out in four steps. The first step is to generate a grid diagram with cooling water mains and plot the cooling water using operations. The second stage is to connect the operations with cooling water mains that is determined from the pinch point at plot of temperature versus heat load of each heat exchanger. Then, the operations that cross the water mains is merge in the next stage and finally the cooling water mains was removed and this will allowed the design of the cooling water network to be achieved with maximum water reuse.

Chen et al., (2006) proposed a superstructure-based MINLP formulation in designing cooling water network with intermediate mains. Their research probes how the number of intermediates of cooling water mains influences the recirculating cooling water system's performance. The mathematical model considers the generic problem confronted in the design of a recirculation cooling water system, including stretching the cooler network design and setting the operation constraints. The study also investigated how the conditional direct connections between cooling units can decrease the consumption of the recirculating cooling water network under little sacrifice of piping complexity.

Their study concludes that the more mains are added, the more recirculating cooling water can be saved since higher return temperature is obtained resulting from more cooling water is reused in the network. In addition, more intermediate mains also increases operational flexibility because more buffer mains reduce the interference between heat exchangers. However, additional intermediate cooling water main will increase the complexity of the piping network due to increase of new additional piping is required to connect the heat exchangers and the intermediate mains.

2.9.3 Cooling Water Network Design Using Mathematical Programming

A superstructure models are also designed in carrying out the optimization of cooling tower system integrated with the cooling water using operations. Cortinovis et al.,

(2009) has developed an integrated mathematical model for the minimization of the operating costs of cooling water, as stated in previous section. The cost minimization was investigated by varying the flow rate of hot water removed, the fan rotation speed and the flow rate of circulating water in the system.

Besides, as inspired by previous study by Kim and Smith (2001) that considering the impact of the cooling water network on the performance of the cooling tower; Majozi and Moodley (2008) developed a mathematical optimization technique for debottlenecking of cooling water systems. The choice of mathematical optimization technique over a typical graphical method is due to the flexibility of the former to handle various constraints from the practical view. In addition of direct cooling water supply, this work also allowed for reuses and recycle streams.

Furthermore, Panjeshashi et al., (2009) has combining the pinch technology and the mathematical programming using MATLAB for minimum cost achievement together with enhanced cycle water quality. The technique is called as Enhanced Cooling Water Design (ECWSD). This work is actually extended of Kim and Smith (2001) by developing the comprehensive simulation model of recirculating cooling water system that accounting the interaction between cooling tower and heat exchanger network. The ozone treatment technology is also integrated in this system in order to improve the cycle water quality. Thus, this study provided an optimized cooling water system with water and energy conservation, minimum cost and environmental impacts.

Then, Gololo et al., (2011) presents a technique for synthesis and optimization of cooling water system which incorporates the performance of the cooling tower involve. A mathematical model for the cooling system that consisting of multiple towers that supply to common sets of heat exchangers is generated. The cooling tower model is used to predict the thermal performance of the cooling towers. Meanwhile, the thermal conditions of the associated heat exchanger network also taking into account.

This proposed technique debottlenecked the cooling towers by decreasing the circulating water flowrate. This can be achieved by exploiting the opportunity for cooling water reuse. In addition, the water outlet from heat exchanger can go to any cooling tower provided that it fulfilled the specified cooling tower inlet temperature. The decreased in the overall circulation water flowrate has added benefit of decreasing the overall power consumption of the circulating pumps. This would also lead for the decreasing of blowdown and water make up.

2.10 Summary

In this chapter, a literature review of design of industrial water system and cooling water system is carried out. Basically, much of the work of cooling tower optimization is focused on improving the performance through changing the operating parameters, adding new equipment, increasing electrical capacity or upgrading treatment system. Very few attentions have been given to the cooling tower design as a system itself, with heat exchangers and condensers, with analyzing the interaction of this system contains to achieve economics savings. Thus, new design or improvement work should consider the entire cooling system component such as the study that is carried out by Kim (2001), where pinch analysis is used. However, the limitation of cooling tower operation is not properly address in his study that could affect on both the cooling tower and heat exchanger performance. Crozier "guidelines" is also a good guide for designing cooling water reuse where the LMTD is used as one of the constraints.

Besides, for controlling fouling and pressure drop issues, equalized pressure drop in cooling water loop may also beneficial. Intermediate cooling water mains can also be used in initial cooling water design. Other studies by Majozi and Moodley (2008), Gololo et al., (2011), Pajeshashi et al., (2009) and Cortinovis et al., (2009) carried out integrated optimization between cooling tower and cooling tower user. Mathematical model and programming used to obtained the new operating parameter of cooling tower without take into account the suitability of existing cooling tower operation that usually describe as the cooling tower characteristics.

In the following chapters, new methodology for the design cooling water networks will be described. In which, instead of simultaneous optimization, a two-steps optimization will be introduced by investigating the limitations and constraints of the existing cooling tower unit, before carried out the optimization procedure. Then only, water reuse and recycle are applied in order to fulfill the new cooling tower supply temperature and circulation rate as well as to satisfy the demand of each heat exchangers. Thus, it is hoped that, this research will promote the wide application of the proposed systematic study because of its relevancy for all the existing running process plants utilizing the cooling water system.

CHAPTER 3

DEVELOPMENT OF COOLING TOWER OPTIMIZATION PROCEDURE

3.1 Introduction

The primary objective for cooling tower optimization is to increase cooling tower efficiency and consequently reduce the cooling tower operating cost.

One of the options to improve cooling tower efficiency is by reducing cooling tower outlet temperature or cooling water supply temperature. The actions results in the lowering of L/G ratio. Higher G value to the tower can be gained by increasing fan power. However, higher fan power increases operating cost. On the other hand, lower L value by decreasing the amount of water circulation in the system will reduce cost of water. In cooling tower operation point of view, the cooling water reduction must be made carefully. This because, it can lead to the fouling problem inside cooling tower and the concentration level of contaminants in cooling water will increase and give a potential of additional water treatment program.

As the amount of cooling water circulating in the system is reduced, the performance of the condenser or heat exchanger will get affected. Low cooling water flow will reduce the heat transfer between process fluid and cooling water and consequently the quality if the process fluid or products may not meet the plant specifications. Besides, low cooling water flow will cause fouling problem inside heat exchanger and will reduce the heat transfer efficiency.

The cooling demand in the cooling water network must be maintained to avoid product quality give-away. Thus, cooling water reuse must be applied in order to maintain the cooling water flow rate into each heat exchanger and retain the same cooling performance.

3.2 Stage-Wise Approach

A two-stage optimization procedure is proposed in this work. The procedure is able to provide greater insights to the designer as compares to an overall optimization approach. In addition, the procedure is able to offer a range of solutions rather than a single solution to the system designer.

In the first stage the approach temperature (the difference between wet-bulb and cooling water supply temperature) is reduced by lowering cooling water circulation rate. By using Merkel's Equation, a set of reduced approach temperatures and water circulation rates are obtained subject to the cooling tower operational constraints. The results from the first stage are then used as initialization for the second stage, in which for water reuse design. In addition to reducing the cooling water circulation rate, air flowrate reduction maybe investigated as well.

In the second stage, data for heat exchangers associated with the cooling tower is collected. These are cooling water flowrate, inlet and outlet cooling water temperatures. These data are required to construct the cooling water composite curve. From the composite curve, reuse opportunity can be identified by identifying overlapping area between the source and the sink curves. The fresh water intake and outlet cooling water return to cooling tower for this system is then checked. If the value of water flowrate or cooling water return temperature is not matched with cooling tower optimized parameters, the calculation is back to the first stage and it is iterated until the cooling water flowrate and temperature supply satisfies the demand respectively.

3.3 Data Extraction

For data extraction, firstly, the information of cooling tower system is collected for first stage procedure. For the existing cooling tower system, the important data that need to be collected is wetbulb temperature, design supply cooling water temperature, design cooling water return temperature, air mass flowrate and cooling water circulation rate. Those data are important to calculate the cooling tower characteristic and consequently, determining the new cooling water supply temperature and cooling water circulation rate.

For second stage procedure, all heat exchangers that associated with the respective cooling tower are gathered and tabulated. The information consist of the type of heat exchanger, cooling water inlet and outlet temperature , process fluid inlet and outlet temperature, heat capacity and heat load of the heat exchangers. Besides, the overall heat transfer coefficient and heat transfer area are also need to be determined.

3.4 Cooling Water Temperature Reduction

The objective of the cooling tower performance optimization in the first stage is to reduce the approach temperature to an acceptable limit. Typically, this value is about 2 to 3^{o}C. The colder cooling water supply, the better the process efficiency is. This can take in the form of process debottlenecking for condensers and greater efficiency requirement for refrigeration and air conditioning system. Temperature reduction can be achieved by reducing cooling water circulation rate or reducing air flowrate inside the cooling tower.

3.4.1 Reducing Cooling Water Circulation Rate

Cooling water circulation rate maybe reduced under different conditions of air flowrate, heat load, hot water temperature and range.

3.4.1.1 Constant Air Flowrate and Heat Load

In order to achieve cooling water supply temperature reduction, L/G value must be reduced. From the characteristic curve, the lower L/G value will move the operating point to the left following the characteristic slope. As a result, a lower approach temperature is produced for constant ambient temperature and air flowrate. The minimum cooling water circulation rate is then limited by both the minimum cooling water flow inside cooling tower and the associated heat exchangers. In the absence of cooling tower characteristic curve, which is usually provided by the manufacturers, Merkel's Equation shall be used.

Prior to temperature estimation, a new KaV/L or NTU must be determined first by solving the Merkel's Equation. For this case, Chebyshev Method is applied. Then, the value of C is calculated using Equation 3.1. C is a constant value regardless of the change of water flow rate in finding the approach at the alternative temperature conditions.

$$C = \frac{KaV/L}{(L/G)^{-m}} = \frac{KaV}{L} x \left(\frac{L}{G}\right)^{m} \tag{3.1}$$

Value of m in this Equation 3.1 is similar to the characteristic curve slope in tower characteristic curve. Then, the new tower characteristic is calculated by inserting new L or L` into Equation 3.1 and it can be rewritten as Equation 3.2.

$$\text{New tower characteristic, C`} = \frac{C}{\left(\frac{L'}{G}\right)^{m}} = Cx\left(\frac{L'}{G}\right)^{-m} \tag{3.2}$$

Equations 3.1 and 3.2 are actually locating original and new KaV/L respectively along the characteristic slope line. It is to ensure that the existing cooling tower is accommodating the new operating parameter L`. The negative value of m in equation 3.2 is because it was originally multiplied with the new cooling tower characteristic value, C`. Then, in order to determine the value of C`, the L/G terms is brought to the right hand side, and thus the m value became negative.

In order to get new cold and hot temperature of the tower, some iterations is needed by varying approach temperature until the KaV/L or NTU value of assumed approach is equal to new tower characteristic, C`. Then the new hot and cold water temperature (HWT and CWT) can be calculated using Equations 3.3 and 3.4.

$$\text{New } T_{cw} = T_{wb} + \text{New Approach} \tag{3.3}$$

$$\text{New } T_{hw} = T_{cw} + R \tag{3.4}$$

The procedure is summarized in Figure 3.1.

3.4.1.2 Constant Air Flowrate, Heat Load and Hot Water Temperature

The calculation step in (3.4.1.1) is applicable if the efficiency and heat transfer area, or water and air contact area is maintained as designed value. However, if the hot water temperature, heat load and air flow is fixed as per previous value, then debottlenecking procedure must be applied.

Hot water temperature is fixed to ensure that cooling tower internals will not be damaged by hotter water. The required cooling water circulation rate is calculated as follow:

$$L` = Q / R \tag{3.5}$$

In equation (3.5),

Q	heat load (BTU/min or kW)
R	Range (^oF or ^oC)
L`	new cooling water circulation rate (GPM or m^3/hr or ib/min)

New L`/G ratio is then calculated while maintaining air flowrate constant. However, by fixing the hot water temperature, the contact area in cooling tower fill will change slightly from original condition. For example, by following the original characteristic slope (slant line in Figure 1.13) in cooling tower characteristic curve, cooling tower with heat load of 50 kW, L/G = 1.23 and range of 13^{o}C is able to cool down hot water with flowrate of 3308 t/hr and temperature of 47.23^{o}C to colder temperature which is at 34.23^{o}C.

On the other hand, with the same range, water and air volume, hot water is entered at 45^{o}C. The KaV/L value will increase by 58.3%. The parameters K,a and V represent the mass transfer coefficient, contact area in active tower volume, and active tower volume in plan area, respectively. Higher KaV/L value within the same cooling water flowrate means larger contact area and active tower volume.

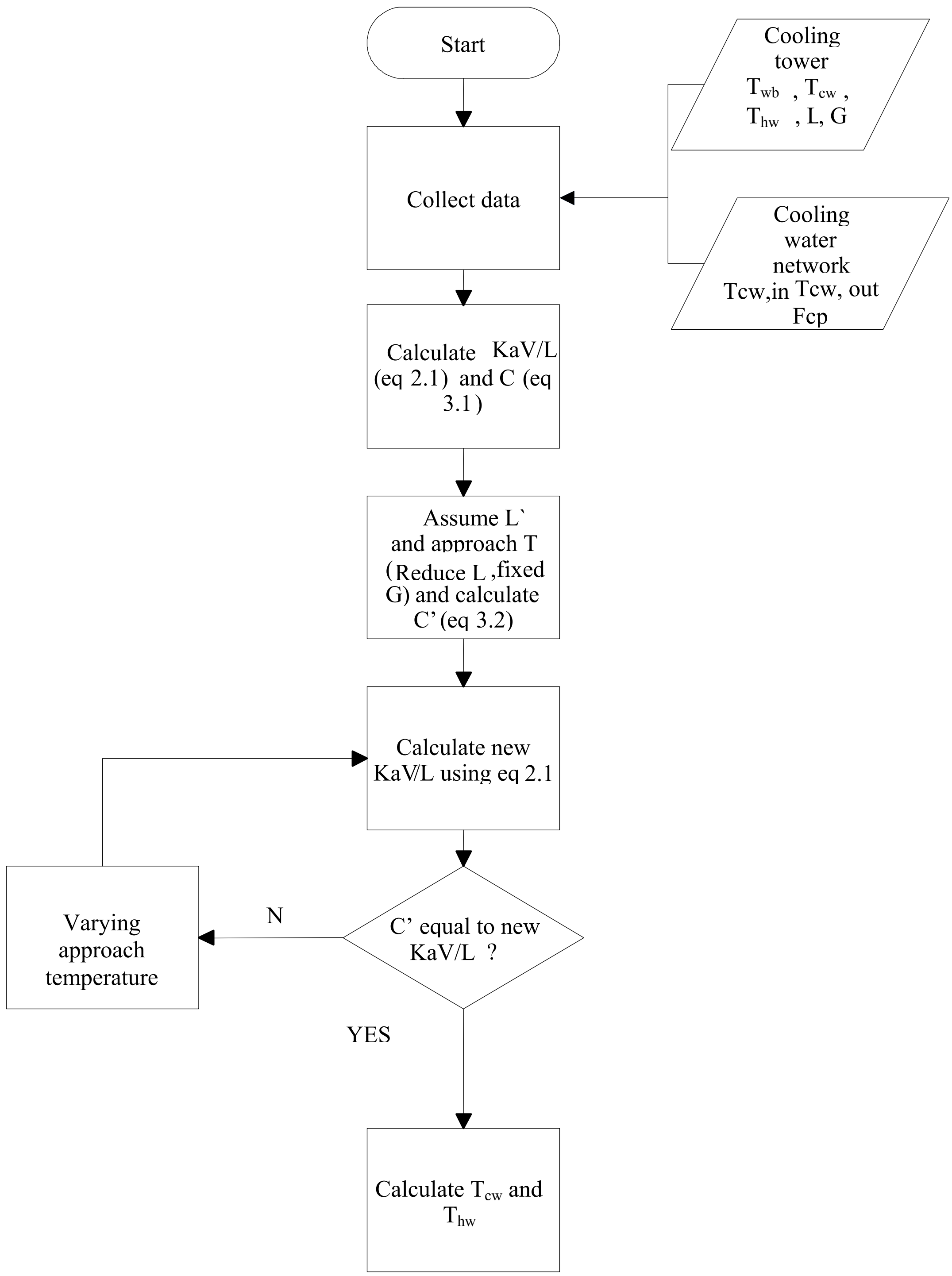

Figure 3.1: Calculation Steps for Reducing Cooling Water Circulation Rate as In Stage 1

This will make cooling tower increase its active tower volume. The increment of cooling tower characteristic is still acceptable since the maximum KaV/L value is 2.5 (Perry and Green, 1997).

3.4.1.3 Constant Air Flowrate and Variable Range

In this case, the L/G value is assumed first. From cooling tower characteristic curve or Merkel's Equation, the respective KaV/L and cooling tower approach that intersect at a design characteristic slope is found. The slope of tower characteristic curve value is usually assumed as -0.6 (Burger, 1995).

For constant heat removal from cooling tower, Equation 3.6 can be used to predict the cooling tower range. On the other hand, if cooling tower inlet temperature that is obtained from cooling water network is lower than calculated value from Equation 3.6, it can be assumed that heat removal in cooling tower is lower than that in the operating condition. The cooling tower characteristic, KaV/L value is constant since change in wet-bulb temperature and range will not affect the relationship of KaV/L, L/G and approach temperature. The relationship can be seen from cooling tower characteristic curve. This is due to the fact that the characteristic curve is plotted in logarithmic scale. If the cooling tower parameters are plotted in the same logarithmic function, the relationship of abscissa L/G and ordinate KaV/L are the same at different wet-bulb and range values (Burger, 1995).

$$R = Q / L` \qquad (3.6)$$

3.4.2 Reducing Air Flowrate

The energy consumed by cooling tower fan also contributes to high electricity cost in operating cooling tower together with electricity used by cooling tower pump. Operating cost savings can also be achieved by reducing air flowrate and consequently reducing the power needed to run the fan. However, reducing air flowrate alone can cause L/G value getting higher and less heat will be removed from hot water returning to a cooling tower. This will affect the cooling water usage in later stage.

One of the options is to maintain the L/G value, in which air flowrate and cooling water recirculation rate is reduced proportionally. Since L/G value is maintained, KaV/L and approach temperature will also be maintained (refer section 1.4.3). However, the cooling water supply temperature will remain the same and thus, the cooling tower efficiency will not be improved.

3.5 Cooling Water Reuse

Reducing cooling water circulation rate will affect the cooling water users, such as condensers. The flowrate cooling water supply is now less than the demand for cooling water by the heat exchangers. The only way to satisfy cooling water user demand is to promote cooling water reuse. Cooling water reuse is initially adapted from water reuse in wastewater minimization (Kim, 2001). In this work, pinch analysis is carried out in early stage of reuse study to determine the reuse opportunity in the system.

3.5.1 Application of Cooling Water Network Composite Curve

The procedure by Dhole (1996) is applied in the construction of cooling water network composite curve. The initial cooling water data is extracted from the cooling water network.

The cooling water inlet to heat exchanger is called as ‘sink’ point and cooling water outlet is called as ‘source’ point. First, the cooling water temperature of source and sink stream is arrange in terms of descending cooling water temperature.

For source streams, a horizontal line is drawn for the highest temperature of cooling water effluent. The quantity of cooling water flowrate at this temperature is then drawn on the horizontal axis. A vertical line is drawn from the current temperature level to the temperature of the next cooling water effluent. The flowrate of the second temperature of cooling water effluent is accumulated by continuing the horizontal line. This procedure is continued for each temperature of cooling water effluent to give the upper "staircase" of the cooling water network composite curve.

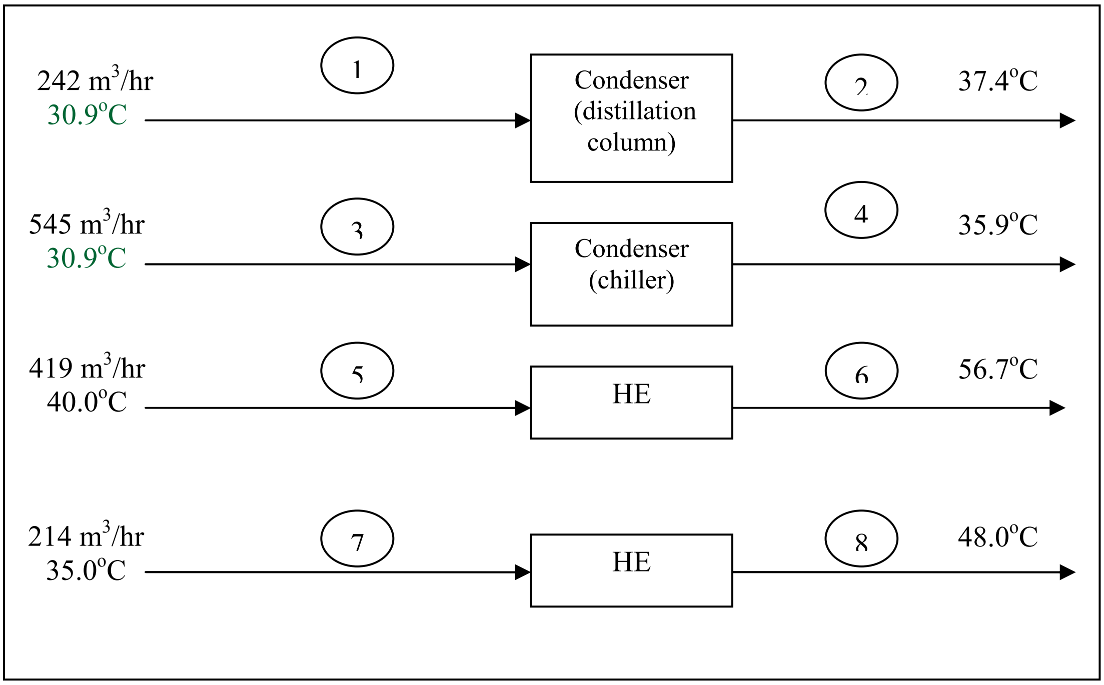

Figure 3.2: Example of Cooling Water Network

For the sink stream, a similar "staircase" is constructed, starting at an arbitrary flow rate such that this second staircase does not overlap with the 'sources' one. Once constructed, the 'sinks' staircase is moved horizontally until it touches the 'sources' staircase. The point at which the two meet is called the *Pinch Point*. With the cooling water network composite curve, opportunities for cooling water minimization shall be determined. For example, water reuse opportunity is possible if the quantity and the temperature are sufficient.

The opening at the top of the composite curve indicates fresh cooling water supply from cooling tower and the opening at the bottom indicates cooling water return to cooling tower. The vertical overlap between the two "staircases" highlights where opportunities exist for water reuse.

Other than using cooling water directly from source point, mixing of stream can also be applied to increase the cooling water recovery and minimize cooling water consumption. The suitable cooling water flowrate and temperature of two streams must be selected properly, so that it can satisfy the sink requirements. Other options is to mix the source stream with fresh cooling water, so that the temperature of source stream can be reduced and can be used by sink stream that require lower temperature than original source temperature. Besides using graphical method (Isahak, 2004), the amount of mixing streams can be identified by using mathematical programming.

3.5.2 Application of Mathematical Programming using GAMS

For any heat exchanger, HE *(i)*, where *i=1,2..,n* acting as sink point, it requires cooling water inlet at flowrate *B(i)* and temperature *Tsink*. The two source streams are flow of *x(j+1)*, where *j=1,2..,n,* with temperature *T(j+1)* and flow of *x(j-1)* with temperature *T(j-1).* This mixture will cause inlet temperature to increase. Fresh cooling water with flowrate of *y(i)* and temperature *Tcw* is added to the mixture to dilute the inlet temperature to *Tsink* value.

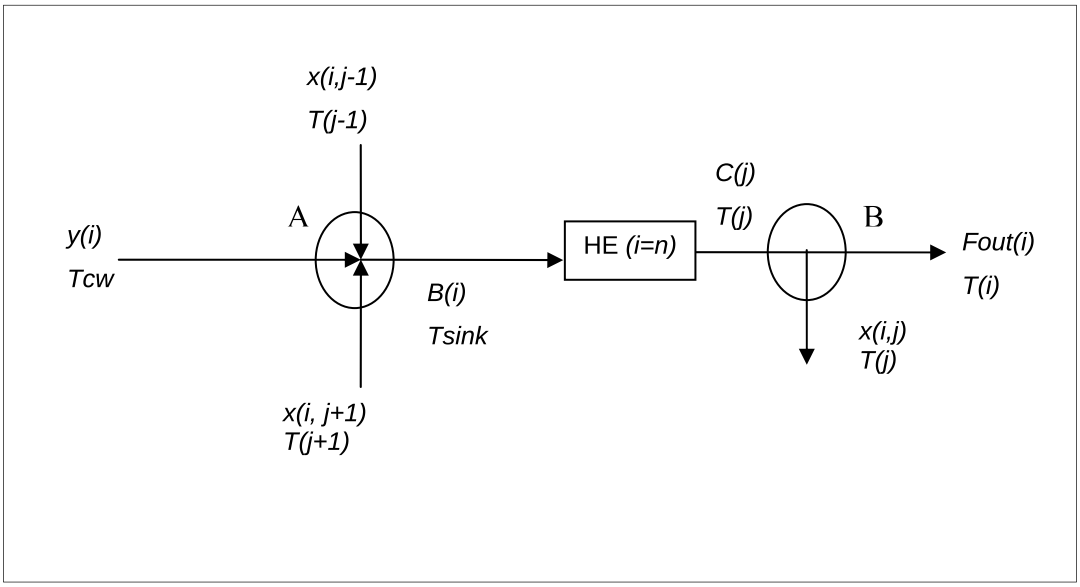

Figure 3.3: Schematic Representation around Heat Exchanger

Figure 3.3 shows the schematic representation around heat exchanger HE *(i)*. The original mass balance around point A is:

F_{cw1} . Cp_{cw} . (T_1-T_{ref}) + F_{cw2} . Cp_{cw} . (T_2-T_{ref}) + F_{cw3} . Cp_{cw} . (T_3-T_{ref}) = F_{cwsink} . Cp_{cw} . (T_{sink}–T_{ref}) (3.6)

Then, by assuming that Cpcw is constant and Tref = 0^oC, Equation 3.6 is translated using the variables used in Figure 3.3:

At i = n, and j = 1,2 ……., n

$$x(i, j+1)T(j+1) + x(i, j-1)T(j-1) + y(i)Tcw = B(i)Tsink \quad (3.7a)$$

If the cooling water sources are more than two streams, the model can be written as:

$$\sum x(i,j)T(j) + y(i)Tcw = B(i)Tsink \quad (3.7b)$$

The following constraints apply in this problem:

(i) Total cooling water reuse must be less or equal than total cooling water outlet of heat exchanger (source point)

$$\sum_j x(i,j) \le c(j) \quad \text{for } i = 1,2\ldots\ldots,n \text{ and } j = 1, 2, \ldots.. , n \quad (3.8)$$

(ii) Total cooling water reuse and fresh cooling water flow into each heat exchanger must be equal to cooling water demanded or needed by respective heat exchanger (sink point)

$$\frac{\sum_i \left[x(i,j) \bullet T(j)\right] + y(j) \bullet T_{cw}}{T_{\sin k}} = b(i) \quad \text{for } i = 1,2\ldots\ldots,n \text{ and } j = 1, 2, \ldots.. , n \quad (3.9)$$

(iii) Total cooling water outlet temperature (source temperature) must be equal to cooling tower return temperature, *Treturn*

$$\frac{\sum_j Fout(j) \bullet T(j)}{\sum_j Fout(j)} = Treturn \qquad \text{for } j = 1,2 \text{ ……, n} \qquad (3.10)$$

Objective function is to optimize fresh cooling water intake which is *z* until it is equal to new cooling tower supply, L`:

$$z = \sum_j y(j) = L' \quad \text{for } j = 1,2 \text{ ……, n} \qquad (3.11)$$

The Non Linear Programming (NLP) formulations here will require initial points for the optimum solutions to be generated. These initializations will be based on the preliminary optimization (stage 1) together with the graphical approach (cooling water network composite curve). Then, based on NLP model, the GAMS/CONOPT solver is used in the programming. This is due to the robustness of the solver.

This simple mathematical programming is an aid to avoid manual iterations in solving the water reuse calculation which is; to calculate the optimum cooling water stream mixing and splitting in order to fulfill the given cooling tower constraints. Based on this two-stage optimization procedure, a cooling tower system optimization can be performed.

3.6 Cost Analysis

The cost savings calculation on optimization work can be calculated based on comparison of operating cost, which is shown as equation below:

Cooling tower operating cost = Electricity cost + Water Cost (3.12)

Electricity cost = Fan Power + Pump Power (3.13)

Operating cost savings = Current operating cost – New operating cost (3.14)

Payback time = Capital cost / (Revenue – Operating Cost) (3.15)

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

As proposed in chapter 3, the two-step optimization procedure provides a practical approach to optimize a cooling water system. In this chapter, three case studies are presented to demonstrate the two-step optimization procedure.

4.2 General assumptions

For all the case studies in this work, the cooling tower internals are assumed to be in good condition, i.e. no internal deterioration. For a cooling tower that consist more than one cell, it is assumed that the cells are in good working order. Cooling water flowing pattern inside fills is assumed to be uniformed for all cells. The cooling water flow is well-distributed and no channeling effect inside the fills occurs. For calculation purposes, the value of cooling water heat capacity is taken as 4.2 kJ/kg.oC and density is 996 kg/m3 and it is assumed that both values are constant for all temperatures and pressures.

4.3 Relationship of Cooling Water Flowrate to Cooling Water Temperature

The data of cooling tower unit from methanol plant has been collected in order to study the relationship of cooling water circulation rate to the cooling water supply temperature as well as range and approach values. The data was taken from the plant's record, in which the data is arranged in descending cooling tower circulation rate. The data is tabulated in table 4.1.

Table 4.1: Results for Cooling Tower Operating Data

Date	Cooling Tower Circulation Rate (m^3/hr)	Cooling Water Supply Temperature (^oC)	Approach (^oC)	Range (^oC)
2 Sept	4920	35.00	9	8
4 Feb	4800	34.00	6	8.5
30 Sept	4400	31.50	6	10.5
Design Data	4350	32.00	7	10

Table 4.2: Results for Calculated Data Using Merkel's Equation

Date	Cooling Tower Circulation Rate (m^3/hr)	Cooling Water Supply Temperature (^oC)	Approach (^oC)	Range (^oC)
2 Sept	4920	35.29	7.29	8.74
4 Feb	4800	35.27	7.27	8.96
30 Sept	4400	35.02	7.02	9.77
Design Data	4350	35.00	7.00	10.00

In addition, the relationship of cooling water flowrate to the approach and range temperature is also investigated using Merkel's Equation. Thermodynamically, as cooling water circulation rate inside the cooling tower is reduced, more heat will be removed as the driving force is larger, and hence the supply cooling water becomes colder. Thus, the range must increase to give larger driving force in order to maximize the cooling tower heat load. This relationship can be seen in Figure 4.1 and 4.2.

Since the cooling tower outlet temperature cannot be lower than the wet-bulb temperature, the incoming hot water temperature is expected to be higher. Lower cooling water circulation rate will also cause the residence time for water contact in the cooling tower is getting higher. This can contribute to more heat exchange between air and cooling tower.

However, the calculation using Merkel's Equation assumed that the wet-bulb temperature is constant at 28°C, this value is taking the average wet-bulb temperature in Malaysia (PRSS, 2005). In real cooling tower operation, the wet-bulb is varies from 26 to 28 °C and thus, the relationship of the cooling water temperature and circulation rate is differed from the calculated value. For the design data, the wet-bulb temperature is taken as 25°C.

Overall, reducing cooling water circulation rate will reduce water make-up as well as cooling water pump work and consequently the cooling tower operating cost. Make-up water reduction is not affected much if heat load is constant and basically pumping work is proportional to the water volumetric rate. From Figure 4.3, it shows that the operating cost is reduced as cooling water circulation rate is reduced.

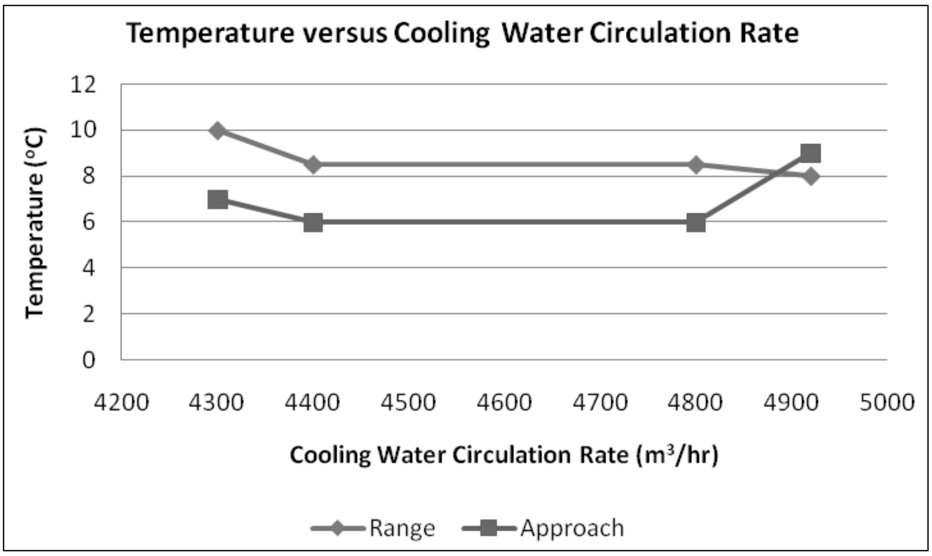

Figure 4.1: Relationship of Approach and Range Temperature to Cooling Water Flowrate (Cooling Tower Operating Data)

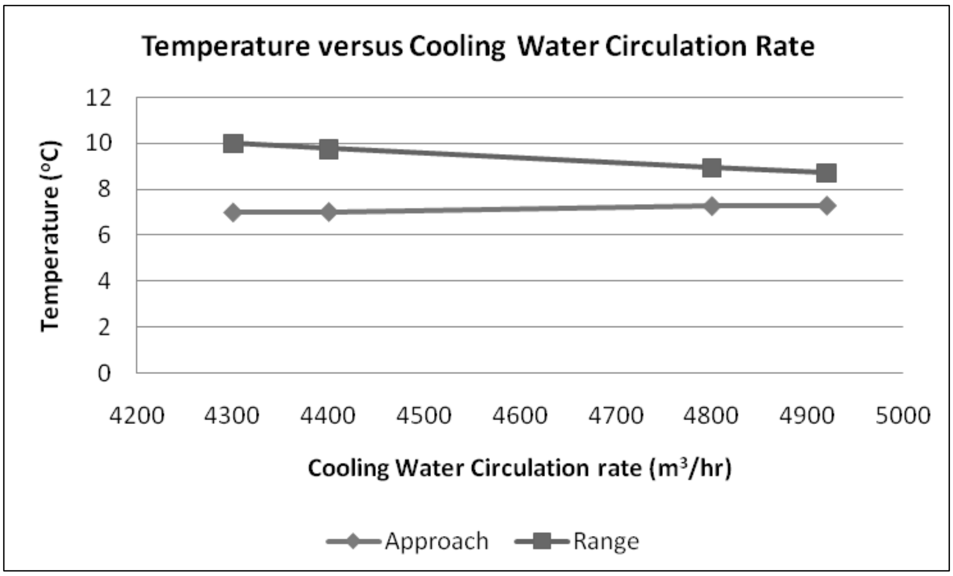

Figure 4.2: Relationship of Approach and Range Temperature to Cooling Water Flowrate (Calculated Using Merkel's Equation)

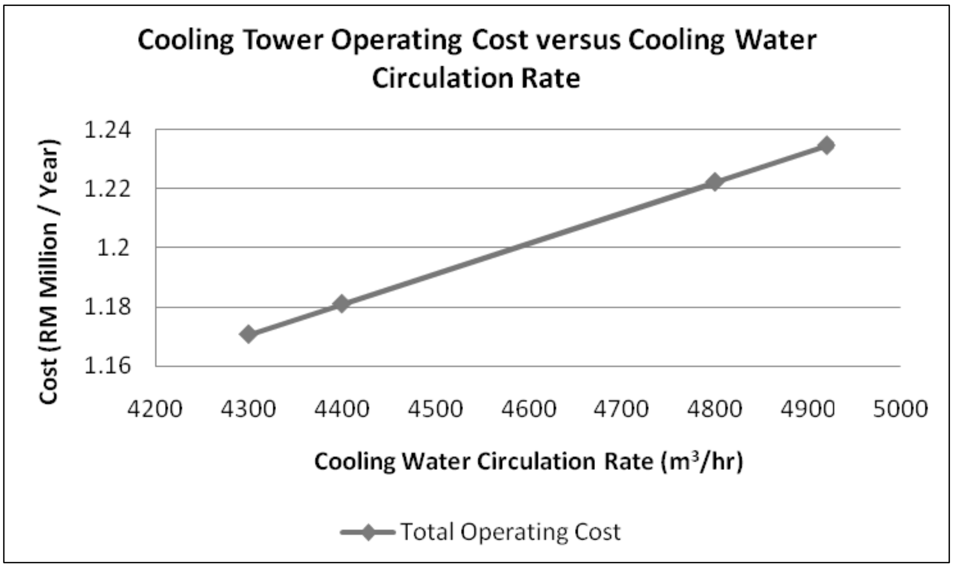

Figure 4.3: Cooling Tower Operating Cost Variation with Cooling Water Circulation Rate

4.4 Effect of Colder Cooling Water Temperature to the Plant

It can be seen that the colder cooling water and a lower cooling water circulation rate allow cost savings to be achieved. With a lower cooling water inlet temperature and maintaining the cooling water flow, the capacity to remove heat from the condenser will increase as colder cooling water creates bigger driving force to transfer heat in the condenser. If the existing area of the condenser is to be exploited, a colder cooling temperature should assist process debottlenecking of the condenser system as higher throughputs can be handled.

For an overhead condenser, the reduction of cooling water temperature from 35^{o}C to 32^{o}C is managed to increase the product capacity from 200 m^3/hr to 250 m^3/hr. As the cooling water flow and cooling water outlet temperature from the condenser, the condenser heat load will be increased. By assuming constant heat capacity and density of product A, the volumetric flow is proportional to condenser heat load. As results, the volumetric flow of product A was increased by 30%. Figure 4.4 shows the schematic diagram of the overhead condenser system that subjected to the cooling water temperature reduction.

Furthermore, Burger (1995) stated that every 0.6^{o}C colder water return to the compressors and condensers in refrigeration and air conditioning system, electrical energy input for compression work will reduced approximately by 3%. This was proven in the calculation at appendix C. Lower cooling water temperature will produce lower condensed refrigerant temperature and hence, the potential temperature difference for refrigerant to reject heat in condenser is reduced. The refrigeration system will operate at a lower head pressure and temperature to produce this temperature differences and thus less compression work is needed in order to produce lower pressure and temperature for the respective system. Besides, electricity consumption in pumping system is reduced as cooling water circulation rate is decreased.

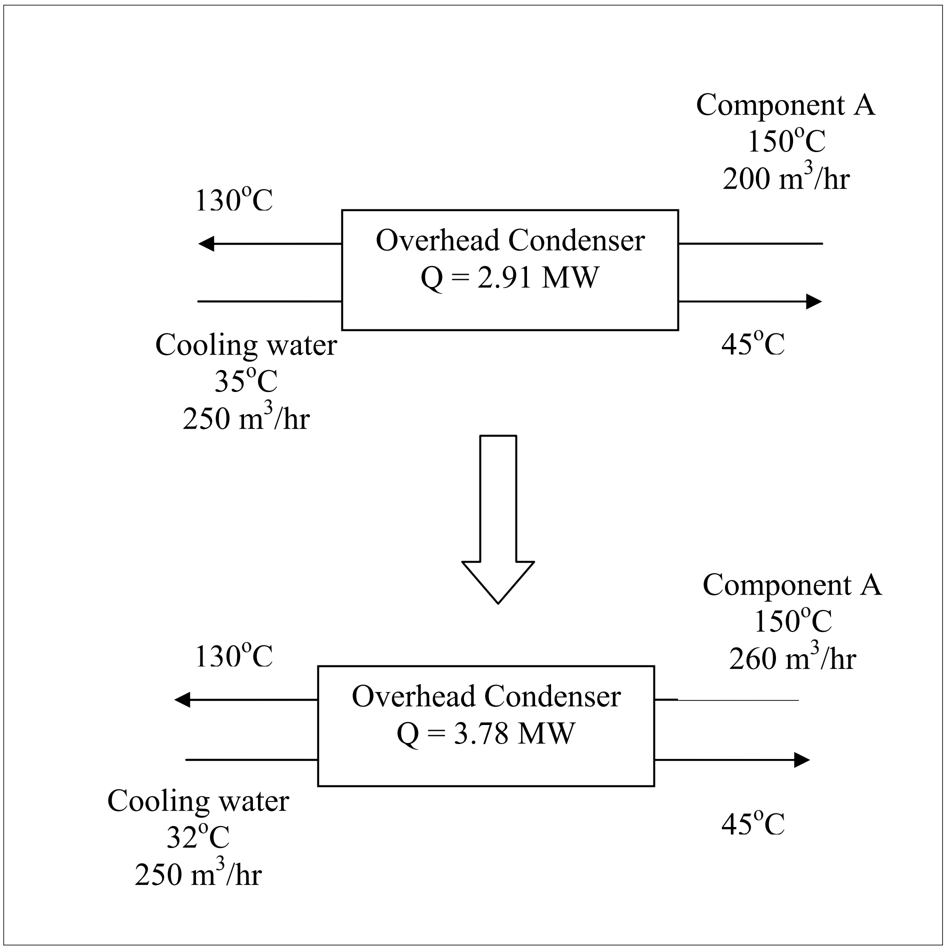

Figure 4.4: Effect of colder cooling water in overhead condenser

4.5 Case Study 1: Cooling Tower for a Chiller System

Assumptions

As discussed in earlier, a chiller system consists of a condenser that remove heat after the working fluid is compressed. Cooling water is used as the cooling medium in the condenser.

Each component of the chiller system is analyzed as a control volume at steady state. Pressure drops in a condenser and evaporator are assumed to be in acceptable region. The compressor operates adiabatically with an efficiency of 80%. The expansion through the valve is a throttling process that operates adiabatically. Kinetic and potential energy effects are negligible. Besides, it is also assumed that 3% of compression work can be saved for every 0.6^{o}C cooling water temperature reduction (Burger, 1995).

4.5.1 Gas District Cooling Tower System

The Gas District Cooling or GDC is a built to produce chiller water with the capacity of 4000 RT and electricity of 8.4 MW. This chiller water is produced for the air-conditioning system for the new academic complex, chancellor hall and mosque at University.

Chiller is one of the units in the GDC plant that produces chilled water at 6.0^{o}C and it is returned at 13.5^{o}C. Refrigerant is evaporated to cool back chilled water. Refrigerant vapor is compressed with 465 kW of power input and then sent to condenser. Conceptually, refrigerant carries heat from the return chilled water and then this heat is removed in a condenser. Cooling water from the cooling tower enters the condenser at a flowrate of 966 m^{3}/hr and a temperature of 32.0^{o}C. The heat load to be removed is 8426 kW/hr, i.e heat from return chilled water and from compression work. Thus, returning cooling water becomes hotter at 39.5^{o}C.

The cooling tower system consists of four cells in which cooling water returning from condenser is split into four streams of 241.5 m^{3}/hr per cells. The calculation for the optimization is evaluated for single cell. However, water from each cell will be combined before supply back to chiller system. The resulting supply water temperature is assumed uniform for all cells. Figure 4.5 shows the flow diagram of cooling tower and chiller water system.

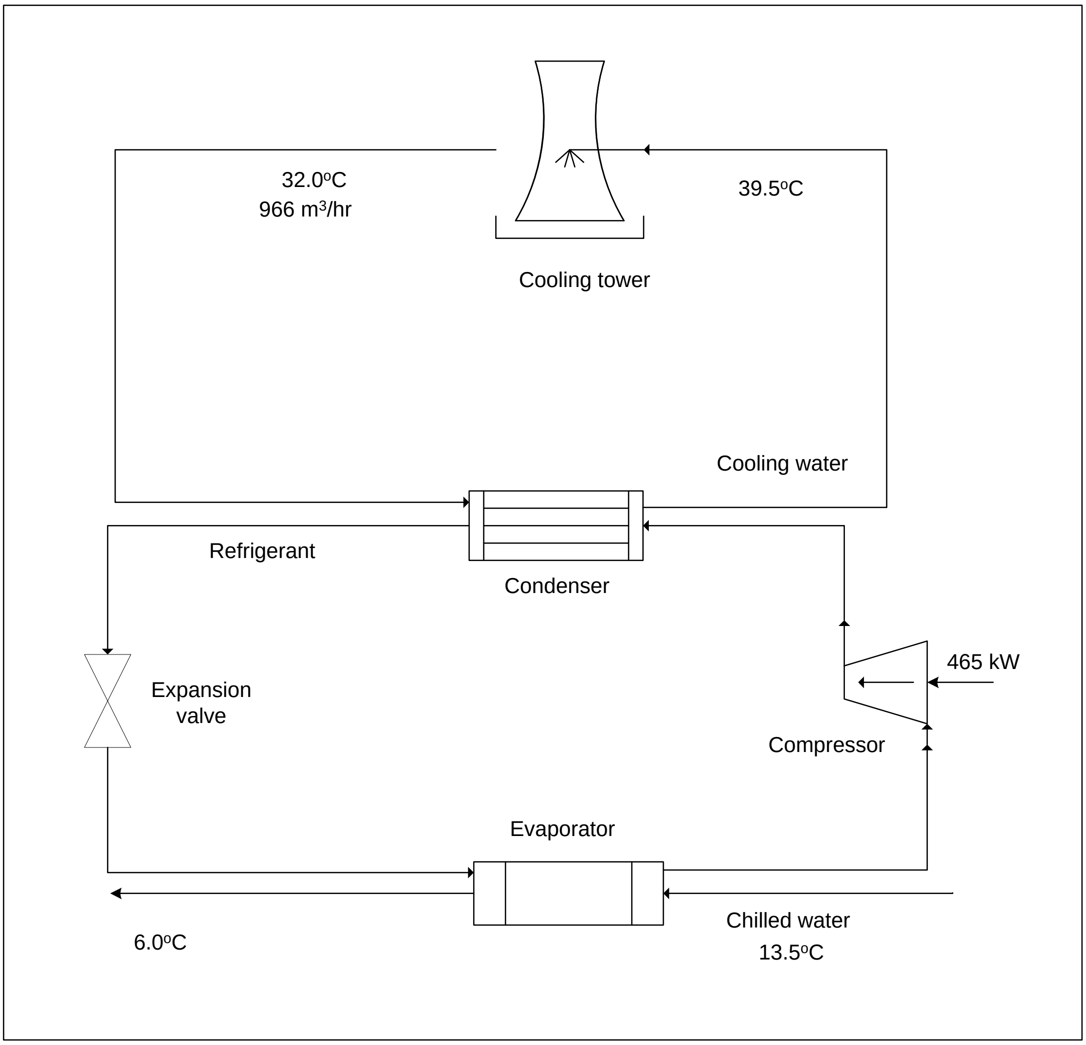

Figure 4.5: A Cooling Tower and a Chiller System (GDC, 2002)

4.5.2 Optimization Results

The objective of the optimization is to reduce cooling water approach as minimum as possible. From Perry and Green (1997), the minimum cooling tower approach is usually set at 2.9°C. Thus, the targeted cooling water supply temperature is 30.9°C and cooling tower approach is reduced from 4.0°C to 2.9°C. In order to reduce cooling water temperature, L/G value is reduced by reducing cooling water circulation rate, L while maintaining cooling tower heat load. Using the two-step procedure as described in chapter 3, a new cooling water circulation rate is determined.

From the first stage, a cooling water circulation rate in each cell is reduced to 158 m^3/hr and the total of cooling water for this system is 632 m^3/hr. As a result of cooling water reduction, cooling tower range is then increased from 7.5^{o}C to 11.4^{o}C. As expected the range has increased to compensate the reduction of cooling water flow in order to maintain the cooling tower heat load. The KaV/L value increases to accommodate more contact area between air and cooling water inside the tower. The operating and optimized parameters are tabulated in Table 4.3.

Table 4.3: Cooling Tower Operating and Optimized Parameters

Parameters	Operating value	Optimized value
Air flowrate, G (m^3/hr)	9849 (Fixed)	
Water circulation rate, L (m^3/hr)	966	632
CW supply temperature, T_{cw} (^{o}C)	32.0	30.9
CW return temperature, T_{hw} (^{o}C)	39.5	42.3
Wet-bulb Temperature, T_{wb} (^{o}C)	28.0	28.0
Approach (^{o}C)	4.0	2.9
Range (^{o}C)	7.5	11.4
L/G	1.5	1.0
KaV/L	1.5	1.9

As for the chiller side, colder cooling water does not affect the chilled water quality. However, the colder cooling water will reduce refrigerant compression work. As stated in assumption, compression work will be reduced by 3% for every 0.6^{o}C cooling water temperature reduction. The detail calculation is shown in Appendix C. In this case, 1.1^{o}C of cooling water temperature has been reduced, thus the compression work is saved by 5.6%. Consequently, the power input to run the compressor reduces to 440 kW. Since the flowrate of the cooling water supply from the cooling tower is reduced, the inlet cooling water flowrate to the condenser is also reduced.

The optimization will also affect the cost of cooling tower system. Because no additional mechanical modification, no additional capital cost is incurred as a results of optimization. For operating cost, savings is obtained from electricity cost and cost of make-up water. Total operating cost savings for overall cooling tower and chiller system is about 27% which is worth for RM 160 500 per year. The comparison between current and new cooling tower operating cost is shown in Table 4.4.

Table 4.4: Cost Comparison for Cooling Tower and Chiller System

Parameters	Current Operating Cost	New Operating Cost
Fan (RM/yr)	24 088	24 088
Pump (RM/yr)	50 799	33 235
Make up water (RM/yr)	400 214	261 826
Compressor (RM/yr)	81 946	77 398
Chiller pump (RM/yr)	37 557	37 557
Total (RM/yr)	594 604	434 104
Savings (RM/yr)	-	160 500
Savings (%)	-	27

It can be seen that, optimization of cooling tower results in cost savings for both the cooling tower and the chiller systems. However, since chiller and cooling water systems only contain single cooling water user, which is the condenser, there is no water reuse design that can be applied in this case.

4.6 Case Study 2: Cooling Tower System with Multiple Heat Exchangers

In the previous study, cooling water is only used by a single unit heat exchanger. In the second case study, a system with cooling tower with multiple heat exchangers is studied. The application of cooling water network composite curve is demonstrated to predict the minimum amount of cooling water reuse.

Assumptions as presented in the previous case study are applied for this case study as well. Hence, the cooling tower internals are assumed to be in good conditions. In addition, the heat exchanger is treated as a shell and tube heat exchanger with cooling water flowing in the tube side. The pressure drop is also assumed to be maintained as existing operating conditions.

The data for the second case study is taken from Kim (2001). Four heat exchangers include two condensers for chiller system and distillation column and another two coolers for the process fluid. The cooling water system for case study 2 is shown in Figure 4.6.

As in the previous case study, approach temperature is reduced to 2.9^{o}C resulting in a new target cooling water temperature of 30.9^{o}C. To achieve the new targeted temperature, the cooling water circulation rate, L must be reduced to 1166 m^3/hr and consequently resulted in new range temperature of 15.0^{o}C. The optimized and original parameters are tabulated in Table 4.5.

As discussed previously, colder cooling water inside distillation column condenser will increase the quantity of fluid condensed and thus increasing production capacity. Besides, for chiller condenser, the effect of colder water will reduce the compression cost and thus reducing operating cost.

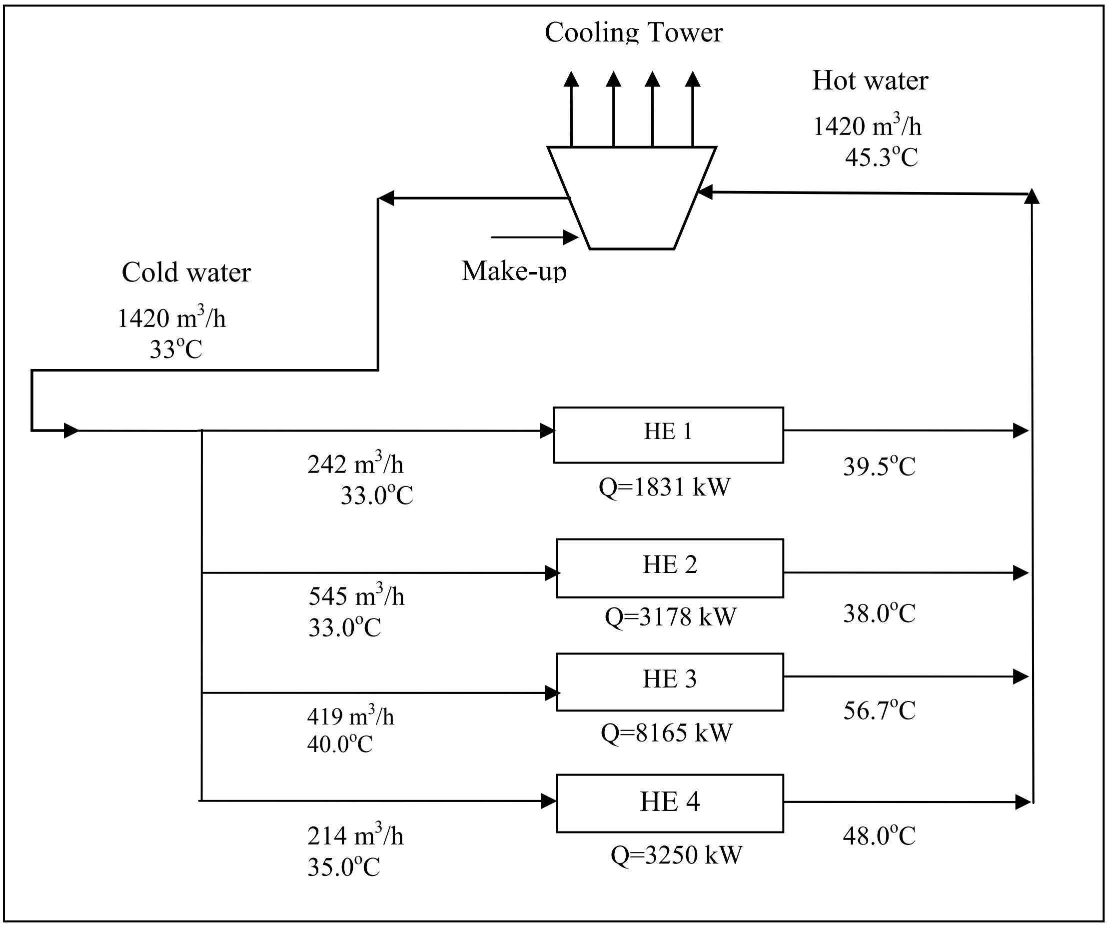

Figure 4.6: Cooling Water System for Case Study 2 (Kim, 2001)

Table 4.5: Cooling Tower Operating and Optimized Parameters for Case Study 2

Parameters	Original	Optimized
Air flowrate, G (m^3/hr)	830784 (fixed)	
Water circulation rate, L (m^3/hr)	1420	1166
CW supply temperature, T_{cw} (^oC)	33.0	30.9
CW return temperature, T_{hw} (^oC)	45.3	45.9
Wet-bulb Temperature, T_{wb} (^oC)	28.0	28.0
Approach (^oC)	5.0	2.9
Range (^oC)	12.3	15.0
L/G	1.5	1.1
KaV/L	1.6	2.3

However, after the optimization, the water circulation rate is lower than the existing condition. This has created a bottleneck for the cooling water users in the process. In addition, this will cause low velocity inside cooling water user equipment and may lead to fouling problem. To overcome this problem, cooling water reuse maybe applied.

Cooling water reuse targeting is carried out using cooling water network composite curve (CWNCC). From the data given, a CWNCC is generated as shown in Figure 4.7. The maximum direct cooling water reuse is shown in CWNCC with shifted sink line. Three options have been identified to achieve the target minimized cooling water circulation rate.

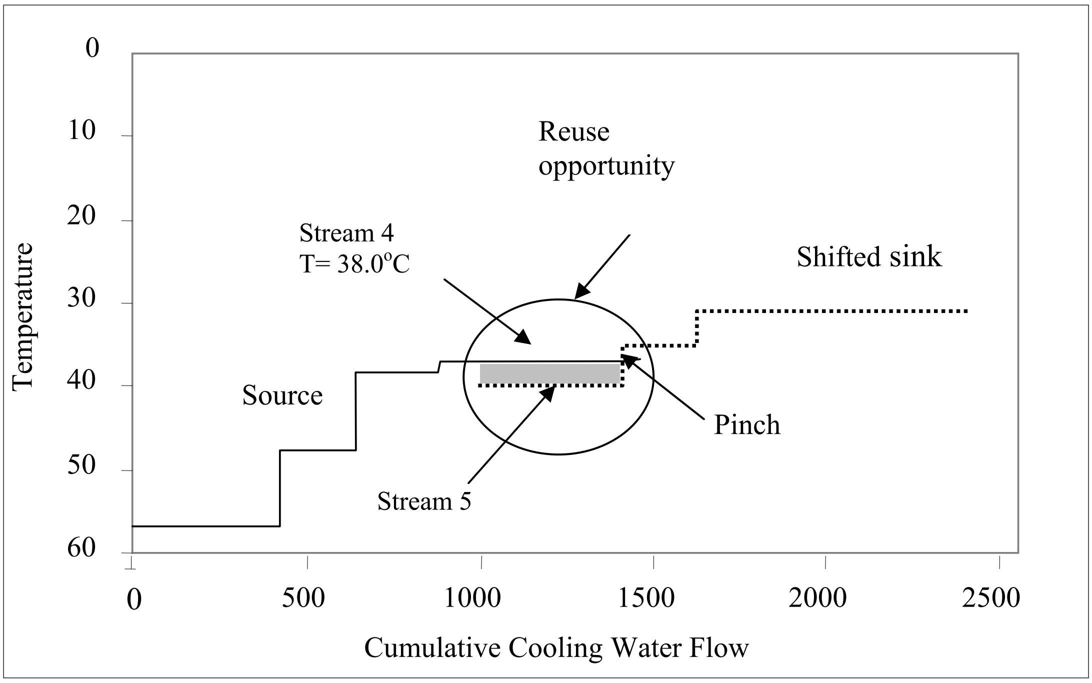

Figure 4.7: Cooling Water Network Composite Curve with shifted sink line

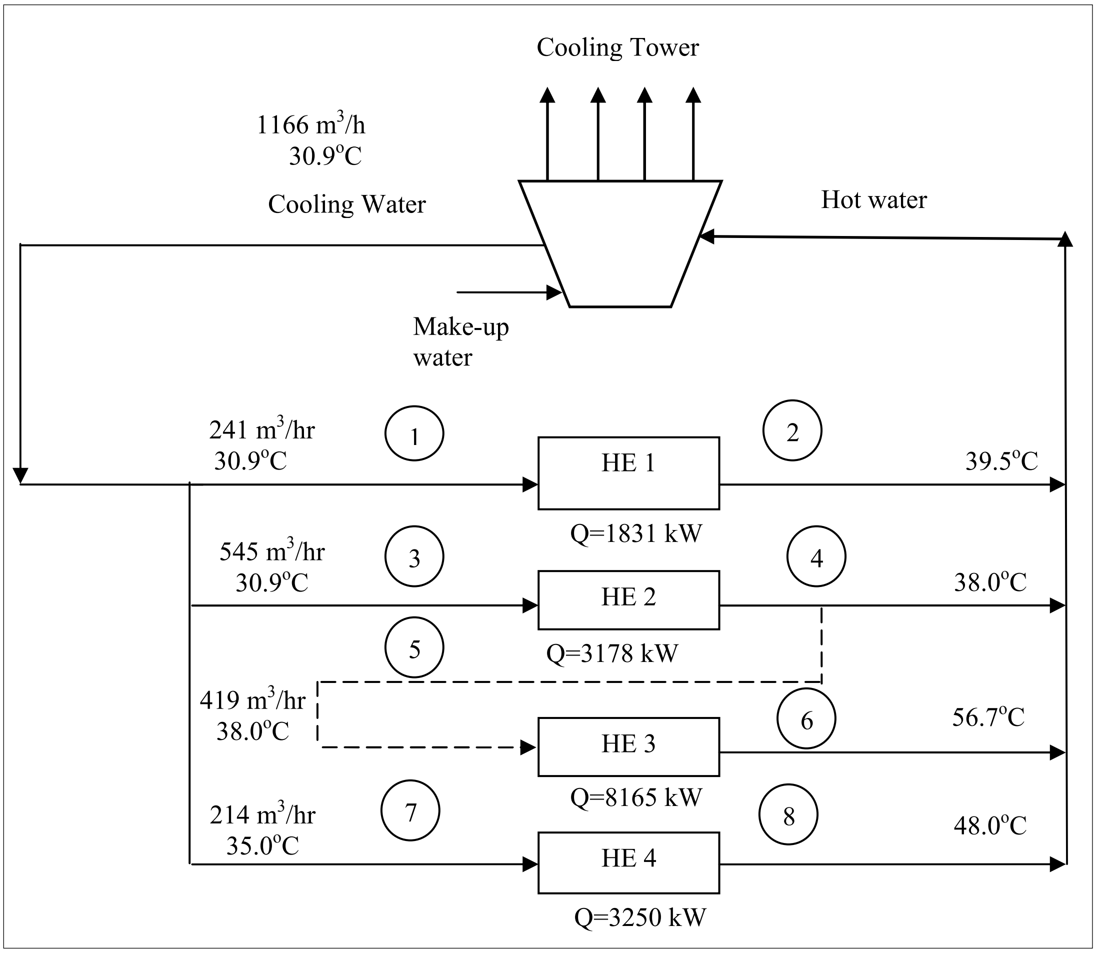

Figure 4.8: Cooling water network configuration with direct reuse (option 1)

Through the Option 1 (Figure 4.8), the maximum cooling water reuse that can be obtained from the cooling water network is 419 m^3/hr. With this maximum reuse, the fresh cooling water supply needed from cooling tower is only about 1001 m^3/hr, whereas the cooling tower circulation rate is 1166 m^3/hr. Thus, there is surplus of cooling water supply from the cooling tower.

In order to ensure that the fresh cooling water amount is maintained at 1166 m^3/hr, the base case CWNCC is modified as shown in Figure 4.9. Here, the stream mixing can be applied, in which the source stream can be mixed with the fresh cooling water. The addition of reuse cooling water to the fresh cooling water from cooling tower will produce colder heat exchanger inlet at 35.2^{o}C than original temperature of 40.0^{o}C. This can be achieved by diluted 254 m^3/hr of hot water from stream 4 with 165 m3/hr fresh cooling water and then produces 419 m^3/hr cooling water with temperature of 35.2°C. The result in Option 2 of cooling water network is shown in Figure 4.10.

Option 3 gives a different network design but with similar cooling total water reuse quantity. The reuse quantities for each heat exchanger are different from option 2. As shown in Figure 4.11, two streams, streams 4 and 8, are being reused by sink streams of 7 and 5, respectively. As in option 2, stream mixing is also applied. Some of streams 4 and 8 are diluted with fresh cooling water and divided into streams a and b. Temperature of streams 4a and 8a are maintained at its original temperature which are 38.0°C and 48.0°C respectively. In addition, the temperature for stream 8b is reduced from 48.0°C to 36.9°C and stream 4b reduced from 38.0°C to 34.4°C. These modifications can be seen from CWNCC as shown in Figure 4.11. Thus, there are opportunities to reduce inlet temperatures for heat exchangers 3 and 4.

For all options, the savings for new cooling tower operating cost are similar and technically are feasible to be applied with a new piping. However, the overall savings vary due to the difference in additional capacity for each option. First option gives 25% additional capacity from HE 3. While, for second option, HE 3 gives higher additional capacity which is about 36% since the lower inlet temperature for cooling water inside HE 3. On the other hand, option 3 gave lower additional capacity which is approximately at 23% since cooling water inlet temperatures for HE 3 and HE 4 is almost similar to the designed values. The cost comparison of cooling tower performance is shown in Table 4.6.

Table 4.6: Comparison for cooling tower operating cost

Parameters	Current Cooling Tower Operating Cost	New Cooling Tower Operating Cost
Fan cost (RM/yr)	24 088	24 088
Pump cost (RM/yr)	298 602	210 454
Make up cost (RM/yr)	2 352 490	1 658 029
Compressor cost (RM/yr)	81 946	73 259
Chiller pump cost (RM/yr)	37 557	37 557
Total Operating Cost (RM/yr)	2 794 682	2 003 387
Savings (RM/yr)	-	791 296
% savings	-	28

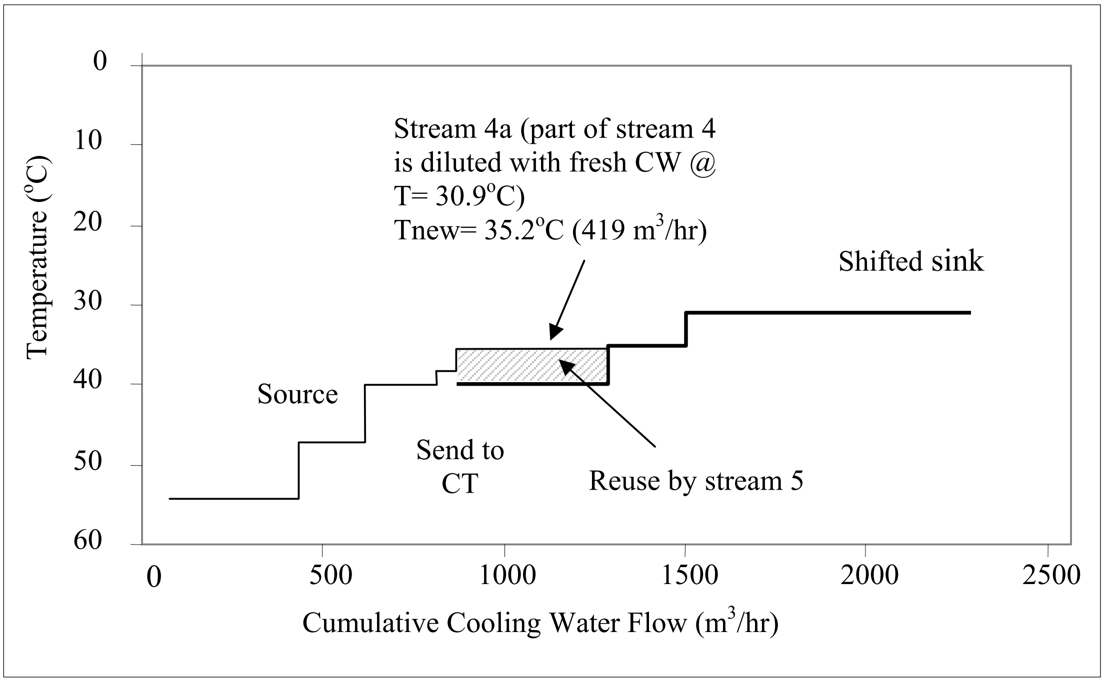

Figure 4.9 Modified Cooling Water Network Composite Curve for option 2

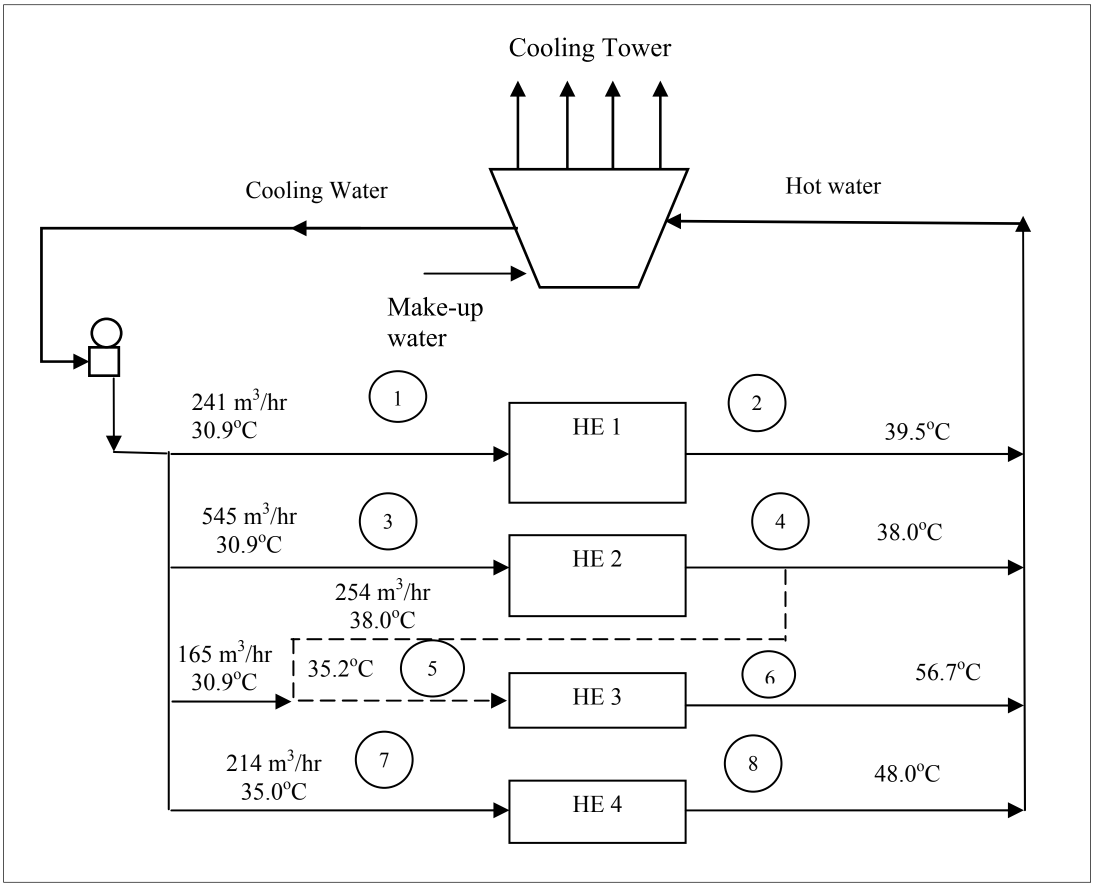

Figure 4.10: Cooling water network configuration with stream mixing (Option 2)

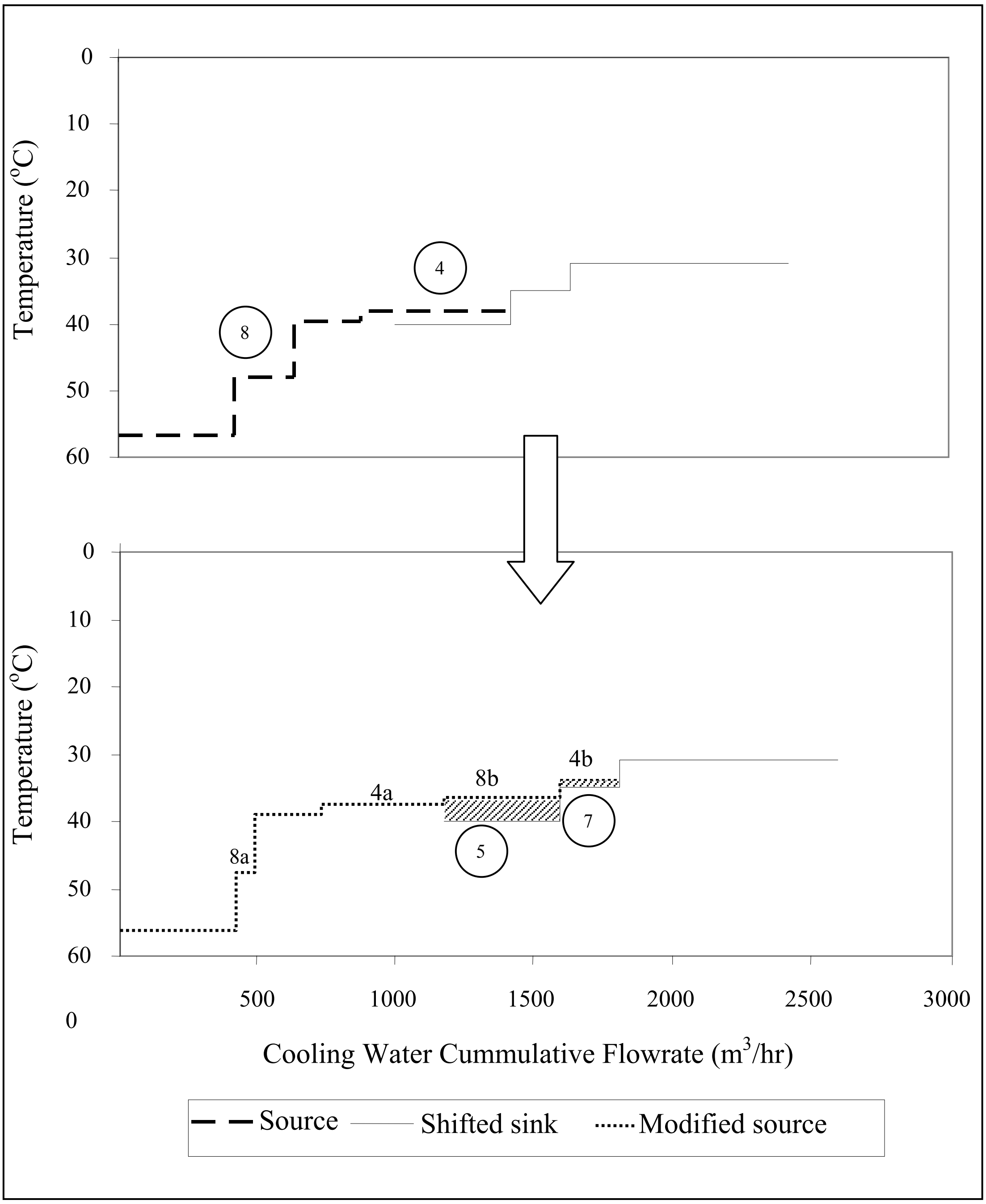

Figure 4.11: Modified Cooling Water Network Composite Curve for option 3

From Case Study 2, it can be shown that a lower cooling water supply temperature can give additional capacity to the plant. Besides, cooling water reuse design is applied in carrying out cooling tower optimization to compensate the reduction of cooling water circulation rate. This study also showed that, cooling tower system can be improved without any mechanical modification and additional capital cost. In fact, it can increase the plant profit through lowering the cooling tower operating cost.

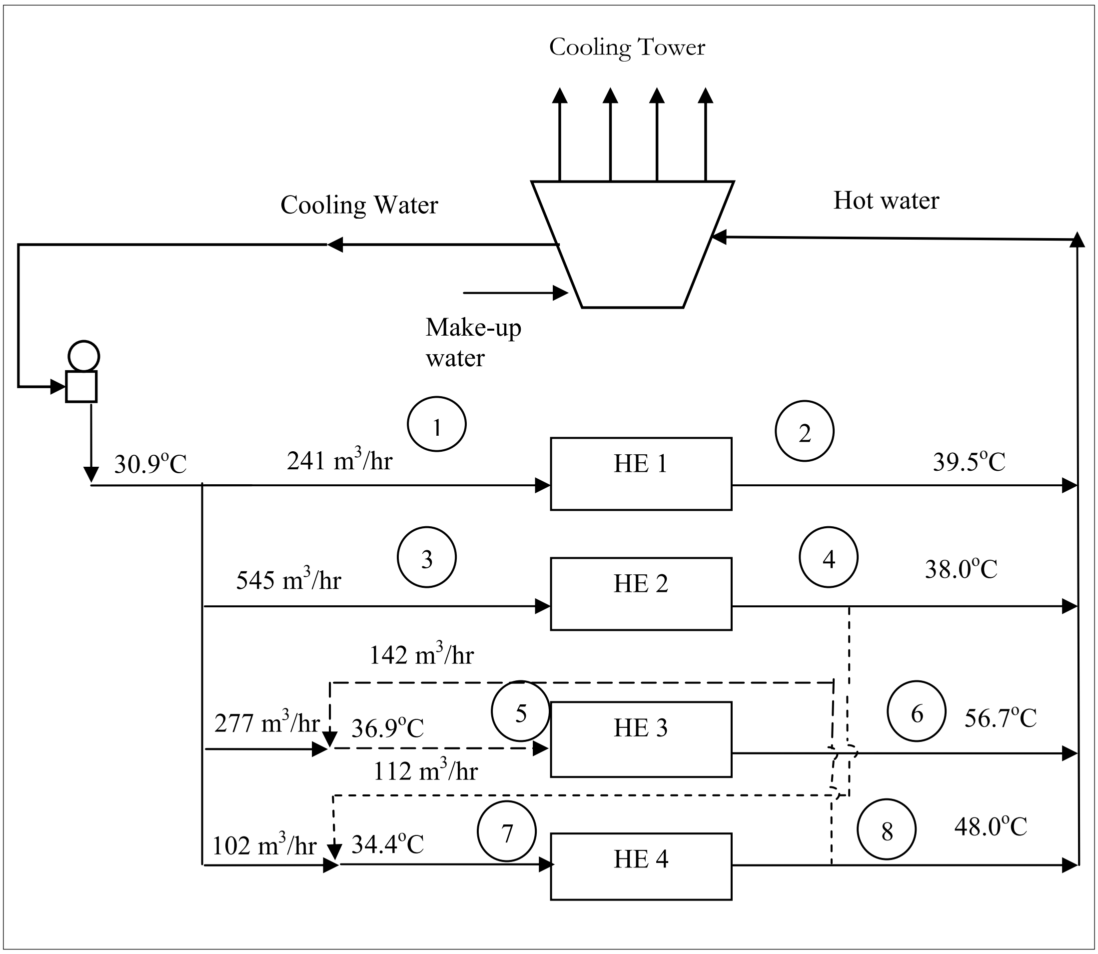

Figure 4.12: Cooling water network configuration with stream mixing (option 3)

In summary, the results from the case study are shown as in table 4.7.

Table 4.7: Summary of Case Study 2

Options	Description
Option 1	• Direct cooling water reuse : 419 m^3/hr • Surplus in CW supply from CT • Less piping cost (only one additional piping)
Option 2	• Cooling water reuse : 419 m^3/hr • Only 1 Stream diluted to get lower CW inlet T • Less piping cost (only one additional piping)
Option 3	• Cooling water reuse : 419 m^3/hr • 2 streams are diluted to get lower CW T • More piping cost

From table above, it can be concluded that the option 2 may the best option. This is due to the less piping cost and complexity, since only one additional piping is needed compared to option 3. In addition, the cooling water inlet to the HE 3 in option 2 is cooler than option 1, and thus may give higher additional capacity.

4.7 Case Study 3: Cooling Tower Optimization in a Methanol Plant

Methanol can be produced in many ways, but most processes use natural gas a feed stock. The natural gas is then converted to synthesis gas or Syngas by steam reforming. Syngas is composed of carbon monoxide (CO), carbon dioxide (CO_2) and hydrogen (H_2). The Syngas is then sent to methanol converter where crude methanol and water are produced. Distillation is used as a means for products separation. Figure 4.13 shows typical methanol processing flow diagram.

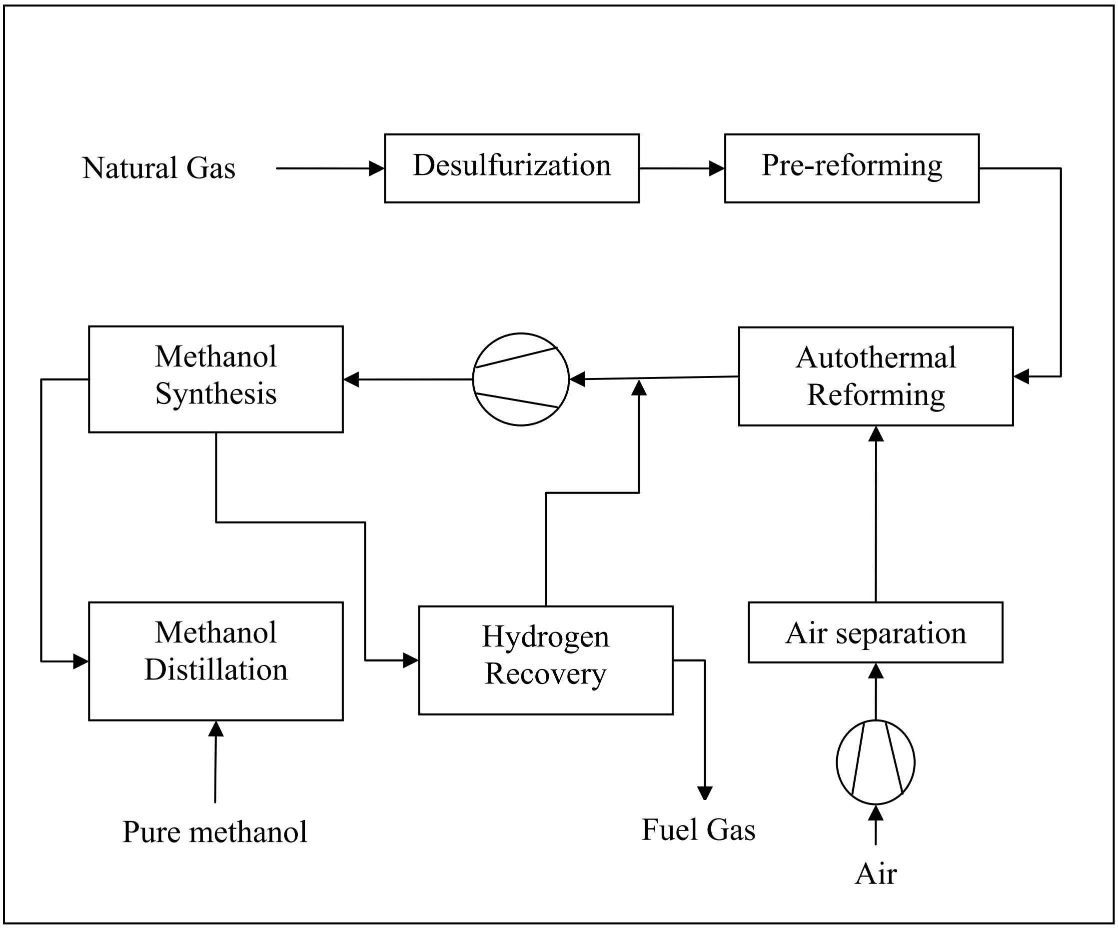

Figure 4.13: Typical layout of Methanol Production using Lurgi Process (Lurgi, 2011)

From above figure, it can be seen that numbers of cooling water heat exchanger (C/W) are used to cool the process fluid. The temperature of cooling water will affect the energy needed for compression work and the purity of the final product.

4.7.1 Cooling Tower Network Data

A methanol plant named Plant I that is using Lurgi Process; is selected and the cooling data were gathered from one of the cooling towers in this plant. All of the heat exchangers that are associated with the cooling tower are operated at the desired operating conditions to ensure that the chemicals produced are within customer specifications. The cooling water network in this case study has 14 heat exchangers that are connected to the cooling tower. All cooling water inlet temperatures is 35^{o}C. The function of the heat exchangers and the operating parameters for all heat exchangers are shown in Table 4.6.

Figure 4.14 shows the flow diagram of cooling water network for this case study. The total cooling water circulated in this system is about 4300 t/hr. The cooling water supply temperature is 35^{o}C and the return temperature is about 45^{o}C. The wet-bulb temperature is assumed at a typical tropical temperature of 28^{o}C and it is uniform over the year. Thus, the approach is at 7^{o}C and the range temperature is 10^{o}C.

Taking the minimum allowable approach temperature of 2.9^{o}C (Perry and Green, 1997), there is an opportunity to improve the cooling tower supply temperature. Thus, the optimization of cooling tower itself is carried out first.

4.7.2 Optimization Approach

In this case study, it is required that the return temperature of cooling tower must be less than 60^{o}C. This is a process constraint to prevent water temperature damage the fill. Furthermore, the heat load for cooling tower is maintained to ensure that the existing cooling tower area is able to cope with new cooling tower operating parameters.

From Table 4.7, it can be seen that, as L/G is reduced, the approach became tight while the range is widen. Therefore, it gives higher hot water temperature but lowers cold water supply temperature. As recommended by Perry and Green (1997), the value of L/G is only varies down to 0.75.

The optimized parameters are tabulated in Table 4.8. Minimum L/G value of 0.75 is selected and thus resulting in cooling water circulating flow of 2000 m^3/hr. Consequently, the cooling tower supply temperature is reduced by 2.4^oC. The return temperature is about 54.1^oC and thus, the new range temperature is about 21.5^oC.

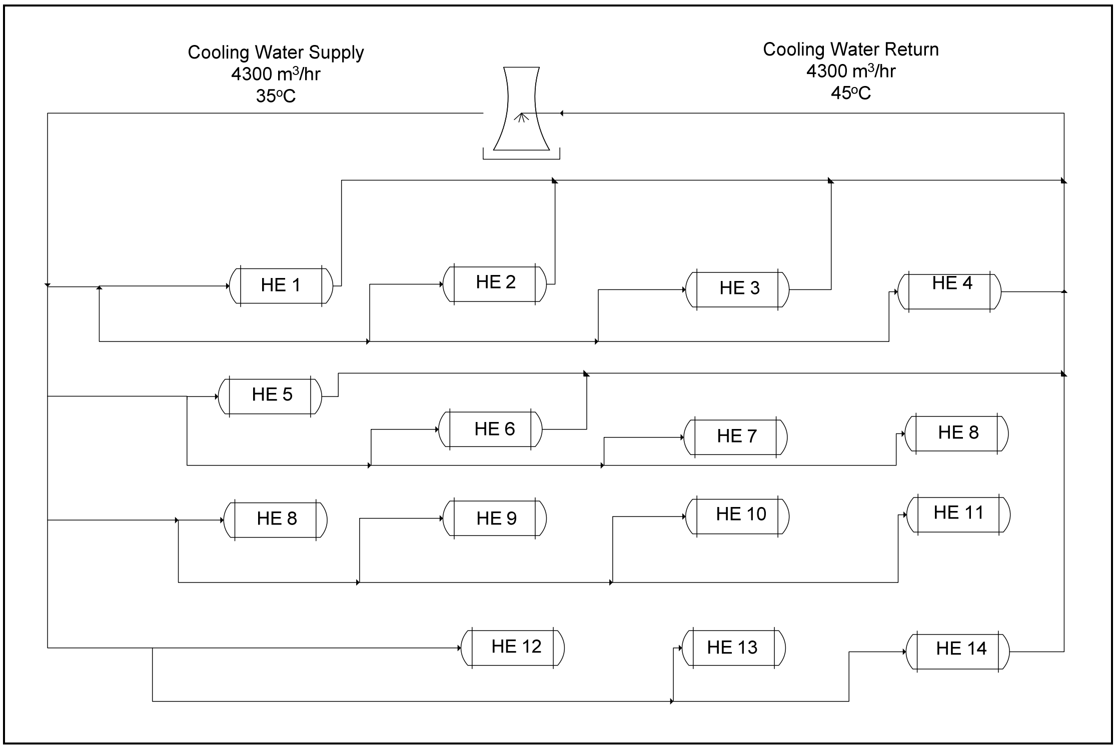

Figure 4.14: Cooling water network for Plant I (PMLSB, 2005)

Table 4.6: Function and Operating Parameters of Heat Exchangers (PMLSB, 2005)

HE	Functions	Cooling Water side			Process side		Q	UA
		Tin	Tout	Flow	Tin	Tout		
		(^oC)	(^oC)	(m^3/hr)	(^oC)	(^oC)	(MW)	(W/^oC)
HE 1	Gas cooler	35	45	727	99	38	8.46	597590
HE 2	methanol cooler	35	45	940	60	38	10.94	1729585
HE 3	off-gas cooler	35	45	53	64	40	0.62	55188
HE 4	Reflux cooler for pressured column	35	45	293	70	40	3.41	520340
HE 5	final product cooler	35	45	293	128	40	3.41	147559
HE 6	reflux cooler for prerun clmn	35	45	817	83	64	9.51	378463
HE 7	gas compressor cooler	35	45	179	131	108	2.08	56831
HE 8	lube oil cooler	35	45	226	60	45	2.63	266654
HE 9	lube oil cooler	35	45	224	60	45	2.61	264294
HE 10	compressor intercooler	35	45	84	137	40	0.98	37139
HE 11	compressor intercooler	35	45	96	151	40	1.12	39753
HE 12	compressor intercooler	35	45	75	145	40	0.87	36089
HE 13	compressor intercooler	35	45	75	125	40	0.87	37375
HE 14	Small exchangers	35	45	218	Group of small coolers		2.49	

Table 4.7: Cooling tower parameters with variation of L/G (Q constant)

L/G	L (t/hr)	Cooling Water Return Temperature (^oC)	Cooling Water Supply Temperature (^oC)	Range (^oC)	Approach (^oC)
1.60	4300	45.0	35.0	10.0	7.0
1.44	3870	45.8	34.7	11.1	6.7
1.35	3620	46.3	34.4	11.9	6.4
1.28	3440	46.9	34.4	12.5	6.4
1.23	3308	47.2	34.2	13.0	6.2
1.12	3010	48.2	33.9	14.3	5.9
1.10	2950	48.5	33.9	14.6	5.9
0.96	2580	50.1	33.4	16.7	5.4
0.84	2250	52.1	32.9	19.2	4.9
0.82	2200	52.4	32.9	19.6	4.9
0.80	2150	52.8	32.8	20.0	4.8
0.75	2000	54.1	32.6	21.5	4.6

Table 4.8: Cooling tower parameters with minimum L/G

Parameters	Operating	Optimized
Approach (oC)	7.0	4.6
Return Temperature,Thw (oC)	45.0	54.1
Supply Temperature, Tcw (oC)	35.0	32.6
Wet-bulb Temperature, Twb (oC)	28.0	28.0
Water Circulation Rate, L1 (t/hr)	4300	2000
Air Flowrate, G1 (m3/hr)	2335608	2335608
L/G	1.61	0.75
KaV/L	0.95	1.50

Those optimized data are then used in cooling water reuse design. To develop the reuse design, the cooling water data is plotted in CWNCC as shown in Figure 4.15. From CWNCC, it can be seen that source stream is having higher temperature than sink stream and thus presents no opportunity for cooling water reuse. Modifications should be made to the source stream in order to locate stream line above the sink line. Mathematical programming is used to find the best mixing streams to fulfill the cooling water network requirements. Reuse design applied are further analyzed.

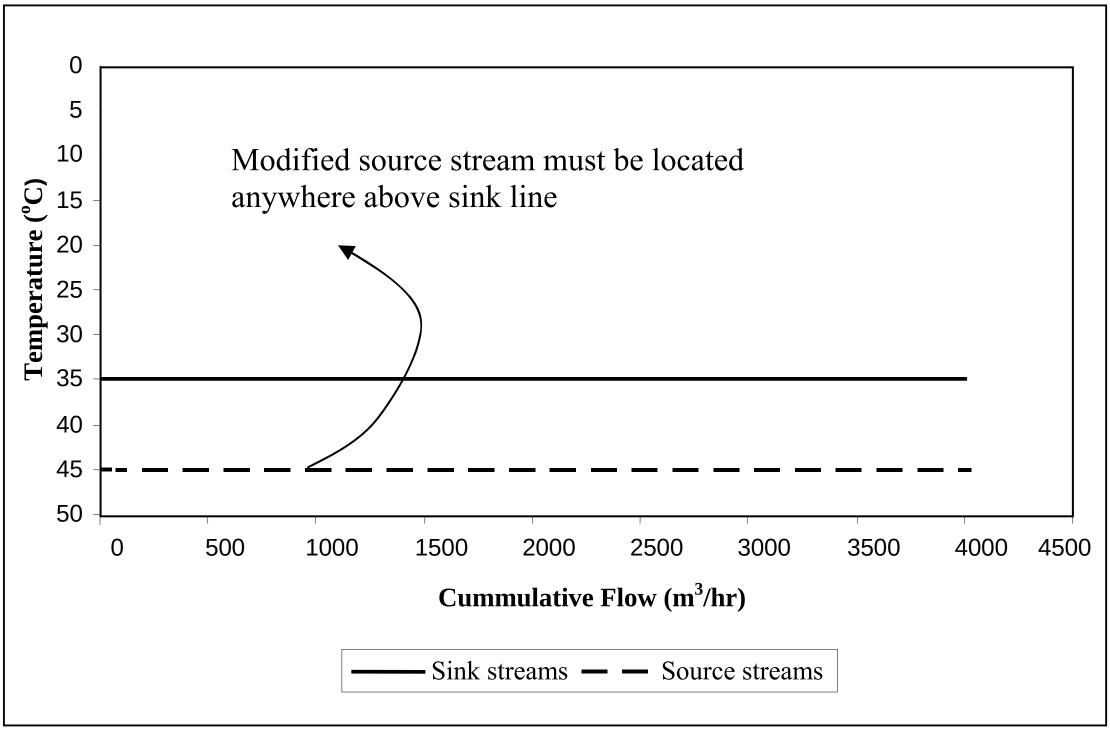

Figure 4.15: Cooling Water Network Composite Curve for Plant I

4.7.2.1 Option 1: Cooling Water Reuse by stream mixing

For this option, the heat exchangers are grouped into 4 clusters to simplify the analysis. Based on the temperature constraint for the heat exchangers system, the new cooling tower parameters are selected as follows:

Table 4.9: Cooling Tower Parameters with Tcw = 33.9°C

Approach (°C)	5.9
Return Temperature, T_{hw} (°C)	48.5
Supply Temperature, T_{cw} (°C)	33.9
Water Circulation Rate, L\` (t/hr)	2950
L\`/G	1.1
KaV/L\`	1.2

The temperature constraints for the heat exchangers are listed in Table 4.10.

Table 4.10: Maximum temperature for heat exchangers network

HE	CW_{in} temperature	CW_{out} temperature
	°C	°C
HE 1	37	47
HE 2	37	47
HE 3	37	47
HE 4	39	49
HE 5	39	49
HE 6	39	49
HE 7	39	49
HE 8	39	49
HE 9	39	49
HE 10	39	49
HE 11	39	49
HE 12	39	49
HE 13	39	49
HE 14	39	49

The reuse design is capable of fulfilling the cooling tower's new parameters and new cooling water reuse network is shown in Figure 4.16. Cooling water consumption is saved by 12% while the cooling tower temperature is reduced by 1.1°C. Even though the cooling tower supply temperature reduction is only 1°C, cooling tower can save the operating cost up to RM 139,000 per year. This savings is obtained from the lesser cooling water consume inside the plant as well as lesser power consumption used by cooling water circulation pump. However, the heat exchanger needs to be revamped and this is estimated to be due the 355 m^2 additional heat exchanger area needed to cope with higher load of the heat exchangers. Thus, the total capital cost for this option is RM 148,000 and the revenue is RM 139,000 and those values made the payback period for this option as 13 months (refer appendix D).

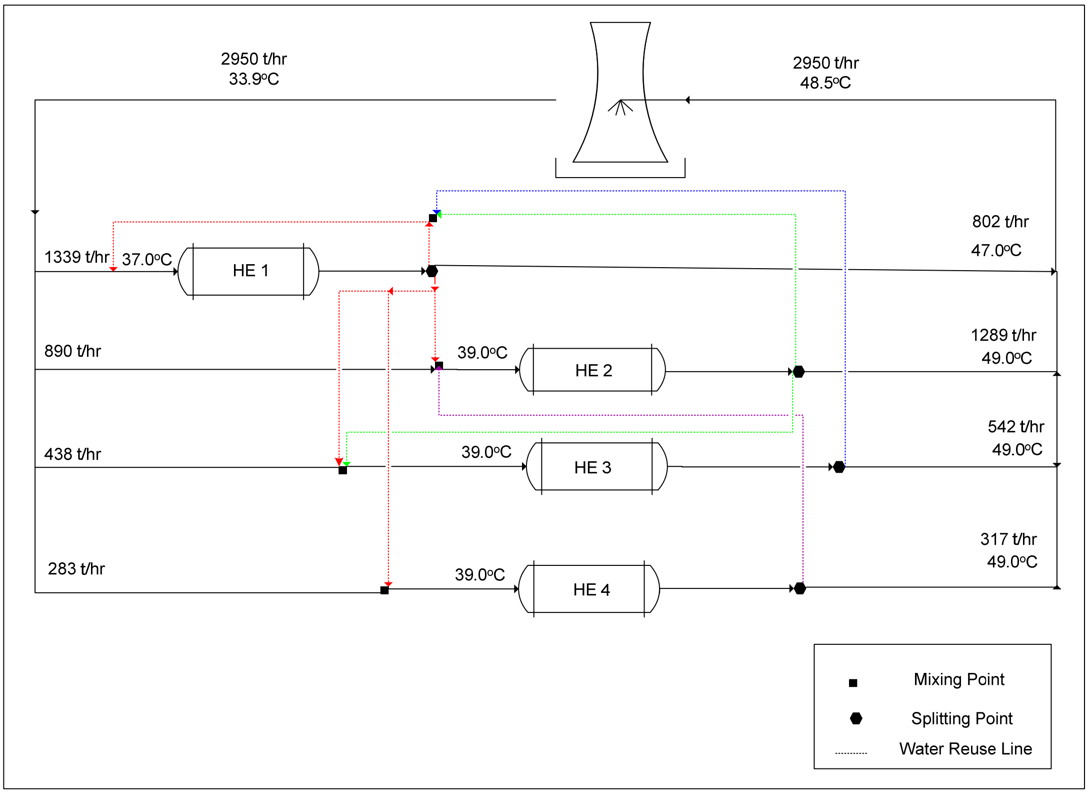

Figure 4.16: Cooling Water Reuse Network for Plant I (Option 1)

4.7.2.2 Option 2: Cooling Water Reuse with Additional Product Capacity

For the second option, some 15% of additional capacity that is gained from additional heat load that is approximated to be worth of RM39 million per year is expected. This can be achieved by increasing LMTD value, provided that there is no temperature cross occurs. Thus, it is proposed that additional heat exchanger area is needed to cope with the new heat load. Cooling water regeneration is introduced in second option design, while stream mixing is still applicable to reduce in regeneration cost.

New cooling tower parameters, as tabulated in Table 4.11, are used for this option. The fresh cooling water supply is at 33.9^{o}C and supply cooling water circulation rate is 2950 m^3/hr. For reuse design, a return cooling water temperature must be set at 48.5^{o}C. This is to ensure that cooling tower area is fully occupied during heat removal process and thus cooling tower can operate efficiently. After reuse design, it is found that 294 m^3/hr of hot water is needed for regeneration by air-cooled heat exchanger (AHE) since only 1056 m^3/hr of hot water can be reused by the system. About 2500 m^2 additional heat exchanger is required and this will cost about RM 2 million. Thus, the total capital cost for this option is 2.8 Million including RM 700,000 for cost of new AHE and RM 2.1 Million for additional heat exchanger area. A very large revenue of RM 39 Million per year, made this option need a very short payback period which is about 1 month (refer appendix D) and cooling water reuse network is shown in Figure 4.17. The AHE unit which is acts as regeneration unit is put in parallel with the cooling tower. This is to ensure that the cooling water circulation rate and its return temperature are satisfying the optimized parameters.

Table 4.11: Cooling Tower Parameters with Tcw = 33.9^{o}C

Approach (^{o}C)	5.9
Return Temperature,Thw (^{o}C)	48.5
Supply Temperature, Tcw (^{o}C)	33.9
Water Circulation Rate, L1 (t/hr)	2950
L/G	1.1
KaV/L	1.2

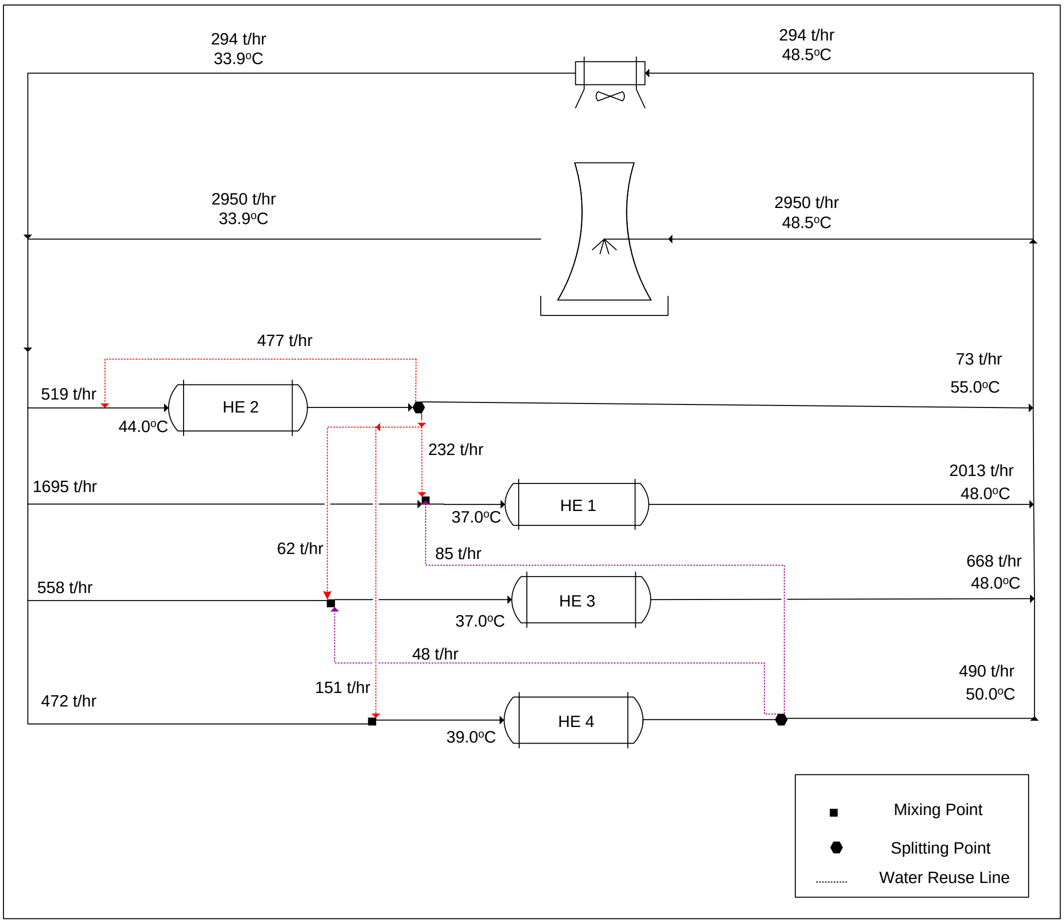

Figure 4.17: Cooling Water Reuse Network for Plant I (Option 2)

4.7.2.3 Option 3: Cooling Water Reuse and regeneration

The third option for this case study is to get increase production capacity without involving any additional heat exchanger area. Cooling water regeneration and stream mixing is still applicable in this design.

Minimum L/G value and low cooling water return temperature are chosen and lower cooling tower circulation rate is obtained. The new cooling water supply temperature is 31.6°C. Besides, in ensuring that UA of heat exchanger is maintained, the temperature of outlet cooling water from heat exchangers are lower in the range of 43.0°C to 48.0°C. New cooling tower parameters are tabulated as follows:

Table 4.12: Cooling Tower Parameters with Tcw = 31.6°C

Approach (°C)	3.6
Return Temperature,Thw (°C)	45.0
Supply Temperature, Tcw (°C)	31.6
Water Circulation Rate, L1 (t/hr)	2000
L/G	0.75
KaV/L	1.50

The reuse design option can be designed by targeting a new inlet cooling water temperature at 34°C. The advantage of this option is small amount of cooling water regeneration amount is needed. The total capital cost for this option is made by the cost of AHE which is RM 700,000. Then, the total operating cost of this option which is about RM 1 Million per year the total of operating cost of cooling tower as well as operating cost of AHE. The payback for this option is 2 months and cooling water reuse network design is shown in Figure 4.18. The payback for this option is shorter because of large additional profit that comes from additional production capacity of 3% and this worth about RM 8 Million per year.

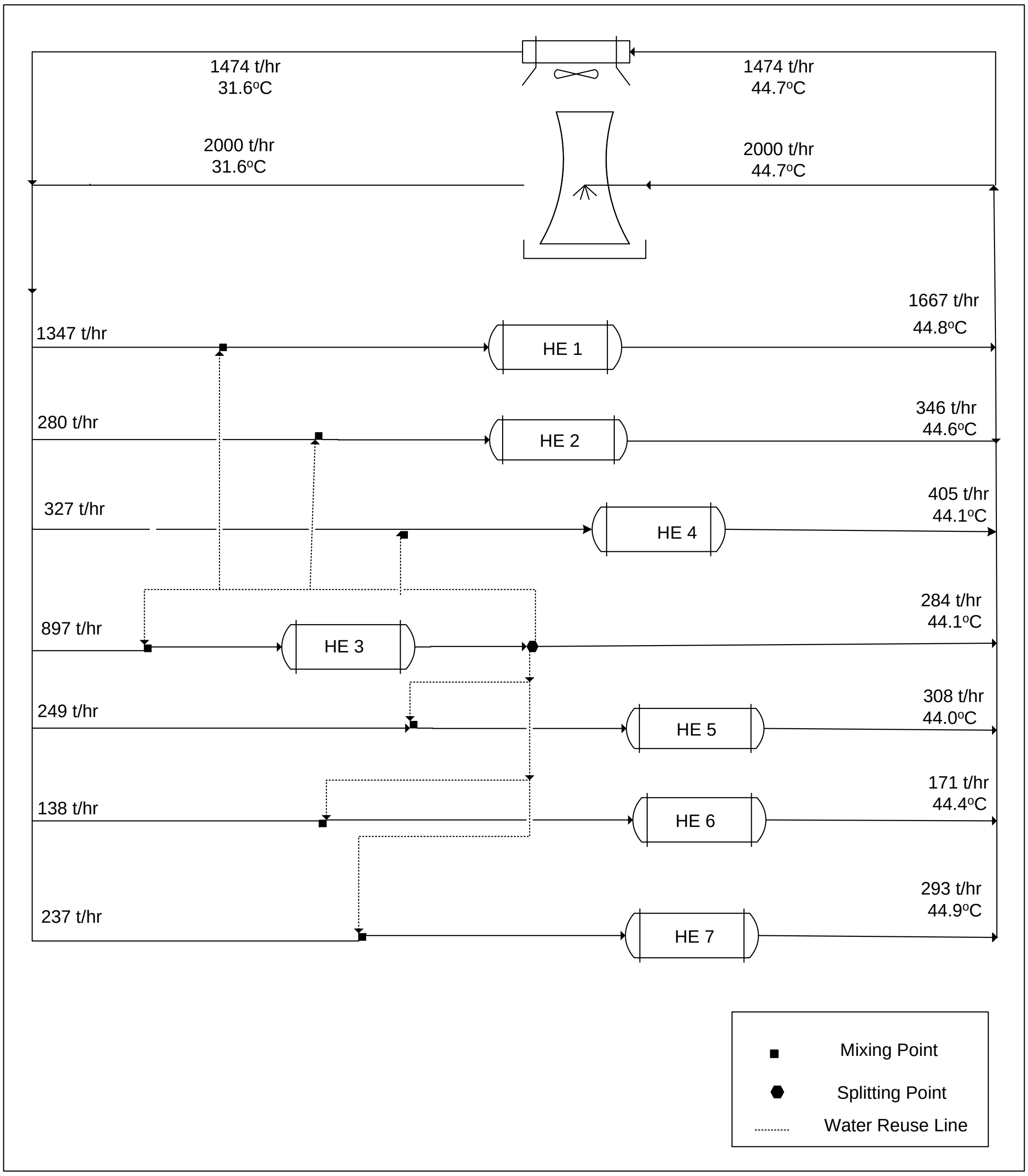

Figure 4.18: Cooling Water Reuse Network for Plant I (Option 3)

4.7.3 Result Summary for Case Study 3

In summary, the results for case study 3 are tabulated as in Table 4.13. It can be concluded that, option 2 is the most attractive, since it having the shorter payback period together with largest additional revenue.

Table 4.13: Result Summary for Case Study 3

Options	Description
Option 1	• Less water make-up=12% • Operating cost savings = RM139,000/Yr • Additional capital cost (new HE area) • Payback period = 13 months
Option 2	• Targeted 15% additional product capacity • Additional product value: RM39 Million / Yr • Needs water regeneration unit • Payback period : 1 months
Option 3	• Additional product capacity by increasing heat load at HE • Needs water regeneration unit • Additional profit : RM8 Million / Yr • Payback period : 2 months

CHAPTER 5
CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

A duo-step optimization procedure was proposed in this thesis, in which optimization of cooling tower parameters provided the opportunity of cooling water savings from cooling water reuse and additional production capacity. The first stage was used to calculate the cooling tower supply temperature with various L/G ratios. The reduction in L/G ratio will reduce cooling water supply temperature and thus increase the cooling tower performance. Optimized parameters were then used as constraints in second stage of optimization process for cooling water reuse design.

In cooling water reuse design, cooling water network composite curve (CWNCC) was used to identify the minimum cooling water reuse opportunity. Most of cooling water network has source temperature that was higher than sink temperature. Consequently no reuse opportunity could be determined from CWNCC. Stream mixing was introduced to create lower source temperature, in which hot water is mixed with fresh cooling water from cooling tower. This enables the inlet temperature of cooling water into heat exchanger to be higher than the cooling water supply temperature.

Mathematical programming was used to calculate and match streams to be mixed. The objective function of this program was to maximize cooling water reuse, while cooling tower optimized parameters were included as constraints. In addition, the operability of heat exchanger was also considered as one of the important constraint in reuse design. Several designs options were produced in each case.

Three case studies were performed to show the effects and the benefits of the proposed two-stage cooling tower optimization procedure. The first case study, which did not use cooling water reuse, showed that cooling tower operating cost can be reduced up to 27%. For the second case study, with cooling water reuse design, savings opportunities can be realized up to 28%. The best option may for option 2 that having less additional piping together with possibilities of giving higher additional capacity than others. Finally, as shown in case study 3, savings and process debottlenecking could generate substantial extra revenue for the plant up to RM 39 Million per year. Due to the shortest payback period, which is 1 month, option 2 is chosen for the best option.

5.2 Future Work

As an alternative to a stage-wise approach, a simultaneous optimization technique could be considered. This combines both stages 1 and 2 together especially with the advent of high power computing.

More detail physical models for heat exchanger can also be considered in order to account for non linear heat transfer. Besides, cooling tower model can also be developed based on thermodynamics and mass transfer rather than just using models that is already develop such as Chebysheve solutions for Merkel's model. Thus, it is easier to incorporate cooling tower optimization with cooling water reuse design.

In addition, this study only considered constant cooling water flow inside heat exchanger to avoid fouling problem and concerns in pressure drop. In future, pressure drop can be also considered as one of optimize parameters, so that it can be utilized in network design. As mentioned in Chapter 2, Nesta and Bennet (2006) suggested that equal pressure drop inside heat exchanger can be applied, so that, cooling water flowrate is based on equal pressure drop by distributing itself to equalize the system pressure drop from inlet to outlet header.

As cooling tower circulation rate is reduced, blowdown quantity is also being reduced. Changes in this quantity may affect water quality and treatment problems. Hence consideration for water chemistry should be incorporated with the debottlenecking and targeting of cooling water network design. Cooling water from blowdown sytem can also be incorporated with waste minimization studied as done by Kim (2001) in his work.

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APPENDIX A

SAMPLE OF GAMS CODING

A.1 Defining constraints

***Decalaration of set*

sets i source/RE1,RE2, RE3, RE4, RE5, RE6,RE7, RE8, RE9,RE10, RE11,RE12, RE13/

***Tabulated constant parameters*

table B(i,) CW inlet to HE*

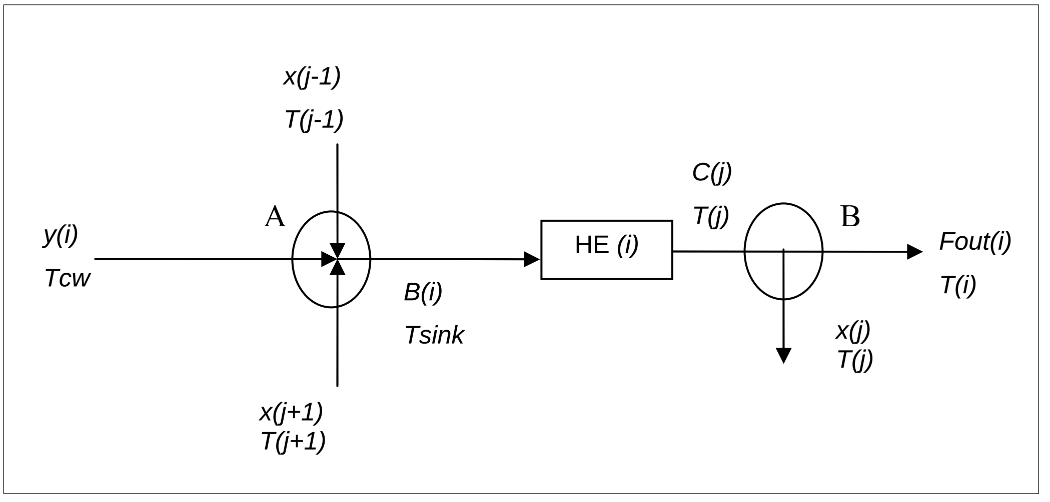
	Fcw	Tpin	Tpout	UA	Qo	LT
RE1	727	98.91	38	597590	8.46	0.80
RE2	940	60	38	1729585	10.94	0.85
RE3	53	64.3	40	55188	0.62	1.06
RE4	293	69.5	40	520340	3.41	0.53
RE5	293	128	40	147559	3.41	0.83
RE6	817	83.4	64.3	378463	9.51	0.75
RE7	179	131	108	56831	2.08	0.46
RE8	226	60	45	266654	2.63	0.80
RE9	224	60	45	264294	2.61	0.80
RE10	84	136.9	40	37139	0.98	0.88
RE11	96	150.5	40	39753	1.12	0.85
RE12	75	145.4	40	36089	0.87	0.76
RE13	75	124.5	40	37375	0.87	0.87

scalar Tcw cooling water tempr/32.58/ ;

```
            Qnew(i)
            Tret
            LMTD(i)

Fcwnew (i)
positive variable     Tcwin, Tcwout, Qnew, UAnew, LMTD, Tret;
equation
    obj
    LMTD1(i)
    Area1 (i)
    Qnew1 (i)
    Qnew2 (i)
    flow(i)
    treturn;

    obj..       z =e= sum(i,Qnew(i));

    LMTD1 (i)..    LMTD(i) =e= [(B(i,'Tpin') - Tcwout(i))- (B(i,'Tpout')-
                    Tcwin(i))]/log [(B(i,'Tpin') - Tcwout(i))/ (B(i,'Tpout')- Tcwin(i))]
                    ;
    Area1 (i)..    Qnew (i)- B(i,'UA')/1000000*[LMTD(i) * B(i,'LT')] =e= 0 ;
    Qnew1(i)..     Qnew(i) =e= 1000*4.19*0.0000002778*Fcwnew(i)*(Tcwout(i) -
                   Tcwin (i) );
    Qnew2 (i)..    Qnew (i) =g= B(i,'Qo');
    flow(i)..      Fcwnew(i) =l= B(i,'fcw');
    treturn..      sum (i,Fcwnew(i)*Tcwout(i))- [sum (i, Fcwnew(i))]* Tret =e= 0;
    Tcwin.lo(i) = 32;  Tcwin.l(i) = 35;   tcwin.up(i)= 35;
    Tcwout.l(i) = 45; Tcwout.up(i) = 50;
    Tret.fx = 45;
model       reuse/all/;
solve       reuse using nlp maximizing z ;
```

A.2 Cooling water reuse design

Schematic Diagram



**Declaration of sets

sets I source/RE1,RE2, RE3, RE4, RE5, RE6,RE7/

J sink /HE1,HE2,HE3,HE4,HE5, HE6,HE7/

***Parameters*

parameter B(I) CW outlet reuse and return-source/

RE1 1667

RE2 346

RE3 1110

RE4 405

RE5 308

RE6 171

RE7 293

/

T(I) Tout or source T for every HE/

RE1 44.99

RE2 44.63

RE3 44.09

RE4 44.11

RE5 44.42

RE6 44.35

```
              RE7      44.86
               /
              C(J)   min flow for each HE-sink/
              HE1      1667
              HE2      346
              HE3      1110
              HE4      405
              HE5      308
              HE6      171
              HE7      293
              /
scalar        tin inlet T /34/          ;

**Declaration of variables
Variables
      Z            objective variable
      x(i,j)       cw reuse in cases
      y(j)         fresh cw in cases
      Tout         hot water T return to CT
      Fout(i)      Cw return to CT
Positive Variable x,y, Fout ;

**Declaration of equations used
equation
         obj                   objective
         supply(i)             observe supply limit j
         demand(j)             satisfy cw demand at i
         demand2(j)            satisfy cw demand at i
         Temp(i)               calculate cw return at i
      tout2                    calculate T return to CT;
**Formulations
  obj..      z   =e= sum(j,y(j));
```

```
  supply(i) ..   sum(j, x(i,j))=l=  b(i) ;
  demand(j)..    (sum(i, x(i,j)*T(i)) + y(j)*31.6 )- tin* c(j)  =e= 0 ;
  demand2(j)..   sum(i, x(i,j))+y(j) =e= c(j);
  temp(i)..      fout(i)+ sum(j,x(i,j)) =e= b(i)  ;
  tout2..        (sum(i,Fout(i)*T(i))) / (sum (i,Fout(i)))  =e= Tout    ;

**initial conditions

  fout.l (i) = 10;
  tout.l = 45;

**Solving equations

model          reuse/all/;
solve          reuse using nlp minimizing z ;
parameter       regen
               fresh
               reusew    ;
               fresh = sum (j, y.l(j));
               reusew = sum ((i,j), x.l(i,j));
                regen = fresh - 2000;
display        x.l, y.l, tout.l, fout.l, regen, fresh, reusew ;
```

APPENDIX B

SAMPLE OF GAMS OUTPUT

GAMS Rev 228 x86/MS Windows   02/06/09 21:00:30 Page 1

G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
C o m p i l a t i o n

```

sets            I      source/RE1,RE2, RE3, RE4, RE5, RE6,RE7/
                J      sink /HE1,HE2,HE3,HE4,HE5, HE6,HE7/


parameter       B(I)   CW outlet reuse and return-source/
                RE1      1667
                RE2      346
                RE3      1110
                RE4      405
                RE5      308
                RE6      171
                RE7      293
                /
                T(I)   Tout or source T for every HE/
                RE1      44.99
                RE2      44.63
                RE3      44.09
                RE4      44.11
                RE5      44.42
                RE6      44.35
                RE7      44.86
                /
                C(J)   min flow for each HE-sink/
                HE1      1667
                HE2      346
                HE3      1110
                HE4      405
                HE5      308
                HE6      171
                HE7      293
                /
```

```
scalar          tin inlet T /34/              ;

**Declaration of variables
Variables
                    Z              objective variable
       x(i,j)          cw reuse in cases
       y(j)            fresh cw in cases
       Tout            hot water T return to CT
       Fout(i)         Cw return to CT
Positive Variable x,y, Fout ;

**Declaration of equations used
equation
obj                             objective
              supply(i)                    observe supply limit j
              demand(j)               satisfy cw demand at i
              demand2(j)              satisfy cw demand at i
           Temp(i)               calculate cw return at i
       tout2                     calculate T return to CT;
**Formulations
  obj..        z   =e= sum(j,y(j));

  supply(i) ..   sum(j, x(i,j))=l=  b(i) ;
  demand(j)..    (sum(i, x(i,j)*T(i)) + y(j)*31.6 )- tin* c(j)  =e= 0 ;
  demand2(j)..   sum(i, x(i,j))+y(j) =e= c(j);
  temp(i)..      fout(i)+ sum(j,x(i,j)) =e= b(i)  ;
  tout2..        (sum(i,Fout(i)*T(i))) / (sum (i,Fout(i)))  =e= Tout    ;

**initial conditions

  fout.l (i) = 10;
  tout.l = 45;

**Solving equations

model                 reuse/all/;
solve                 reuse using nlp minimizing z ;
parameter        regen
                 fresh
                 reusew    ;
                 fresh = sum (j, y.l(j));
                 reusew = sum ((i,j), x.l(i,j));
                 regen = fresh - 2000;
display               x.l, y.l, tout.l, fout.l, regen, fresh, reusew ;
```

COMPILATION TIME   =   0.000 SECONDS   3 Mb WIN228-228 Jul 26, 2008

---- obj =E= objective

obj.. Z - y(HE1) - y(HE2) - y(HE3) - y(HE4) - y(HE5) - y(HE6) - y(HE7) =E= 0 ;

(LHS = 0)

---- supply =L= observe supply limit j

supply(RE1).. x(RE1,HE1) + x(RE1,HE2) + x(RE1,HE3) + x(RE1,HE4) + x(RE1,HE5)

+ x(RE1,HE6) + x(RE1,HE7) =L= 1667 ; (LHS = 0)

supply(RE2).. x(RE2,HE1) + x(RE2,HE2) + x(RE2,HE3) + x(RE2,HE4) + x(RE2,HE5)

+ x(RE2,HE6) + x(RE2,HE7) =L= 346 ; (LHS = 0)

supply(RE3).. x(RE3,HE1) + x(RE3,HE2) + x(RE3,HE3) + x(RE3,HE4) + x(RE3,HE5)

+ x(RE3,HE6) + x(RE3,HE7) =L= 1110 ; (LHS = 0)

REMAINING 4 ENTRIES SKIPPED

---- demand =E= satisfy cw demand at i

*demand(HE1).. 44.99*x(RE1,HE1) + 44.63*x(RE2,HE1) + 44.09*x(RE3,HE1)*

*+ 44.11*x(RE4,HE1) + 44.42*x(RE5,HE1) + 44.35*x(RE6,HE1)*

*+ 44.86*x(RE7,HE1) + 31.6*y(HE1) =E= 56678 ; (LHS = 0, INFES = 56678 ****)*

*demand(HE2).. 44.99*x(RE1,HE2) + 44.63*x(RE2,HE2) + 44.09*x(RE3,HE2)*

*+ 44.11*x(RE4,HE2) + 44.42*x(RE5,HE2) + 44.35*x(RE6,HE2)*

*+ 44.86*x(RE7,HE2) + 31.6*y(HE2) =E= 11764 ; (LHS = 0, INFES = 11764 ****)*

*demand(HE3).. 44.99*x(RE1,HE3) + 44.63*x(RE2,HE3) + 44.09*x(RE3,HE3)*

*+ 44.11*x(RE4,HE3) + 44.42*x(RE5,HE3) + 44.35*x(RE6,HE3)*

*+ 44.86*x(RE7,HE3) + 31.6*y(HE3) =E= 37740 ; (LHS = 0, INFES = 37740 ****)*

REMAINING 4 ENTRIES SKIPPED

---- demand2 =E= satisfy cw demand at i

demand2(HE1).. x(RE1,HE1) + x(RE2,HE1) + x(RE3,HE1) + x(RE4,HE1) + x(RE5,HE1)

*+ x(RE6,HE1) + x(RE7,HE1) + y(HE1) =E= 1667 ; (LHS = 0, INFES = 1667 ****)*

demand2(HE2).. x(RE1,HE2) + x(RE2,HE2) + x(RE3,HE2) + x(RE4,HE2) + x(RE5,HE2)

*+ x(RE6,HE2) + x(RE7,HE2) + y(HE2) =E= 346 ; (LHS = 0, INFES = 346 ****)*

demand2(HE3).. x(RE1,HE3) + x(RE2,HE3) + x(RE3,HE3) + x(RE4,HE3) + x(RE5,HE3)

*+ x(RE6,HE3) + x(RE7,HE3) + y(HE3) =E= 1110 ; (LHS = 0, INFES = 1110 ****)*

REMAINING 4 ENTRIES SKIPPED

---- Temp =E= calculate cw return at i

Temp(RE1).. x(RE1,HE1) + x(RE1,HE2) + x(RE1,HE3) + x(RE1,HE4) + x(RE1,HE5)

+ x(RE1,HE6) + x(RE1,HE7) + Fout(RE1) =E= 1667 ;

*(LHS = 10, INFES = 1657 ****)*

Temp(RE2).. x(RE2,HE1) + x(RE2,HE2) + x(RE2,HE3) + x(RE2,HE4) + x(RE2,HE5)

+ x(RE2,HE6) + x(RE2,HE7) + Fout(RE2) =E= 346 ;

*(LHS = 10, INFES = 336 ****)*

Temp(RE3).. x(RE3,HE1) + x(RE3,HE2) + x(RE3,HE3) + x(RE3,HE4) + x(RE3,HE5)
+ x(RE3,HE6) + x(RE3,HE7) + Fout(RE3) =E= 1110 ;

*(LHS = 10, INFES = 1100 ****)*

REMAINING 4 ENTRIES SKIPPED

---- tout2 =E= calculate T return to CT

*tout2.. - Tout + (0.00710204081632648)*Fout(RE1)*

*+ (0.00195918367346937)*Fout(RE2) - (0.00575510204081631)*Fout(RE3)*

*- (0.00546938775510208)*Fout(RE4) - (0.00104081632653064)*Fout(RE5)*

*- (0.00204081632653064)*Fout(RE6) + (0.00524489795918359)*Fout(RE7)*
=E= 0
*; (LHS = -0.507142857142853, INFES = 0.507142857142853 ****)*

GAMS Rev 228 x86/MS Windows   02/06/09 21:00:30 Page 3
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Column Listing   SOLVE reuse Using NLP From line 69

---- Z objective variable

Z
(.LO, .L, .UP, .M = -INF, 0, +INF, 0)
1   obj

---- x cw reuse in cases

x(RE1,HE1)
(.LO, .L, .UP, .M = 0, 0, +INF, 0)
1   supply(RE1)
44.99   demand(HE1)
1   demand2(HE1)
1   Temp(RE1)

x(RE1,HE2)
(.LO, .L, .UP, .M = 0, 0, +INF, 0)
1   supply(RE1)
44.99   demand(HE2)
1   demand2(HE2)
1   Temp(RE1)

x(RE1,HE3)
(.LO, .L, .UP, .M = 0, 0, +INF, 0)
1   supply(RE1)
44.99   demand(HE3)

1 demand2(HE3)
1 Temp(RE1)

REMAINING 46 ENTRIES SKIPPED

---- y fresh cw in cases

y(HE1)
(.LO, .L, .UP, .M = 0, 0, +INF, 0)
-1 obj
31.6 demand(HE1)
1 demand2(HE1)

y(HE2)
(.LO, .L, .UP, .M = 0, 0, +INF, 0)
-1 obj
31.6 demand(HE2)
1 demand2(HE2)

y(HE3)
(.LO, .L, .UP, .M = 0, 0, +INF, 0)
-1 obj
31.6 demand(HE3)
1 demand2(HE3)

REMAINING 4 ENTRIES SKIPPED

---- Tout hot water T return to CT

Tout
(.LO, .L, .UP, .M = -INF, 45, +INF, 0)
-1 tout2

---- Fout Cw return to CT

Fout(RE1)
(.LO, .L, .UP, .M = 0, 10, +INF, 0)
1 Temp(RE1)
(0.0071) tout2

Fout(RE2)
(.LO, .L, .UP, .M = 0, 10, +INF, 0)
1 Temp(RE2)
(0.002) tout2

Fout(RE3)
(.LO, .L, .UP, .M = 0, 10, +INF, 0)
1 Temp(RE3)

```
   (-0.0058) tout2

REMAINING 4 ENTRIES SKIPPED

GAMS Rev 228  x86/MS Windows                    02/06/09 21:00:30 Page 4
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Model Statistics    SOLVE reuse Using NLP From line 69


MODEL STATISTICS

BLOCKS OF EQUATIONS           6     SINGLE EQUATIONS           30
BLOCKS OF VARIABLES           5     SINGLE VARIABLES           65
NON ZERO ELEMENTS           233     NON LINEAR N-Z              7
DERIVATIVE POOL              20     CONSTANT POOL              23
CODE LENGTH                  74


GENERATION TIME      =        0.031 SECONDS      4 Mb  WIN228-228 Jul 26, 2008


EXECUTION TIME       =        0.031 SECONDS      4 Mb  WIN228-228 Jul 26, 2008

GAMS Rev 228  x86/MS Windows                    02/06/09 21:00:30 Page 5
G e n e r a l   A l g e b r a i c   M o d e l i n g   S y s t e m
Solution Report     SOLVE reuse Using NLP From line 69


               S O L V E      S U M M A R Y

     MODEL   reuse               OBJECTIVE  Z
     TYPE    NLP                 DIRECTION  MINIMIZE
     SOLVER  CONOPT              FROM LINE  69

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE             3473.7390

 RESOURCE USAGE, LIMIT          0.023      1000.000
 ITERATION COUNT, LIMIT        10         10000
 EVALUATION ERRORS              0             0


    C O N O P T 3   version 3.14S
    Copyright (C)   ARKI Consulting and Development A/S
                    Bagsvaerdvej 246 A
                    DK-2880 Bagsvaerd, Denmark

 Second order sparsety pattern was not generated.
```

The Hessian of the Lagrangian became too dense because of equation tout2.
You may try to increase Rvhess from its current value of 10.0 in the CONOPT Options file.
Using default options.

*** Optimal solution. There are no superbasic variables.*

CONOPT time Total 0.000 seconds
of which: Function evaluations 0.000 = 0.0%
1st Derivative evaluations 0.000 = 0.0%

Workspace = 0.18 Mbytes
Estimate = 0.18 Mbytes
Max used = 0.07 Mbytes

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU obj	.	.	.	1.000

obj objective

---- EQU supply observe supply limit j

	LOWER	LEVEL	UPPER	MARGINAL
RE1	-INF	.	1667.000	.
RE2	-INF	.	346.000	.
RE3	-INF	826.261	1110.000	.
RE4	-INF	.	405.000	.
RE5	-INF	.	308.000	.
RE6	-INF	.	171.000	.
RE7	-INF	.	293.000	.

---- EQU demand satisfy cw demand at i

	LOWER	LEVEL	UPPER	MARGINAL
HE1	56678.000	56678.000	56678.000	-0.080
HE2	11764.000	11764.000	11764.000	-0.080
HE3	37740.000	37740.000	37740.000	-0.080
HE4	13770.000	13770.000	13770.000	-0.080
HE5	10472.000	10472.000	10472.000	-0.080
HE6	5814.000	5814.000	5814.000	-0.080
HE7	9962.000	9962.000	9962.000	-0.080

---- EQU demand2 satisfy cw demand at i

	LOWER	LEVEL	UPPER	MARGINAL
HE1	1667.000	1667.000	1667.000	3.530
HE2	346.000	346.000	346.000	3.530
HE3	1110.000	1110.000	1110.000	3.530
HE4	405.000	405.000	405.000	3.530
HE5	308.000	308.000	308.000	3.530
HE6	171.000	171.000	171.000	3.530
HE7	293.000	293.000	293.000	3.530

---- EQU Temp calculate cw return at i

	LOWER	LEVEL	UPPER	MARGINAL
RE1	1667.000	1667.000	1667.000	EPS
RE2	346.000	346.000	346.000	EPS
RE3	1110.000	1110.000	1110.000	EPS
RE4	405.000	405.000	405.000	EPS
RE5	308.000	308.000	308.000	EPS
RE6	171.000	171.000	171.000	EPS
RE7	293.000	293.000	293.000	EPS

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU tout2	.	.	.	EPS

tout2 calculate T return to CT

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR Z	-INF	3473.739	+INF	.

Z objective variable

---- VAR x cw reuse in cases

	LOWER	LEVEL	UPPER	MARGINAL
RE1.HE1	.	.	+INF	0.072
RE1.HE2	.	.	+INF	0.072
RE1.HE3	.	.	+INF	0.072
RE1.HE4	.	.	+INF	0.072
RE1.HE5	.	.	+INF	0.072
RE1.HE6	.	.	+INF	0.072
RE1.HE7	.	.	+INF	0.072
RE2.HE1	.	.	+INF	0.043
RE2.HE2	.	.	+INF	0.043
RE2.HE3	.	.	+INF	0.043
RE2.HE4	.	.	+INF	0.043

RE2.HE5	.	.	+INF	0.043
RE2.HE6	.	.	+INF	0.043
RE2.HE7	.	.	+INF	0.043
RE3.HE1	.	320.320	+INF	.
RE3.HE2	.	66.485	+INF	.
RE3.HE3	.	213.291	+INF	.
RE3.HE4	.	77.822	+INF	.
RE3.HE5	.	59.183	+INF	.
RE3.HE6	.	32.858	+INF	.
RE3.HE7	.	56.301	+INF	.
RE4.HE1	.	.	+INF	0.002
RE4.HE2	.	.	+INF	0.002
RE4.HE3	.	.	+INF	0.002
RE4.HE4	.	.	+INF	0.002
RE4.HE5	.	.	+INF	0.002
RE4.HE6	.	.	+INF	0.002
RE4.HE7	.	.	+INF	0.002
RE5.HE1	.	.	+INF	0.026
RE5.HE2	.	.	+INF	0.026
RE5.HE3	.	.	+INF	0.026
RE5.HE4	.	.	+INF	0.026
RE5.HE5	.	.	+INF	0.026
RE5.HE6	.	.	+INF	0.026
RE5.HE7	.	.	+INF	0.026
RE6.HE1	.	.	+INF	0.021
RE6.HE2	.	.	+INF	0.021
RE6.HE3	.	.	+INF	0.021
RE6.HE4	.	.	+INF	0.021
RE6.HE5	.	.	+INF	0.021
RE6.HE6	.	.	+INF	0.021
RE6.HE7	.	.	+INF	0.021
RE7.HE1	.	.	+INF	0.062
RE7.HE2	.	.	+INF	0.062
RE7.HE3	.	.	+INF	0.062
RE7.HE4	.	.	+INF	0.062
RE7.HE5	.	.	+INF	0.062
RE7.HE6	.	.	+INF	0.062
RE7.HE7	.	.	+INF	0.062

---- VAR y fresh cw in cases

	LOWER	LEVEL	UPPER	MARGINAL
HE1	.	1346.680	+INF	.
HE2	.	279.515	+INF	.
HE3	.	896.709	+INF	.
HE4	.	327.178	+INF	.
HE5	.	248.817	+INF	.
HE6	.	138.142	+INF	.

HE7 . 236.699 +INF .

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR Tout	*-INF*	*44.685*	*+INF*	*.*

Tout hot water T return to CT

---- VAR Fout Cw return to CT

	LOWER	LEVEL	UPPER	MARGINAL
RE1	*.*	*1667.000*	*+INF*	*.*
RE2	*.*	*346.000*	*+INF*	*.*
RE3	*.*	*283.739*	*+INF*	*.*
RE4	*.*	*405.000*	*+INF*	*.*
RE5	*.*	*308.000*	*+INF*	*.*
RE6	*.*	*171.000*	*+INF*	*.*
RE7	*.*	*293.000*	*+INF*	*.*

***** REPORT SUMMARY : 0 NONOPT*
0 INFEASIBLE
0 UNBOUNDED
0 ERRORS

GAMS Rev 228 x86/MS Windows 02/06/09 21:00:30 Page 6
G e n e r a l A l g e b r a i c M o d e l i n g S y s t e m
E x e c u t i o n

---- 76 VARIABLE x.L cw reuse in cases

	HE1	HE2	HE3	HE4	HE5	HE6
RE3	*320.320*	*66.485*	*213.291*	*77.822*	*59.183*	*32.858*

+	HE7
RE3	*56.301*

---- 76 VARIABLE y.L fresh cw in cases

HE1 1346.680, HE2 279.515, HE3 896.709, HE4 327.178, HE5 248.817
HE6 138.142, HE7 236.699

---- 76 VARIABLE Tout.L = 44.685 hot water T return to CT

---- 76 VARIABLE Fout.L Cw return to CT

RE1 1667.000, RE2 346.000, RE3 283.739, RE4 405.000, RE5 308.000
RE6 171.000, RE7 293.000

---- 76 PARAMETER regen = 1473.739
PARAMETER fresh = 3473.739
PARAMETER reusew = 826.261

EXECUTION TIME = 0.437 SECONDS 3 Mb WIN228-228 Jul 26, 2008

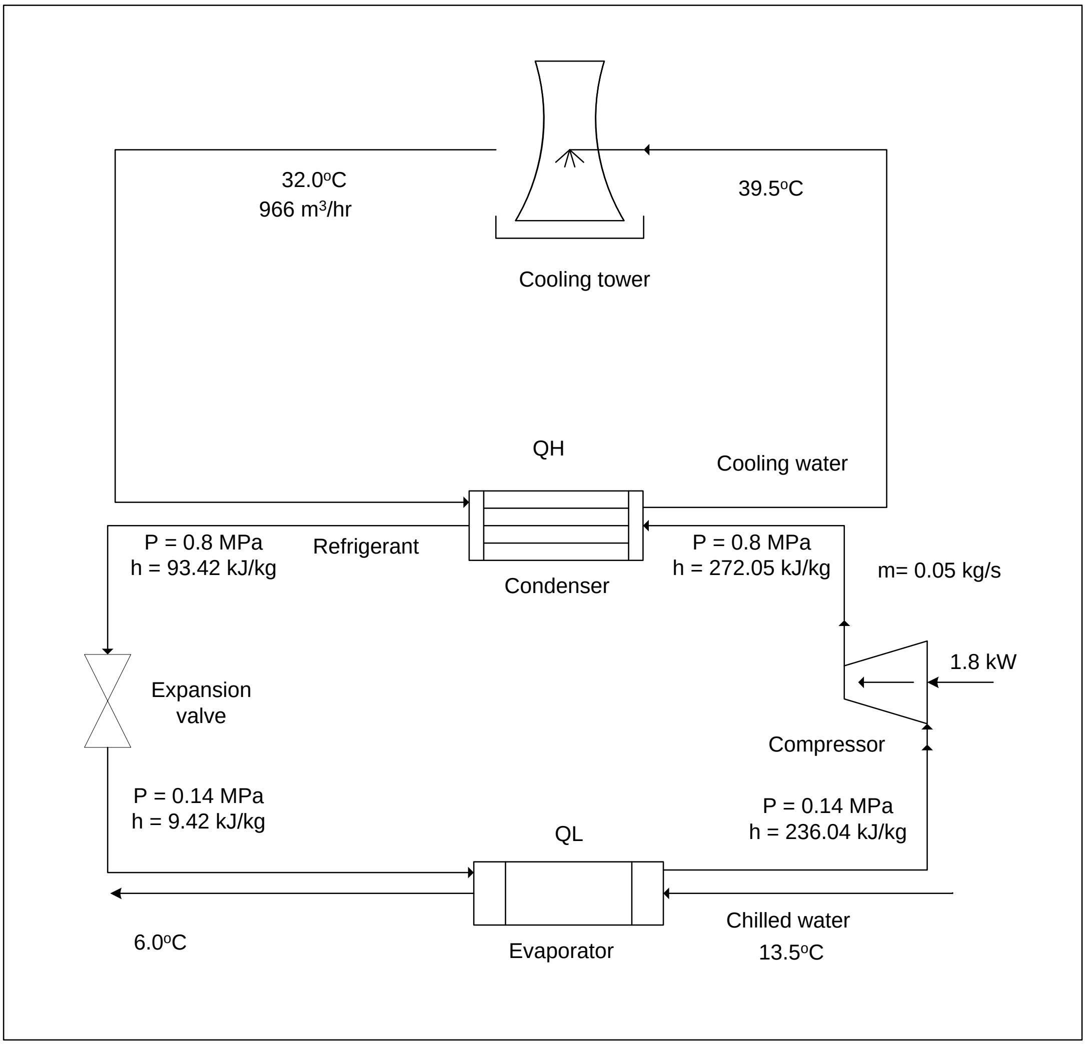
USER: GAMS Development Corporation, Washington, DC G871201/0000CA-ANY
Free Demo, 202-342-0180, sales@gams.com, www.gams.com DC0000

***** FILE SUMMARY*

Input C:\Documents and Settings\User\My Documents\draft thesis february 09\appendix B.gms
Output C:\Documents and Settings\User\My Documents\gamsdir\projdir\appendix B.lst

APPENDIX C

CHILLER SYSTEM



Assume ideal refrigeration cycle.

$$QH = 0.05\frac{kg}{s}x(272.05 - 93.42) = 8.93 \text{ kW}$$

$QL = 0.05\frac{kg}{s}x(236.04 - 93.42)$ = 7.13 kW

Compression work, Wnet,in = $0.05\frac{kg}{s}x(272.05 - 236.04)$ = 1.80 kW

Compression work is also can be calculated as follows:
= 8.93 – 7.13
=1.8 kW

As temperature of cooling water is reduced by 0.6 deg C, liquid refrigerant is also reduced by 0.6 deg C to maintain dTmin of condenser. Thus, new liquid refrigerant temperature is 30.7 deg C (saturated liquid, thus pressure is reduced a bit)

New enthalpy of saturated liquid @ 30.7 deg C is 92.53 kJ/kg
QH is constant at 8.93 kW
Thus, New QL = $0.05\frac{kg}{s}x(236.04 - 92.53)$ =7.18 kW
New compression work, New Wnet,in;
=8.93 – 7.18
=1.75 kW

Compression work reduction = $\frac{(1.80 - 1.75)}{1.80}x100 = 2.78 \approx 3$ %

APPENDIX D

SAMPLE OF CALCULATIONS

Assumptions

a) Price of methanol, C_M = USD 300/tonne

b) Price of electricity, C_E = RM 0.26/kW

c) Price of water, C_W = RM 0.90/m^3

d) Pump efficiency = 80%

e) Fan efficiency = 70%

f) Motor efficiency = 85%

g) Working hours = 8000 hr/year

h) Density of air = 1.2 kg/m^3

i) Density of water=1000 kg/m3

Equations

1. Cooling tower operating cost

a) Pump power

$$kW.h = 0.746(hp)(H)$$
$$= \frac{0.746(gal/\min)(h_d)(SG)(H)}{3960}$$

Where;

Gal/min	= flowrate
hp	= horsepower
H	= hours of operation
h_d	= head of fluid (ft)
SG	= specific gravity relative to water

Source: www.osha.gov

b) Fan power

$$kW.h = 0.746(hp)(H)$$

$$= \frac{0.746(ft^3/\min)(\Delta P)(SG)(H)}{6356\eta}$$

Where;

kW.h	= kilowatt hour
hp	= horsepower
ft^3/min	= actual volumetric of air flowrate
P	= pressure loss in wg
η	=mechanical efficiency, usually 60-70%
H	= hours of operation
h_d	= head of fluid (ft)
SG	= specific gravity relative to water

Source: www.osha.gov

c) Cost of electric (RM/year)

= Fan Power + Pump Power (kW.hr) x price of electric (RM/kW)

d) Cost of water (RM/year)

= Make-up Water (m^3/hr) x price of water (RM/m^3) x Working hours (hr/year)

3. heat exchanger system

a) LMTD calculation

$$\theta_m = LMTD = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \dfrac{(T_1 - t_2)}{(T_2 - t_1)}}$$

Eq D.1

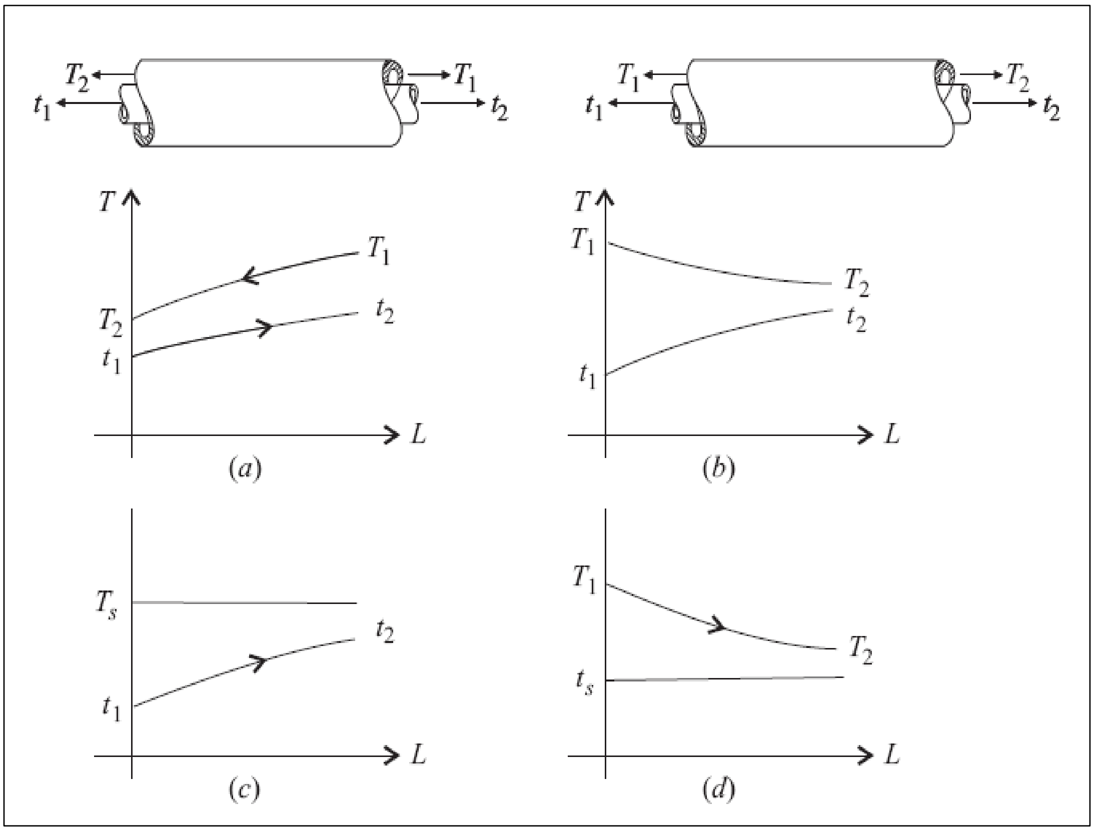


Figure D.1 : Four Basic Arrangements for LMTD may be determine from eq. D.1: (a) counterflow; (b) co-current or parallel flow; (c) constant-temperature source and rising-temperature receiver; (d) constant-temperature receiver and falling-temperature source (Kraus, 2006)

4. Payback Calculation

a) cost estimation of new cell

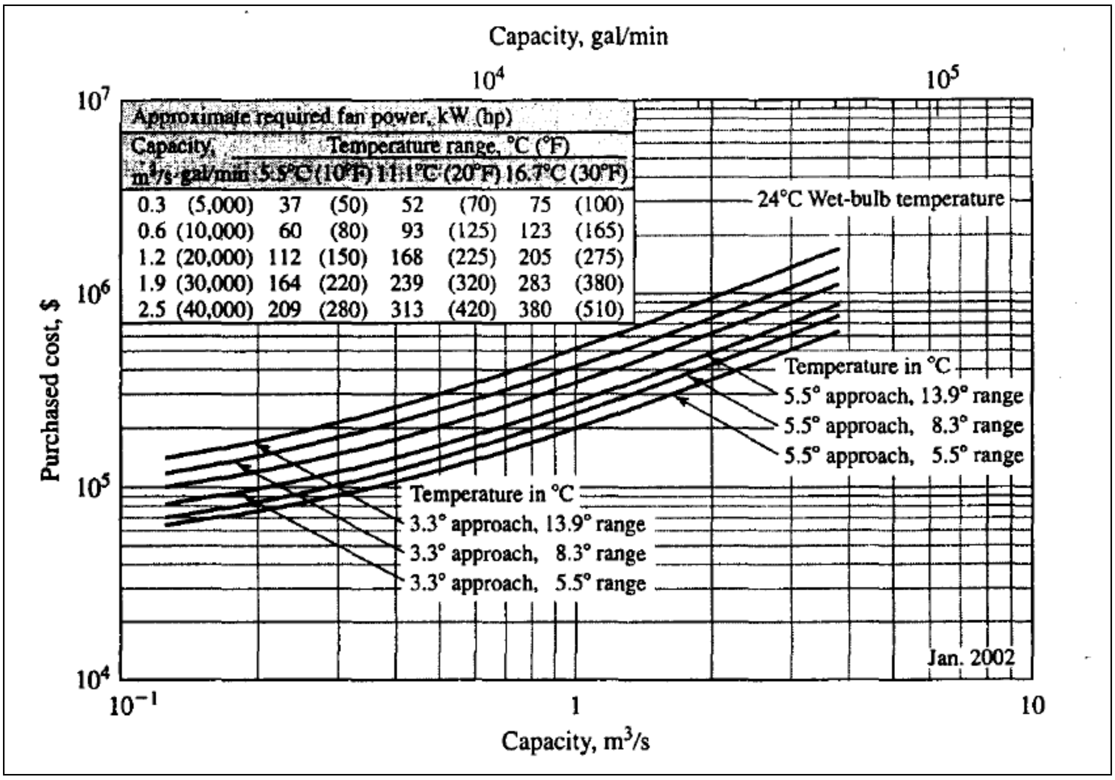


Figure D.2: Purchased cost of cooling towers. Prices are for conventional, wood-frame, induced-draft, cross-flow cooling towers. Price does not include external piping, power wiring, special foundation work, or field labor. (Smith R, 2005).

b) cost estimation of additional heat exchanger area,

$$A' (m^2) = \frac{UA_{old} - UA_{new}}{U}$$

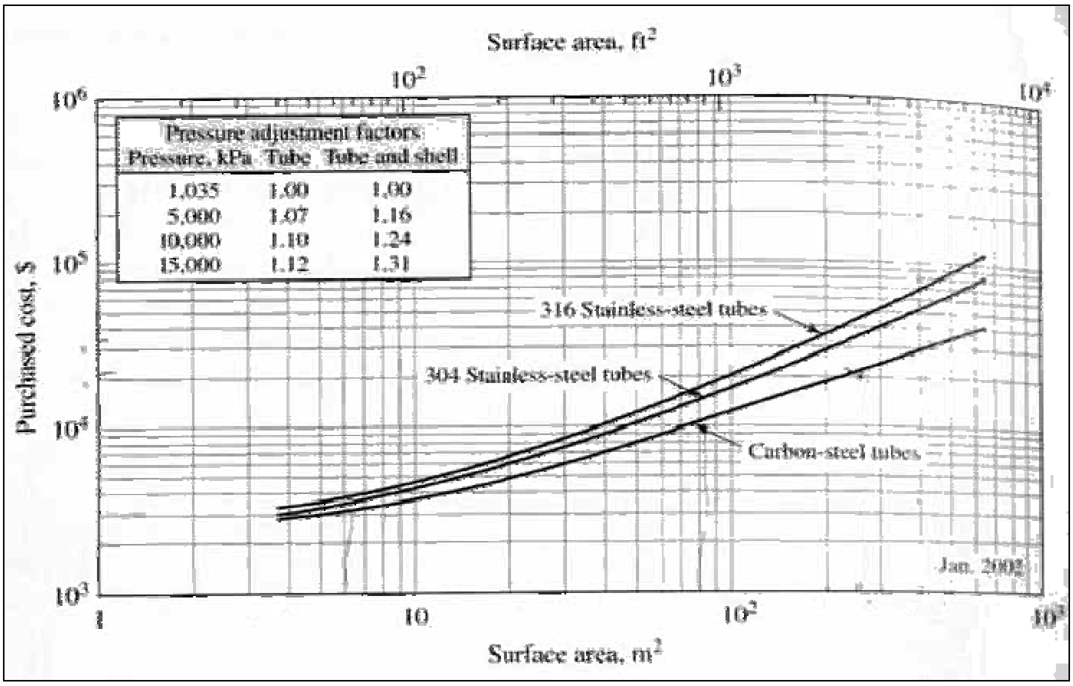


Figure D.3: Purchase cost of fixe-tube-sheet heat exchangers with 0.019-m (¾ in.) OD x 0.025-m (1-in.) square pitch and 4.88- or 6.10-m (16- or 20-ft) bundles and carbon-steel shell operating at 103.5 kPa (150 psia) (Smith R, 2005).

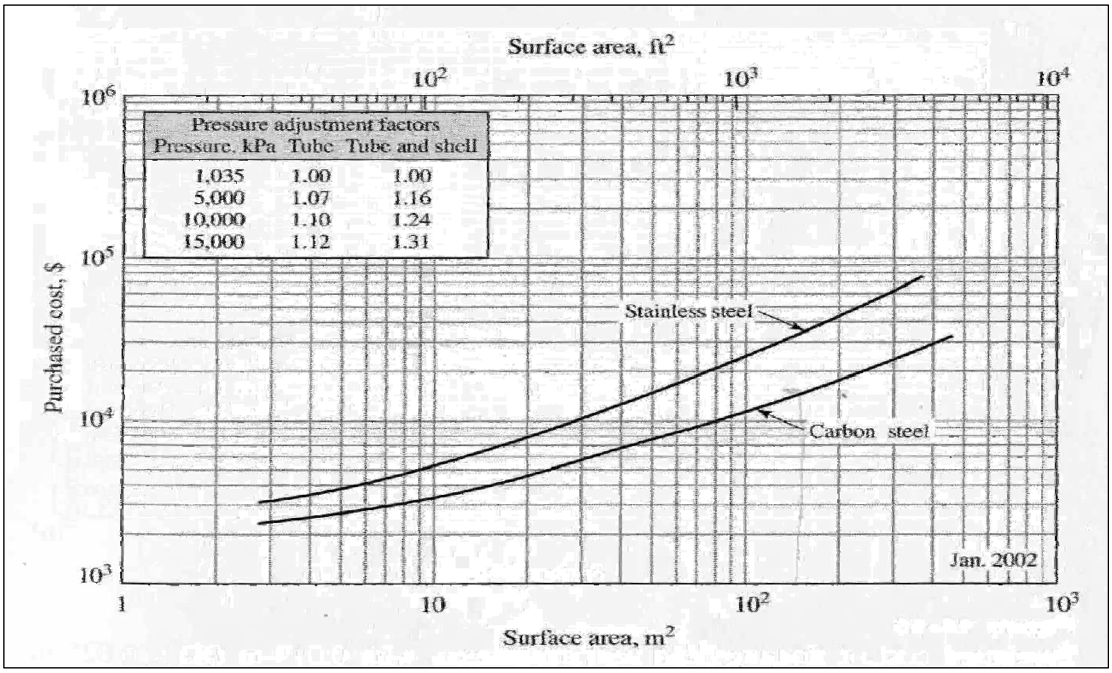


Figure D.4: Purchased cost of U-tube heat exchangers with 0.0254-m (1-in.) OD tubes x 0.0254-m (1-in) square pitch and 4.88-m (16-ft) bundles operating at 103.5 kPa (150 psia). Source: Smith R, , Chemical Process Design and Integration, 2005

c) energy used for air-cooled heat exchanger(hp)

= 2 x AHE cooling load (MW) x 3.4121

d) operating cost for air-cooled heat exchanger

= Energy used (kW) x C_E x operating hours per year

e) cost estimation of air-cooled heat exchanger

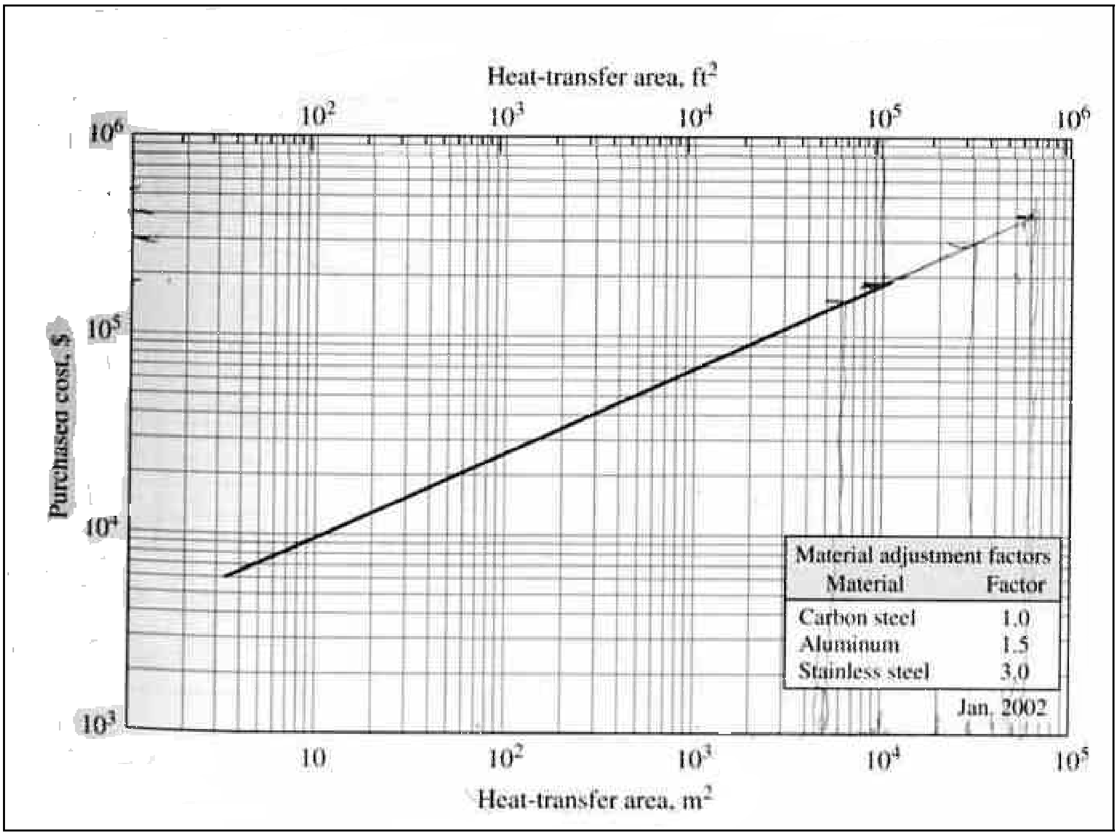


Figure D.4: Purchase cost of air-cooled heat exchangers. Source: Smith R, , Chemical Process Design and Integration, 2005

f) New capacity estimation, F_{new} (kg/hr) = $\frac{F_{old}}{Q_{old}} x Q_{new}$

g) Additional revenue (RM/year) =

$$Fnew(\frac{kg}{hr}) \times C_M (\frac{RM}{tonne}) \times \frac{8000hr}{1yr} \times \frac{1tonne}{1000kg} \times \frac{RM\,3.7}{1USD}$$

h) Payback period calculation

Payback time (months) = $\frac{\text{Capital Cost}}{\text{Income – Operating Cost}}$ x12

Sample of calculation

<u>Case study 3 – Option 1</u>

Fan Power $= \dfrac{0.746 \times 13746 cfm \times 0.483 in.H_2 0 \times 8000 \, {}^{hr}\!/\!_{yr}}{6356 \times 0.7}$

= 890631 kW.hr / yr

Pump power $= \dfrac{0.746 \times 12988 gpm \times 35\, ft \times 8000 \, {}^{hr}\!/\!_{yr}}{3960 \times 0.85 \times 0.8}$

= 1007505 kW.hr/yr

Electricity cost $= (890631.04 \, {}^{kW.hr}\!/\!_{yr} + 1007505 \, {}^{kW.hr}\!/\!_{yr}) \times RM\, 0.26 / kW$

$= RM\, 493515 \, /\!_{yr}$

Water cost $= 74.70 \, {}^{m^3}\!/\!_{hr} \times {}^{RM\, 0.9}\!/\!_{m^3} \times 8000 \, {}^{hr}\!/\!_{yr} = {}^{RM\, 537840}\!/\!_{yr}$

= RM 537840 per year

Cooling Tower Operating cost = RM 493515 + RM 537840

= RM 1,031,355 per year.

Original cooling tower operating cost = RM 1,170,671 per year.

Operating savings cost = RM 139,315 / yr

Total heat exchanger additional area = 355 m^2

Cost of heat exchanger = RM 148,000 (from figure D.3 x RM3.7 / USD)

Payback time (month) $= \dfrac{RM148000 \times 12 month}{RM139{,}315}$ = 12.7 ≈ <u>13 months</u>

Case study 3 – Option 2

Fan Power $= \dfrac{0.746 \times 13746 cfm \times 0.483 in.H_2 0 \times 8000 \, {}^{hr}\!/_{yr}}{6356 \times 0.7}$

= 890631 kW.hr / yr

Pump power $= \dfrac{0.746 \times 12988 gpm \times 35\, ft \times 8000 \, {}^{hr}\!/_{yr}}{3960 \times 0.85 \times 0.8}$

= 1007505 kW.hr/yr

Electricity cost $= (890631.04 \, {}^{kW.hr}\!/_{yr} + 1007505 \, {}^{kW.hr}\!/_{yr}) \times RM\,0.26 / kW$

$= RM\,493515 \, /_{yr}$

Water cost $= 74.70 \, {}^{m^3}\!/_{hr} \times {}^{RM\,0.9}\!/_{m^3} \times 8000 \, {}^{hr}\!/_{yr} = RM\,537840 \, /_{yr}$

Cooling Tower Operating cost = RM 493515 + RM 537840

= RM 1,031,355 per year.

HP for air-cooled heat exchanger (HE) = 2 X 4.38 MW x 3.4121 = 29.91 hp

Operating cost air-cooled HE $= 0.746 \times 29.91 hp \times {}^{RM\,0.26}\!/_{kW} \times 8000 \, {}^{hr}\!/_{yr}$

= RM46417 per year.

Total heat exchanger additional area = 2541 m^2

Cost of heat exchanger = RM 2,025,700 (from Figure D.3 x RM3.7 / USD)

Cost of air-cooled HE = RM 703,000 (from Figure D.4 x RM3.7 / USD)

Total Capital Cost = RM 2,025,700 + RM 703,000 = RM 2,778,700

New product capacity $= \dfrac{29527 \, {}^{kg}\!/\!_{hr} \times 10.94MW}{9.51MW} = 33966 \, {}^{kg}\!/\!_{hr}$

Additional profit = $\dfrac{(33966 \, {}^{kg}\!/\!_{hr} - 29527 \, {}^{kg}\!/\!_{hr}) \times USD300 / tonne \times 8000 \, {}^{hr}\!/\!_{yr}}{1000kg / 1tonne \times 1USD}$

= RM 39,426,462 per year

Payback time (month) $= \dfrac{RM\,2,778,700 \times 12month}{RM\,39,426,462 / yr - (RM\,1,031,355 / yr + RM\,53100 / yr)}$

= 0.9 ≈ 1 months

Case study 3 – Option 3

Fan Power $= \dfrac{0.746 \times 13746cfm \times 0.483in.H_2 0 \times 8000 \, {}^{hr}\!/\!_{yr}}{6356 \times 0.7}$

= 890631 kW.hr / yr

Cooling Tower Operating cost = RM 982,114

Operating cost air-cooled HE = RM 238, 545 per year.

Cost of air-cooled HE = RM 703,000 (from Figure D.4 x RM3.7 / USD)

Additional capacity in prerun column calculation: 3%

Additional profit

$$= \frac{(30427 \, {}^{kg}\!/\!_{hr} - 29527 \, {}^{kg}\!/\!_{hr}) \times USD300 / tonne \times RM\,3.7 \times 8000h \, {}^{hr}\!/\!_{yr}}{1000 \, {}^{kg}\!/\!_{1tonne} \times 1USD}$$

= RM 7,995,577 per year

Payback time (month) $= \dfrac{RM\,70300}{RM\,7,995,577 / yr - 982114 / yr} \times 12month$

= 1.2 ≈ 2 months