

# **WATER CONSERVATION THROUGH ENERGY CONSERVATION**

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## *Synopsis*

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South Africa is one of the driest countries in the world and rivers and dams are the main source of water. The continuous pollution of the rivers and streams as well as the growing demand for water has led to stringent environmental regulations to limit the consumption of water as well as to set the acceptable contamination levels of water before it is discharged to the main water cycle. Various techniques have been used to address the issue of the usage and contamination of water in industry.

In recent years, Pinch Analysis has been extended to cooling water systems design following its success in heat exchanger networks (HENs) and mass exchanger networks (MENs). The most significant work on cooling water network design was developed by Kim and Smith (2001) where a graphical methodology for designing cooling water systems was developed. Research on cooling water networks was necessitated by the need to optimize the amount of cooling water used in process industries. It is always important to conserve water as well as reduce the amount of contaminated water that is discharged to the main sources of water.

In this study, the consumption of water and effluent reduction opportunities in a nitric acid production plant at African Explosives Limited (AEL), Modderfontein, South Africa, was investigated. This investigation led to the development of a cooling water network design technique for systems with multiple cooling water sources. The results from this analysis have shown that there is potential to reduce the blowdown by 47%.

Moreover, the cooling water used in the cooling water network could be reduced by 23% and freshwater makeup by 10%.

## *Dedication*

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*To my mum, dad and hubby Addie with love*

## *Preface*

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I, Nongezile Sibhekile Nyathi, declare that unless indicated to the contrary in the text, this dissertation is my own work and that it has not been submitted, in whole or part, for a degree at another University or Institution.

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Nongezile Sibhekile Nyathi

May 2006

## *Acknowledgements*

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My husband, Addie for being my pillar of strength.

My mum and dad for believing in me and for their moral support.

## *Glossary*

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<b><u>Name</u></b>	<b><u>Definition</u></b>
<b>Approach</b>	A measure of how close the exit water temperature is to the entering wet bulb temperature in a cooling tower.
<b>Contaminant</b>	Undesirable chemicals present in the cooling water stream.
<b>Cooling tower</b>	A specialized heat exchanger in which two fluids (air and water) are brought into direct contact with each other to affect the transfer of heat and mass.
<b>Cooling water network</b>	A system consisting of cooling water using operations.
<b>Cooling water system</b>	A system which consists of four major components, namely, cooling water using operations, cooling towers, circulating pipes and pumps.
<b>Cycles of concentration</b>	The ratio of the concentration of a soluble component in the blowdown to that in the makeup stream.
<b>Effectiveness</b>	The ratio of actual heat removed to the theoretical amount of heat removed in a

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	cooling tower. It measures the thermal performance of a cooling tower.
<b>Heat capacity flowrate</b>	The product of mass flowrate and heat capacity.
<b>Heat exchanger network design</b>	This entails the placement of process streams from specified supply to specified target temperatures. The objective is to minimize total cost.
<b>Limiting composite curve</b>	A composite curve constructed by plotting the maximum acceptable inlet and outlet cooling water temperatures against the heat load. It sets the boundary between the feasible and infeasible region.
<b>Minimum temperature difference</b>	The minimum acceptable temperature approach between the cold and hot streams at each end of a heat exchanger.
<b>Pinch analysis</b>	It is a heat-flow-based technique that can be used to address a very diverse range of objectives e.g. capital costs and area targets for heat exchangers.
<b>Pinch point</b>	The point where two composite curves are closest to each other.

**Range**

The difference between the inlet water temperature and the exit temperature in a cooling tower.

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## *List of Abbreviations*

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<b><u>Abbreviation</u></b>	<b><u>Full Name</u></b>
CW	Cooling Water
GCC	Grand Composite Curve
HENs	Heat Exchanger Networks
HP	High Pressure
LP	Low Pressure
MENs	Mass Exchanger Networks
MP	Medium Pressure

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## *Nomenclature*

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<u>Symbol</u>	<u>Definition</u>
$CC$	cycles of concentration
$CP$	heat capacity flowrate
$Q$	heat duty
$T$	temperature
$T_1$	inlet water temperature for the cooling tower
$T_2$	outlet water temperature for the cooling tower
$\Delta T_{\min}$	minimum temperature difference
$W_b$	blowdown
$W_c$	circulating water flow at cooling tower inlet
$W_d$	drift loss
$W_e$	drift loss
$W_m$	makeup water
 <i>Greek letters</i>	
$\phi$	artificial performance factor
 <i>Subscripts</i>	
$CW$	cooling water
$in$	inlet conditions
$int$	intermediate

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max	maximum
min	minimum
<i>pinch</i>	pinch point
<i>return</i>	return temperature
<i>s</i>	source

**1.1 Background**

South Africa is one of the cheapest energy countries in the world and it is rich in mineral resources. The inefficient use of the resources in the process industry has led to South Africa being classified as environmentally dirty. Furthermore, South Africa has limited water resources and measures are being taken to conserve the little water that is available. Most of the water is used for agriculture and irrigation (59%), forestry (4%), rural (4%), urban (25%), power generation (2%) and mining and bulk industry (6%). (Mukheibir and Sparks, 2003)

The democratization of South Africa resulted in a new National Water Act being implemented in 1998 to redress the shortfalls of the previous Act of 1956. The White Paper on Water Supply and Sanitation published in 1994 by the Department of Water Affairs and Forestry states that water and related policies are important issues for all South Africans (DWAF) (DWAF, 1994 quoted by Mukheibir and Sparks, 2003). The principles of the policy include that access to clean water is a basic human right as well as an environmental integrity. According to the 2001 census, 84% of South Africans have access to piped water, 32% directly into their homes (SSA, 2003 quoted by Mukheibir and Sparks, 2003). A large percentage of those without access to clean water live in the historically disadvantaged rural areas, specifically in the previously demarcated homelands. These statistics indicate that there is a need to ensure that more people have access to clean water. Pollution of rivers, which are the main source of water in South Africa, should thus be minimized. Most of the pollution comes from industry.

In March 2003, the Department of Water Affairs and Forestry had a National Water Week which focused on protecting and respecting the country's water resources. As at March 2003, 6 million people living in South Africa still had no access to safe clean water. It was noted that the increasing demands, pollution, changing climatic patterns as well as the challenge of ensuring that everyone has access to clean water and sanitation services created a need for a concerted effort by all to maintain and improve the quality and quantity of water in South Africa.

Rivers are the main source of water in South Africa and they are continuously contaminated by effluent from industry. Most of the contaminants in the effluent are a result of water getting into direct contact with chemicals in process industries. The effluent is sometimes discharged into rivers thus contaminating the water in the water cycle making it unsuitable for human consumption. Furthermore, significant amount of water is also used in process industries to remove excess energy from the processes. Cooling towers are used to remove the excess energy from the cooling water. This is always accompanied by the evaporation of the water, which results in water loss from the cycle and concentration of salts contained in the cooling water. The concentrated cooling water leaves the cooling tower as cooling tower blowdown, thus contaminating the water system. Loss of water via evaporation and cooling tower blowdown has the effect of increasing the amount of water required as makeup, thus increasing the overall cooling water consumption. The industries that have a problem with high cooling water consumption and wastewater generation in South Africa include, the power generation

sector, the chemical and petrochemical sector, the metallurgical sector as well as the pulp and paper sector.

## 1.2 The AEL situation

African Explosives Limited (AEL) produces products mainly for use in the mining sector in Africa and beyond. It has facilities in East Africa, Central Africa, Zimbabwe and South Africa.

The AEL production site which was used for the investigation is in Modderfontein, South Africa. One of the intermediates that are produced at the facility is nitric acid ( $\text{HNO}_3$ ). The primary reactants used in the production of  $\text{HNO}_3$  are ammonia ( $\text{NH}_3$ ) and oxygen ( $\text{O}_2$ ).  $\text{NH}_3$  and  $\text{O}_2$  react to form nitric oxide ( $\text{NO}$ ) and water ( $\text{H}_2\text{O}$ ).  $\text{NO}$  further reacts with  $\text{H}_2\text{O}$  to produce  $\text{NO}_2$ . Then  $\text{NO}_2$  reacts with  $\text{H}_2\text{O}$  to form  $\text{HNO}_3$  through an absorptive reaction in an absorption tower. The  $\text{HNO}_3$  produced is used in the production of ammonium nitrates, explosives and fertilizers. Details of the process are given in Chapter 4. In the production of  $\text{HNO}_3$ , water is mainly used for cooling the process streams to the desired temperatures. At the production site investigated, cooling towers are used to remove excess heat from the cooling water before it is recycled to the cooling water network. Cooling water blowdown is removed from the cooling tower to reduce the concentration of salts that occur naturally in water. The main problem at the facility is that the amount of blowdown removed is high (23.5 ton/hr) at the current cycles of concentration, i.e. 6 cycles of concentration. The amount of cooling water lost via

evaporation is 60 ton/hr and another 6.5 ton/hr is lost via drift. The overall amount of cooling water required as makeup is 90 ton/hr which is significantly high.

In the light of these problems, AEL decided to conduct research to develop techniques to reduce the overall cooling water consumption as well as to reduce the amount of effluent produced in the form of blowdown. The cooling tower interacts with the cooling water network and thus initially, the cooling water network was assessed to investigate the possibility to reduce the cooling water required from that end of the cooling water system. Preliminary investigations of the cooling water system indicated that the cooling water network had two cooling water sources, namely, the cooling tower and the absorption tower. A review of the literature indicated that there was no existing technique for optimally designing a cooling water network consisting of multiple cooling water sources. Thus there was a need to develop a technique for designing a cooling water system consisting of multiple cooling water sources before investigating methods of reducing the amount of effluent produced in the cooling tower. Once the technique is developed, opportunities for reducing the cooling tower blowdown are investigated.

### **1.3 Objectives of the study**

The main aim of this study is to develop a methodology to target and design cooling water networks, using basic principles of Pinch Analysis, for a system with multiple cooling water sources.

This research was motivated by observation made in practical systems. In practice, one sometimes encounters multiple cooling towers supplying a given set of cooling water using operations. In most instances, each cooling tower is dedicated to a specific number of cooling water using operations within the given set. It is thus imperative to develop a specific technique for this scenario since the work published in literature assumes a single source of cooling water to a given set of cooling water using operations. In short, the problem addressed in this study can be stated as follows.

### **Problem Statement**

Given,

- (i) a set of cooling towers with different supply temperatures,
- (ii) maximum design capacity for each of the cooling towers,
- (iii) a set of cooling water using operations with limiting temperature requirements  
and
- (iv) the duty requirements for each of the cooling water using operations,

determine the minimum amount of cooling water required by the overall cooling water network as well as the optimal amount required from each of the cooling towers, without compromising the performance of each cooling tower.

### 1.4 Scope of thesis

The scope of the research study involved developing a methodology for the design of cooling water networks for systems with multiple cooling water sources. Furthermore, techniques for reducing the amount of effluent produced from the cooling tower were investigated.

### 1.5 Thesis Structure

*Chapter 1* introduces the nature and purpose of this thesis.

*Chapter 2* reviews the work which has been done in the field of cooling towers, heat exchanger networks, wastewater minimization as well as cooling water network design. This gives a background on the work that has been done over the past few decades in the abovementioned fields with particular focus on the application of Pinch Analysis.

*Chapter 3* focuses on the development of a graphical methodology for designing cooling water systems when there are multiple cooling water sources. The technique is further applied to an illustrative example.

*Chapter 4* discusses the application of the graphical technique to a case study which has two cooling water sources.

*Chapter 5* describes the application of a cooling tower model presented by Kim and Smith (2001) to the illustrative example as well as the case study.

*Chapter 6* presents the conclusions drawn from the research study conducted as well as the recommendations based on the research findings.

*Chapter 7* gives details of the references referred to in various sections of this thesis.

These chapters are followed by the Appendices.

**2.1 Introduction**

This chapter presents a detailed analysis of the work that has been done in the field of cooling water systems in the last few decades. The main components of the cooling water system are cooling towers, cooling water using operations, circulation piping and pumps. All these components interact with each other. The focus of this thesis is on developments in cooling towers, cooling water networks and overall cooling water systems. Most research has been dedicated to cooling tower design and the analysis of the characteristics of cooling towers. Also, there is extensive research which has been conducted on heat exchanger networks (HENs), primarily with the intention of overall energy reduction. Pinch Analysis still remains the single greatest contribution in this regard. Following the success of Pinch Analysis in HENs, it was later extended to mass exchanger networks (MENs). Drawing the analogy between HENs and MENs led to the development of wastewater minimization techniques. The stringent environmental regulations, which set the contamination levels that are acceptable for process industry aqueous discharge, necessitated the research on wastewater reduction. Recently, research has been conducted on systems characterized by both heat and mass transfer as encountered in cooling water systems. This has led to the development of techniques to assess the interactions between the cooling tower and the cooling water network.

This chapter presents a review of the work done on the abovementioned research areas.

The chapter is organized as follows.

- (i) Section 2.2 focuses on cooling towers addressed as a separate entity from the cooling water system.

- (ii) Section 2.3 analyses the work done on heat exchanger networks using pinch principles.
- (iii) Section 2.4 addresses wastewater minimization techniques which have been developed thus far.
- (iv) Section 2.5 presents methodologies which address cooling water system designs as a holistic unit.
- (v) Section 2.6 identifies the limitations of the research which has been done thus far.
- (vi) Section 2.7 presents the conclusions of the review.

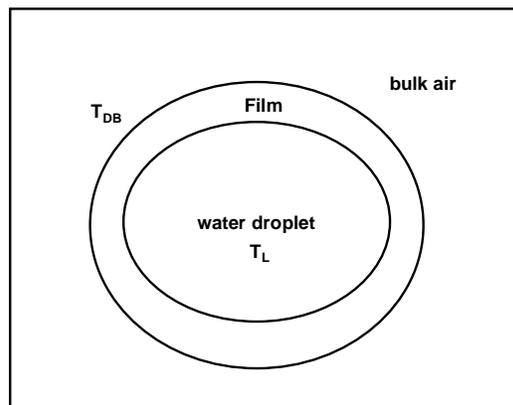
## 2.2 Cooling Towers

A cooling tower is a specialized heat exchanger in which two fluids (air and water) are brought into direct contact with each other to affect the transfer of heat and mass. A more technical description of a cooling tower is that it represents a heat rejection solution to the chemical process, or correction of the heat penalty generation of compression equipment (Burger quoted by Cheremisinoff, 1989). Work on cooling towers dates back to 1925 when Merkel developed a generally accepted concept for cooling tower performance. The main assumptions of the theory are as follows.

- (i) The resistance to mass transfer from bulk water to the interface can be ignored.
- (ii) The temperature differential between the bulk water and interface is negligible.

- (iii) The effect of evaporation is negligible.

Additionally, it assumes that each water droplet is surrounded by a film of air, and the enthalpy difference between the film and surrounding air provides the driving force for the cooling process. This is shown in Figure 2.1.



*Figure 2.1* Heat transfer process in cooling towers

Figure 2.1 shows a water droplet which is surrounded by a film of air. Heat is transferred from the water droplet to the film and then to the bulk air by a transfer of sensible heat and by the latent heat equivalent to the mass transfer resulting from the evaporation of a portion of the water droplet (Baker and Shryock, 1961). It is assumed the water droplet is spherical and its diameter is small enough so that the temperature of the water droplet can be assumed to be uniform.

Baker and Shryock (1961) used the Merkel theory to analyse the cooling tower performance. The basic equation derived for the performance characteristic is based on energy balance on the system as shown in Equation 2.1.

$$\frac{KaV}{L} = \int_{T_2}^{T_1} \frac{dT}{h' - h} \quad (2.1)$$

In Equation 2.1,  $\frac{KaV}{L}$  is the performance characteristic,  $K$  is the mass transfer coefficient,  $a$  is the contact area per tower volume,  $V$  is the active volume per plan area,  $L$  is the water flowrate,  $h'$  is the enthalpy of saturated air at the water temperature,  $h$  is the enthalpy of air stream,  $T_1$  and  $T_2$  are the inlet and outlet water temperatures, respectively.

The performance characteristic has been used extensively in the analysis of the performance of cooling towers. Baker and Shryock (1961) suggested that when air velocity variation is considered, the performance characteristic can be approximated as shown in Equation 2.2.

$$\frac{KaV}{L} \approx (L)^n (G)^m \quad (2.2)$$

In Equation 2.2, the exponent  $n$  varies from -0.35 to -1.1 and  $m$  falls within a range of 0.60 to 1.1 and is usually less than unity. In normal applications, the performance characteristic  $\frac{KaV}{L}$  varies between 0.5 and 2.5 (Coulson and Richardson, 1996).

Crozier (1980) suggested that increasing the temperature of the water to the cooling tower cuts down the quantity of water circulated through the tower, thus increasing the performance of the cooling tower. Additionally, he investigated the effects of cooling tower design on investment and operating costs. It was also suggested that cooling tower investment and operating cost are reduced by returning the water to the tower as hot as possible (increasing  $T_{in}$ ). This is due to the fact that the hotter the water, the larger the temperature difference between it and the ambient air, hence less heat-transfer area, i.e. tower packing, is required. Also, as the effluent air temperature is raised, so is the moisture content of the exiting air, hence less air flow is necessary.

Most cooling towers used in industry have a counterflow arrangement, where air flows parallel but in the opposite direction to water flow. This arrangement is more efficient because the coldest water contacts the coldest air, thus obtaining maximum enthalpy potential (Perry, 1997). The process of heat transfer in cooling towers involves latent heat transfer due to the evaporation of water as well as sensible heat due to the difference in temperature of water and air.

Only a small amount of water is lost by evaporation in a cooling tower. Since the latent heat of vaporization of water is about 2300 kJ/kg, a typical change of about 8°C in water temperature corresponds to an evaporation loss of about 1.5%. Hence the total flow of water is usually assumed to be constant in cooling tower calculations (Geankoplis, 1978). Coulson and Richardson (1996) and Perry (1997) suggested that approximately 80% of the heat transfer is due to latent heat and 20% due to sensible heat.

Figure 2.2 shows the water-air relationships and the driving potential which exist in a counterflow cooling tower.

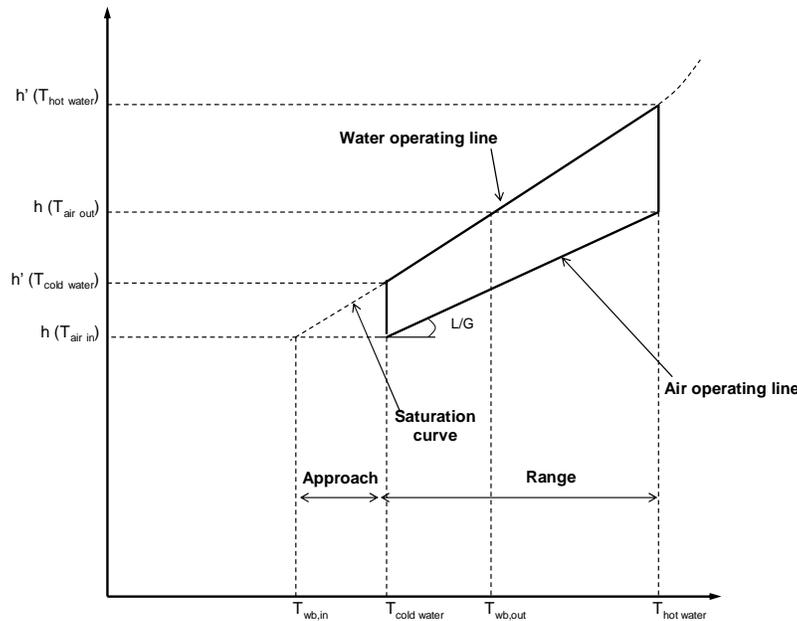


Figure 2.2 Cooling tower process heat balance

Figure 2.2 helps in understanding and visualizing the cooling tower process. The approach is the difference between the exit water temperature and the air wet bulb temperature. The range is the difference between the inlet and the exit temperatures of the water. Ideally, the approach should be small and the range significantly larger. Air and water conditions are constant across any horizontal section of the counterflow tower. Theoretically, the wet bulb temperature is the lowest temperature to which the water can be cooled. In practice, however, the cold water temperature approaches but does not equal the air wet bulb temperature because it is impossible to contact all the water with fresh air as the water drops through the wetted fill surface to the basin. In general, cooling towers are designed for approaches close to  $2.8^{\circ}\text{C}$  (Perry, 1997).

Experiments conducted by Bernier (1994), as well as results from the cooling tower model indicated that changing the dry bulb temperature,  $T_{DB}$ , at a constant wet bulb temperature,  $T_{WB}$ , has no significant impact on the temperature of the water droplet,  $T_L$ . While, increasing the wet bulb temperature has the effect of reducing the approach thus increasing the water cooling. Also, when the diameter of the water droplet is reduced, water cooling is increased because a smaller diameter implies a smaller ratio of water droplet volume to surface area and increases the value of the film heat transfer coefficient. It was also discovered that the thermal performance of a cooling tower is increased by reducing the cooling water flowrate, thus increasing the return temperature to the cooling tower. Since this work forms the basis of recent developments in cooling water system design, the results obtained by Bernier (1994) are reproduced in Table 2.1. The equation used to determine the performance characteristic is as follows.

$$\frac{KaV}{\dot{m}_w} = x \left( \frac{\dot{m}_w}{\dot{m}_a} \right)^y \quad (2.3)$$

In Eq. 2.3  $x$  and  $y$  are determined experimentally.

Table 2.1 Summary of experimental results on the determination of  $\frac{KaV}{\dot{m}_w}$  [adapted from Bernier, 1994]

Run	1	2	3	4	5
<b>Measurement</b>					
$\dot{m}_w$ (kg/s)	0.200	0.398	0.775	0.300	0.495
$\dot{m}_a$ (kg/s)	0.670	0.664	0.665	0.656	0.658
$T_{w,1}$ (°C)	36.7	29.3	25.9	32.0	27.9
$T_{w,N}$ (°C)	19.8	20.7	21.3	20.4	20.8
$WB_{a,N}$ (°C)	15.8	16.0	16.0	15.9	16.0
$\frac{KaV}{\dot{m}_w}$	2.337	1.771	1.288	2.030	1.686
$\frac{\dot{m}_w}{\dot{m}_a}$	0.298	0.599	1.166	0.457	0.752

It is clear from Table 2.1 that the reduction of water flowrate ( $\dot{m}_w$ ), is concomitant with relatively higher performance characteristic,  $\frac{KaV}{\dot{m}_w}$ .

The analysis of heat transfer in cooling towers using water droplets is informative but it does not give the overall representation of what happens practically. There are millions of droplets in a cooling tower with changing air and water conditions from top to bottom. Therefore, techniques which encompass most of the changes in a cooling tower have been developed.

Most publications in literature consider one-dimensional steady state models for the analysis of the working principles of countercurrent cooling towers. Various assumptions are made when deriving these cooling tower models in order to make the models simple

and easy to understand. Usually, a control volume as shown in Figure 2.3 is chosen for the derivation of the cooling tower model.

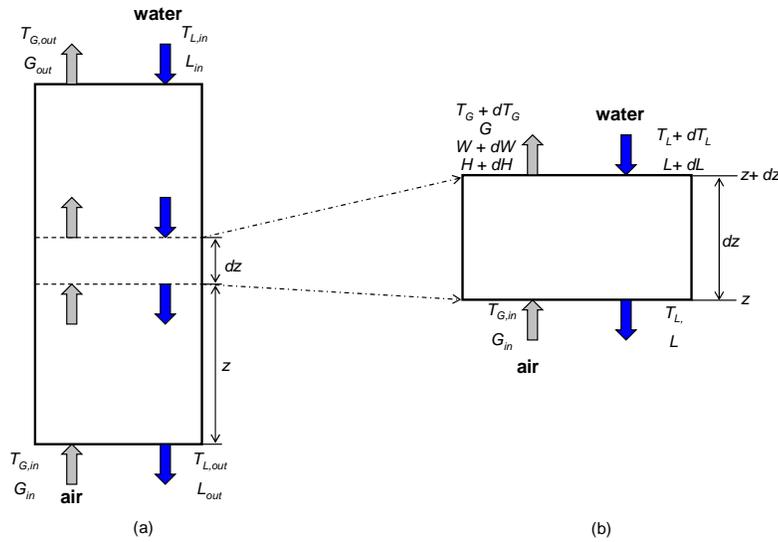


Figure 2.3 Schematic diagram of a cooling tower and control volume

The following assumptions in the derivation of most cooling tower models (Kim and Smith, 2001; Khan and Zubair, 2001; Khan et al., 2003; and Naphon, 2005) are common.

- (i) Thermodynamic properties are constant across the cross section of the tower.
- (ii) Adiabatic operation in the cooling tower.
- (iii) Temperature distribution at any cross section is uniform.
- (iv) Uniform cross sectional area of the tower.

Furthermore, Milosavljevic and Heikkilä (2001) assume the Lewis number ( $Le$ ), is unity while Khan and Zubair (2001), Khan et al. (2003) and Naphon (2005) assume that  $Le$  is constant, but not necessarily unity, along the column. The  $Le$  number is, in essence, a

dimensionless group which relates the heat transfer coefficient to the mass transfer coefficient.

The models developed by Bernier (1994) and Fisenko et al. (2004) are for spray type cooling towers, which assumes that water droplets fall freely at a constant velocity. This is not a true reflection of most cooling towers used in industry. In most cooling towers baffles or film-type packing are placed inside towers to increase retention time and to break up the water droplets so as to increase the air-water surface area. The main objectives of the models were to help readers understand the concept of cooling tower thermal performance (Bernier, 1994) and to assess the performance of a mechanical draft cooling tower (Fisenko et al., 2004). Water cooling in cooling towers is increased by increasing the air flowrate. However, there has to be a compromise between high air flowrates and fan energy consumption because high air mass flowrate leads to high fan energy consumption. These models show the basic operation of a cooling tower however, they neglect the presence of tower filling material.

Kim and Smith (2001) developed a cooling tower model using basic material and energy balances. The main objective of the model is to assess the thermal performance of the cooling tower. This model assumes that the cooling tower is in countercurrent contact with air drafted by a mechanical fan. Due to the level of difficulty in obtaining interfacial area between the air and water, a volumetric coefficient is used. Heat and mass transfer coefficients are based on the experimental measurements as cited in Coulson and Richardson (1996). The Runge-Kutta method is then used for solving the ordinary

differential equations that arise from the material and energy balances. Results from the model confirmed findings from Bernier (1994), i.e. the performance of a cooling tower is increased by decreasing the water flowrate thus increasing the inlet temperature to the cooling tower. To characterize and assess the performance of a cooling tower, Kim and Smith (2001) defined the cooling tower effectiveness, ( $e$ ), which is defined as the ratio of actual heat removed to the theoretical amount of heat removed. Thus, high effectiveness of the cooling tower represents better cooling performance and high heat removal. Ideally, for the best cooling tower performance, the effectiveness is unity. In practice the effectiveness can be close to but never reaches unity due to heat losses in the cooling tower.

The major assumption in this model is that the drift and evaporation losses are neglected, which implies that the water flowrate at the top and bottom of the cooling tower is considered to be the same. This assumption simplifies both the development of the equations and their application in the solution of cooling tower problems. Recently work has been done to incorporate evaporation losses, but this results in complex models (Milosavljevic and Heikkilä, 2001; Khan and Zubair, 2001).

The addition of the evaporative heat transfer gives the total heat transfer rate for the individual control volume and gives a better representation of what actually takes place in a cooling tower. Both models use computer programs to solve the nonlinear equations numerically. Milosavljevic and Heikkilä (2001) used their model to analyze the performance of different cooling tower filling materials, as well as the performance of

other cooling tower elements. On the other hand, Khan and Zubair (2001) used their model to investigate the effects of the  $Le$  number, the heat transfer resistance in the air-water interface and the effect of evaporation on the air process states, along the vertical length of the tower. Increasing the  $Le$  number increases the effectiveness, which can be used as a measure of the performance of the cooling tower. Recently, several improvements have been reported on this work as detailed below.

Khan et al. (2003) developed a model to investigate the heat and mass transfer mechanisms from a water droplet in a cooling tower as the air moves in the vertical direction as well as the thermal performance of the cooling tower. The air which enters from the bottom of the tower with initial dry bulb temperature, decreases in temperature and then increases before leaving from the top of the tower. This can be explained from the fact that the water, which enters from the top of the tower, when it reaches the lower part, is cooled because of predominantly evaporation mechanism. In this region, the water temperature is much lower than the entering air dry bulb temperature. This results in heat transfer from the air to the water, which implies that negative convection and the evaporation rate in this region is generally high.

Moreover, Khan et al. (2004) extended the work done by Khan and Zubair (2001) and Kuehn et al. (1998), on cooling tower thermal performance, by investigating the effects of fouling on thermal performance. Fouling, as defined for cooling towers, is the process of deposition of foreign matter, including bio-growth, on the water film flow area. It inhibits the cooling process and allows excessive weight to build up in the cooling tower.

Using the fouling model in conjunction with the cooling tower model, it was discovered that fouling reduces the performance of a cooling tower. This is reflected in the reduction of the tower effectiveness. In order to achieve a constant value of the cooling tower effectiveness under fouled conditions its volume has to be increased.

Naphon (2005) assessed the heat and mass transfer characteristics of the evaporative cooling tower. In order to maintain the heat transfer rate equal to the air side heat transfer rate, the outlet water temperature must be decreased as air mass flowrate increases. Also, pressure drop tends to increase as the air mass flowrate increases. At given inlet air and inlet water temperatures, and water mass flowrate, the temperature ratio increases with increasing air mass flowrate. This phenomenon can be explained by Equation 2.4 in which the outlet water temperature decreases as the air mass flowrate increases.

$$R = \frac{T_{w,in} - T_{w,out}}{T_{w,in} - T_{a,wb,in}} \quad (2.4)$$

In Equation 2.4,  $R$  is the temperature ratio,  $T_{w,in}$  is the inlet water temperature,  $T_{w,out}$  is the outlet water temperature and  $T_{a,wb,in}$  is the inlet wet bulb temperature of air.

For a given air mass flowrate, the inlet water temperature has no significant effect on the decrease of the temperature ratio.

The work presented above gives a comprehensive review of how cooling towers are designed and how different characteristics are assessed. However, the other major component of the cooling water system, which is the cooling water using operations, is

not considered. Cooling water using operations are part of a heat exchanger network (HEN). The single biggest contribution in HEN design still remains Pinch Analysis, which was popularized by Linnhoff and coworkers in the late 1970's and early 1980's. As can be inferred from the time of its development, Pinch Analysis was mainly intended for energy minimization in process industries. The following section gives a brief overview of developments in this area.

### 2.3 Heat Exchanger Networks and Pinch Analysis

As mentioned above, the need for reduced energy consumption in the process industries in the 1970's led to research on techniques for better process integration, with the view of saving energy. One of the earliest techniques to be developed was the temperature interval method or TI method (Linnhoff and Flower, 1978). Further analysis of the technique resulted in an improved method, called Pinch Analysis (Linnhoff and Hindmarsh, 1983). Pinch Analysis is essentially a heat-flow-based technique that can be used to address a very diverse range of objectives, for example, capital costs and area targets for heat exchangers (Linnhoff et al., 1988). This method has been extensively used in the heat exchanger network synthesis and has also been applied to mass exchanger network targeting and design. This section of the chapter will focus on the application of Pinch Analysis to heat exchanger networks (HENs).

The initial step in Pinch Analysis is performing heat and material balances of the process. This is followed by setting energy targets for saving energy prior to the design of the heat exchanger network.

*Targeting for energy savings*

The energy target set using Pinch Analysis is for minimum energy consumption. To set the energy target, process stream data is required. This should include hot streams that require cooling and cold streams which have to be heated. Essentially, the information needed includes the supply temperature ( $T_{supply}$ ), target temperature ( $T_{target}$ ) and the heat duty ( $Q$ ) of the individual streams. The heat capacity flowrate ( $CP$ ) of the streams, which is the product of mass flowrate and the heat capacity ( $c_p$ ), is calculated using Equation 2.5.

$$CP = \frac{Q}{|T_{supply} - T_{target}|} \quad (2.5)$$

Prior to setting energy targets, the minimum temperature difference,  $\Delta T_{min}$ , is specified.  $\Delta T_{min}$  is the minimum acceptable temperature approach between the cold and hot stream at each end of the heat exchanger.

There are two methods which can be used to set the targets, i.e. Problem Table Algorithm and Composite Curve approach. The Problem Table Algorithm was first introduced by Linnhoff and Flower (1982). When using this approach, the energy targets are set algebraically. In this thesis, the focus is on the second method, i.e. Composite Curves approach, (Linnhoff et al., 1982 and Linnhoff et al., 1988) which is discussed in detail below.

Construction of the composite curves involves the addition of enthalpy changes of the streams in the respective temperature intervals. Figure 2.4 shows a typical composite curve representation.

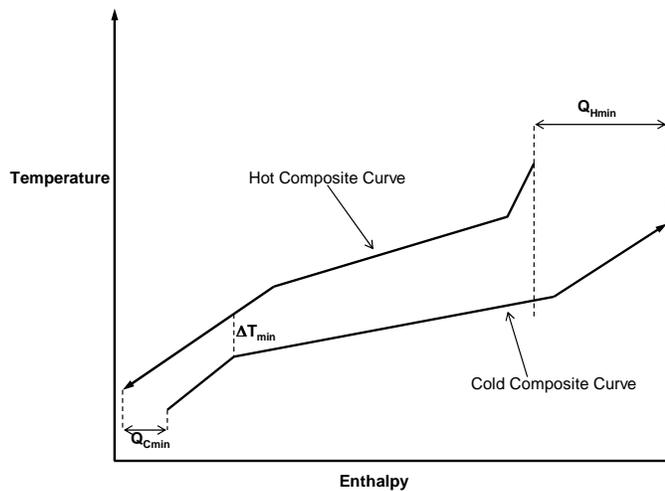


Figure 2.4 Prediction of energy targets using hot and cold composite curves

In Figure 2.4, the “overshoot” of the hot composite curve represents the minimum amount of external cooling required ( $Q_{Cmin}$ ) and the “overshoot” of the cold composite curve represents the minimum amount of external heating required ( $Q_{Hmin}$ ), (Linnhoff et al., 1982). The point where the two composite curves are closest is called the “pinch point” (Linnhoff et al., 1979). The temperature difference between the hot and cold composite curves, at this point, is equal to  $\Delta T_{min}$ . Realising the implications of the pinch allows energy targets to be realized in practice. The pinch point divides the problem into two sections, i.e. above and below the pinch. In the section above the pinch, the hot composite gives all its heat to the cold composite with only residual heating required.

This region is therefore a heat sink. Heat goes in from hot utility, but no heat goes out. In contrast, the region below the pinch is a heat source. Heat goes out to cold utility but no heat goes in. Hence in a design which achieves utility targets the heat flow across the pinch is zero (Linnhoff et al., 1982). A process where there is no “overshoot of either the hot composite or the cold composite is called a threshold problem. This means either the cold or the hot utility is not required, respectively. The understanding of the pinch gives three rules that must be obeyed in order to achieve the minimum energy targets for a process.

- (i) Heat must not be transferred across the pinch.
- (ii) There must be no external heating below the pinch.
- (iii) There must be no external cooling above the pinch.

Violating any of these rules will lead to cross-pinch heat transfer resulting in the increase in the energy requirement beyond the target (Linnhoff, 1998). It is worth mentioning however, that heat can be transferred across the pinch when a heat pump is integrated into the system. A heat pump accepts heat at a lower temperature and, by using mechanical power, rejects the heat at a higher temperature (Linnhoff et al., 1982 and Linnhoff, 1998).

The target set is the same regardless of the method (Problem Table or Composite Curves) adopted to obtain it. However, the Problem Table approach has an advantage over the Composite Curve approach because the energy targets are obtained algebraically, while the Composite Curves approach is more involving as it requires a “graph paper and



cheaper utility level to a more expensive utility level (Linnhoff, 1998). Once the utility targets have been set, the heat exchanger network that meets the target is designed as outlined in the following section.

*Design for energy savings*

As mentioned above, when the utility targets have been set, the heat exchanger network is designed using the grid diagram which was first introduced by Linnhoff and Flower (1982). The process streams are placed on the grid diagram with the hot stream running from left to right, on top and the cold streams running from right to left, at the bottom of the grid diagram. Figure 2.6 shows a typical grid diagram representation used for designing the heat exchanger network.

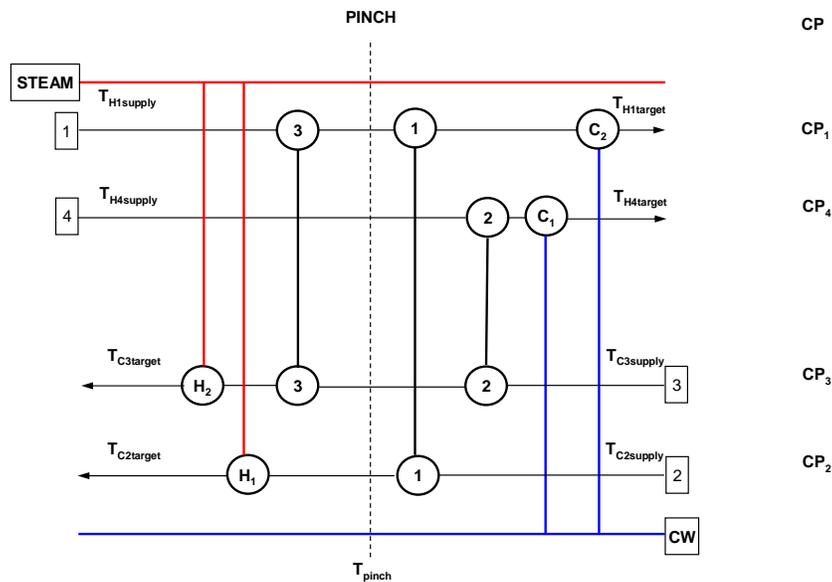


Figure 2.6 Heat exchanger network representation

In Figure 2.6, the heat exchangers labeled **1**, **2**, and **3** are process-process heat exchangers while **H<sub>1</sub>** and **H<sub>2</sub>** are heaters and **C<sub>1</sub>** and **C<sub>2</sub>** are coolers, which use external utilities. For a design that meets the target, the sum of **H<sub>1</sub>** and **H<sub>2</sub>** is equal to  $Q_{Hmin}$  and the sum of **C<sub>1</sub>** and **C<sub>2</sub>** is equal to  $Q_{Cmin}$ . To achieve a design that meets the energy targets, Linnhoff and Hindmarsh (1982) proposed the Pinch Design philosophy. The Pinch Design philosophy exploits the constraints inherent at the pinch and uses the grid diagram shown in Figure 2.6. The main advantages of the grid representation (Linnhoff et al., 1982) are as follows.

- (i) The heat exchange matches can be placed in any order without redrawing the streams.
- (ii) The grid represents the countercurrent nature of the heat exchange, making it easier to check exchanger temperature feasibility.
- (iii) The pinch is easily represented in the grid.

When the design steps are followed in accordance with the Pinch Design philosophy, the designer can come up with different designs which meet the target. The designer may select a design based on capital cost, controllability, layout, safety or any other reason, and still be sure that an energy efficient design will result.

The Pinch Design technique presented above has been applied directly to different problems in process industries (Tjoe and Linnhoff, 1986; Linnhoff et al., 1988; Ciric and Floudas, 1988; Kemp and Macdonald, 1988; and Matijašević and Otmaèiæ, 2002). Furthermore, research has been done to extend Pinch principles beyond simple heat

exchanger networks and energy targets, but also to cost target and optimization of heat exchanger networks (Gundersen and Neass, 1988; Linnhoff et al., 1988; Hall et al., 1990; Jegede and Polley, 1992); mass exchanger networks (El-Halwagi and Manousiouthakis, 1989; Hallale and Fraser, 2000).

Tjoe and Linnhoff (1986) introduced the design methodology for retrofit founded on the same thermodynamic principles that underlie the established Pinch Analysis. In the context of retrofitting, the philosophy of targeting implies setting targets for energy savings, capital cost and payback. The targets recognize the specifics of the existing design and the procedure is simple, practical and quick to apply. In addition, it often leads to retrofit projects of significantly shorter payback periods than those obtained by conventional inspection methods. Moreover, the retrofit design procedure emphasizes the importance of reusing existing exchangers as much as possible. The retrofit methodology relies on a mixture of past experience with the process, a few technical developments and some inspired guesses. The results are retrofit projects that range from those that pay for themselves within a few weeks, to others that are recognized, soon after installation, to be a hindrance to further improvement.

Linnhoff et al. (1988) used Pinch Analysis to make savings in effluent treatment, yield improvement and process debottlenecking. The effluent treatment problem was solved by removing cross-pinch heat transfer and reducing the cooling water demand. These improvements saved the energy.

The work by Castillo et al. (1998) showed that the application of Pinch Analysis to processes makes it possible to reduce the demand for cooling water and steam of a nitric acid plant by more than 40% and also reduce the overall environmental impact. The application of Pinch Analysis to the process shows how cleaner production can be obtained without substantial capital investments. Moreover, the retrofitting of old chemical plants to new environmental requirements generally implies a considerable amount of capital but not in this particular case. Furthermore, Pinch Analysis was applied to another nitric acid plant (Matijašević and Otmačević, 2002) and similar results were obtained. In both applications, the nitric acid process is a threshold case where only cold utility is needed. The results discussed above, further prove the reliability of Pinch Analysis when it is used for retrofitting processes.

Furthermore, there are mathematical programming models which have been developed using Pinch Analysis (Reimann and Steiner, 1988; and Smith and Parker, 1988 and Ciric and Floudas, 1988). These have also been applied to process industries. However, the mathematical methods of Pinch Analysis will not be discussed in detail in this thesis as mathematical modeling is beyond the scope of this thesis.

Implicit in the Pinch Design technique is the assumption that heat exchangers using external utilities exhibit a parallel configuration. A Pinch design grid diagram is shown in Figure 2.7.

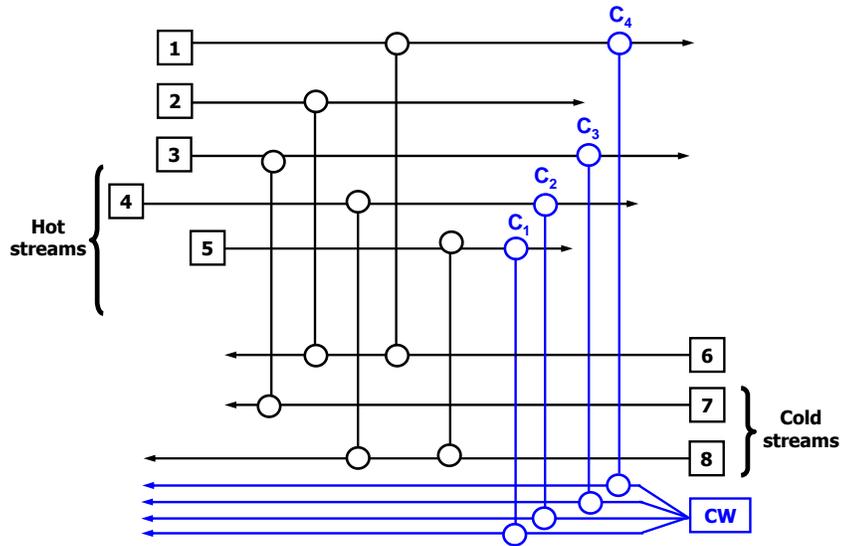


Figure 2.7 Heat exchanger network design

In Figure 2.7, coolers  $C_1$  to  $C_4$  use external cooling water. Figure 2.8 below shows how the coolers are connected to the cooling tower.

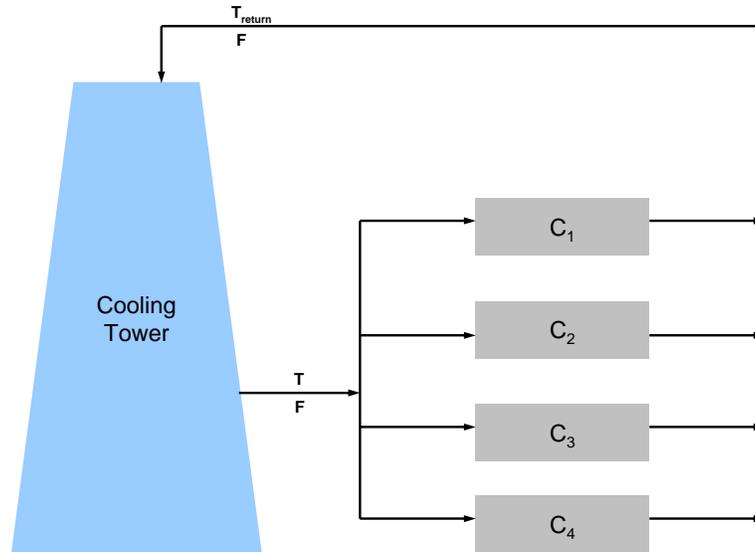


Figure 2.8 Cooling water network configuration

In Figure 2.8, all the coolers are directly supplied with cooling water by the cooling tower and the cooling water is returned to the cooling tower without any reuse or recycle. This results in high cooling water flowrate ( $F$ ) and low return temperature ( $T_{return}$ ) to the cooling tower. As mentioned early on in this chapter (section 2.2), this leads to low performance of the cooling tower. In general, not all heat exchangers in a cooling water network require cooling water at low temperatures. Reuse of cooling water between heat exchangers could thus be exploited in order to reduce the overall cooling water requirement.

Successful application of Pinch Analysis to heat exchanger networks led to its extension to mass exchanger networks (MENs) in the last 15 years. This was achieved by exploiting the analogies between heat and mass exchange. One of the major issues addressed in MENs is wastewater minimization. Wastewater is produced in process industries when water gets into direct contact with the process streams, thus picking up some chemicals. Stringent environmental regulations have led to the need for rigorous and robust techniques for wastewater minimization in chemical processes. Section 2.4 below discusses the developments in the field of wastewater minimization in the past few decades.

## 2.4 Wastewater Minimization

Significant amount of water is used in process industries for various reasons, which ultimately result in contamination. Paramount among these, is the use of water as a selective solvent in liquid-liquid extraction for product purification. Water is also used

extensively in operations that do not necessarily involve traditional mass transfer, like simple washing operations. In traditional mass transfer, three phases are always encountered, i.e. a phase with high concentration of the diffusing species, a phase with low concentration of the diffusing species as well as the diffusing species. When the contamination levels are very high water cannot be reused in the process and is discharged to the water system. Environmental stipulations have been set to limit the amount of pollutants in the water discharged into the water system. Consequently great deal of research has been conducted to develop techniques that can help combat the problem of wastewater production and reduce the overall water consumption. In solving wastewater minimization problems there are two well known schools of thought, i.e. the conceptual approach, which is predominantly based on graphical analysis (El-Halwagi and Manousiouthakis, 1989; Wang and Smith, 1994; Wang and Smith, 1995; Kuo and Smith, 1998; Kim et al., 2001; Hallale, 2002 and Majozi et al., 2006) and the mathematical programming, which is based on mixed integer (non)linear programming (Alva-Argáez et al., 1998; Doyle and Smith, 1997 and Majozi, 2005). The focus of this section of the thesis is on the conceptual approach.

El-Halwagi and Manousiouthakis (1989) adapted the method developed for heat exchanger network by Linnhoff and Hindmarsh (1983), to a general problem of mass exchange between a set of rich process streams and a set of lean process streams. A minimum acceptable concentration difference is defined, which is analogous to the minimum temperature difference in heat exchanger networks. The main drawback with this method is that it only applies to processes characterized by mass transfer. Wang and

Smith (1994) developed a graphical technique for wastewater minimization that is applicable to both processes characterized by mass transfer and processes not involving traditional mass transfer. Wang and Smith (1994) suggested that the first step in wastewater treatment is to ensure that wastewater generated is minimized. There are three techniques which can be used before making fundamental changes to the processes to reduce their inherent demand for water, i.e. reuse, regeneration reuse and regeneration recycle.

Reuse involves using water, which has been used in some operations, directly in other operations provided the contamination level does not exceed the maximum permissible inlet concentration for the particular operations. Reuse means it is used in other processes other than the one where it was used initially. Regeneration reuse involves treating the wastewater partially to remove the contaminants, which would otherwise prevent its reuse, before it is reused in other operations. Regeneration has the advantage of reducing the contamination level of the wastewater before it is reused. On the other hand, regeneration recycle ensures that the wastewater which has been regenerated is used in the same processes where it was used before.

Wang and Smith (1994) developed an entirely conceptually based graphical methodology to target the minimum water and wastewater for the above three cases. The method is for single and two components and it has some similarities and dissimilarities to the heat exchanger network design presented above. It is similar in that, it is divided into two sections, targeting and design and this allows the minimum water requirement to be set

before commitment to actual design. On the other hand, it is dissimilar in that, only the water stream data is directly considered whilst the process stream is indirectly considered. In heat exchanger networks both streams are considered in the design. The “limiting water profile” approach is introduced where the maximum permissible inlet and outlet concentrations are used to construct the composite curve. Any water supply line below the limiting water profile meets the requirements of the process. Figure 2.9 is used to illustrate this point. In Figure 2.9, concentration is plotted against the mass load of the contaminant, which implies that the flowrate of water required can be obtained from the gradient of the water supply line. The amount of water required is the inverse of the gradient of the water supply line in accordance with Equation 2.6 below.

$$F = \frac{\Delta M}{C_{out} - C_{in}} \quad (2.6)$$

In Equation 2.6,  $F$  is the flowrate,  $\Delta m$  is the mass load of contaminant removed from the process and  $C_{in}$  and  $C_{out}$  are the inlet and outlet concentration, respectively.

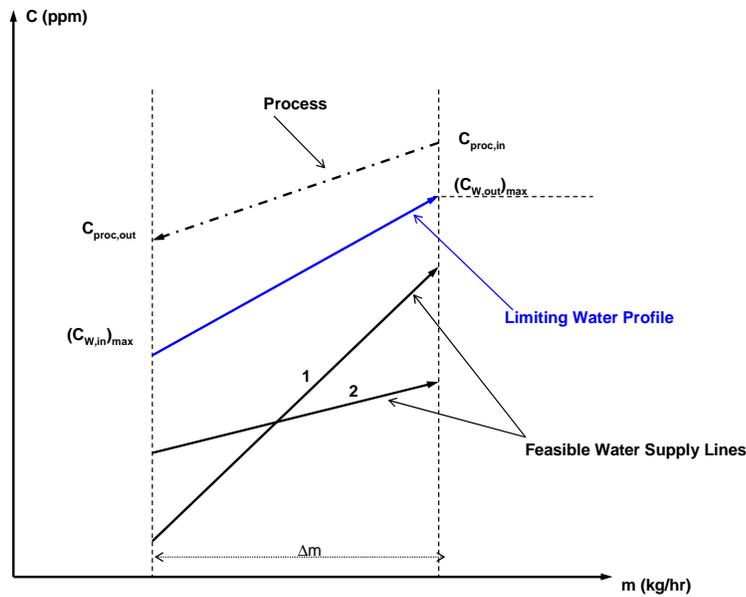


Figure 2.9 Representation of water using process and the limiting water profile

The water supply lines labeled **1** and **2** meet the requirement of the process although their gradients are not the same as that of the limiting water profile. The limiting water profile is set by the maximum inlet and outlet concentrations. These may be fixed by among other considerations, minimum mass transfer driving force, corrosion limitations, fouling of equipment, maximum solubility, the need to avoid precipitation of material from solution and minimum flowrate requirements to avoid settling of solid material. Since any water supply line below the limiting water profile meets the cooling water requirement and can be used in the design step, it sets the boundary between the feasible and infeasible regions. When given the limiting water data, the limiting composite curve can be constructed. The water data required is the maximum inlet and outlet concentrations and the mass loads of each of the processes. To obtain the minimum water

required, a water supply line is matched against the limiting composite curve as shown in Figure 2.10.

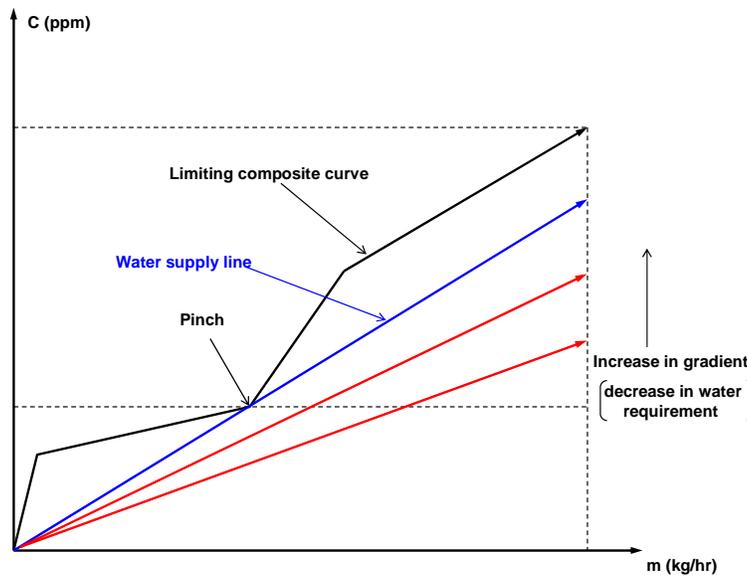


Figure 2.10 Limiting water composite curve and the water supply line

The fact that the water supply line touches the limiting water line at the pinch does not mean that there is a zero mass transfer driving force at that point since the mass transfer driving forces have been built into the data. Rather, it means that at the pinch there is minimum mass transfer driving force between the process streams and the water supply line. The pinch also highlights the most constrained region in terms of mass transfer in the overall process. Once the target for water requirement has been set, the network is designed using the method developed by Kuo and Smith (1998). This design method is discussed in detail later in this chapter.

The major advantages of the graphical presentation discussed above, are that it provides insights into which parts of the problem require more accurate data than others, which operations are candidates for basic changes to allow the targets to be improved and where regeneration is likely to be beneficial. This has been a major step in understanding water system design and more work has been done to improve this technique.

Wang and Smith (1995) further improved on their work by looking at systems with flowrates constraints. Local recycling and splitting of water using operations were used as alternative ways to meet flowrate constraints. Furthermore, Wang and Smith (1995) investigated targeting for systems with multiple sources of freshwater. It was suggested that the amount of the highest quality water should be minimized and that of the lowest quality should be maximized. This is because the higher the quality, the more expensive the water is. The methods presented thus far can be extended to problems involving a maximum of two contaminants and cannot address larger problems as a result of complex interactions that can occur in multiple contaminant media.

Doyle and Smith (1997) used mathematical programming to address multiple dimensions encountered when water has multiple contaminants. The problem representation was such that it incorporated not only concentration, flowrates constraints and multiple sources of water, but it also included forbidden matches due to large geographical distances or safety reasons. Since this method is based on mathematical programming, it will not be discussed further as it is beyond the scope of this thesis. The aforementioned methods do not consider the interactions between water use and effluent treatment.

Kuo and Smith (1998) addressed the interactions between the design of water using operations and effluent treatment in process industries. The technique enables a water network to be designed which meets the freshwater target and creates the most favourable wastewater streams for treatment. It is also divided into two steps, targeting and design as detailed below.

#### *Targeting for wastewater minimization*

The information that is required to target for wastewater minimization is given below.

- (i) The environmental limit.
- (ii) The regeneration removal ratio of the treatment units.
- (iii) The process water stream data, i.e. the maximum inlet and outlet concentrations as well as the mass load of contaminants or flowrates

This information is used to set the target by matching a water supply line against the limiting composite curve as suggested by Wang and Smith (1994). The lowest flowrate composite effluent curve is obtained by simply constructing a curve around the limiting composite curve which cuts out the local concave regions (or pockets). This technique provides an opportunity to consider the water minimization and effluent treatment problems simultaneously. The procedure is illustrated using an example given in Kuo and Smith (1998). The limiting process water data is shown in Table 2.2.

Table 2.2 Limiting process water data

Process Number	Mass Load of Contaminant	$C_{in}$ (ppm)	$C_{out}$ (ppm)	Water Flowrate (ton/hr)
1	10	0	200	50
2	10	100	300	50
3	12	100	500	30
4	12	300	500	60

Using the data given in Table 2.2, the water and effluent targets are shown in Figure 2.11.

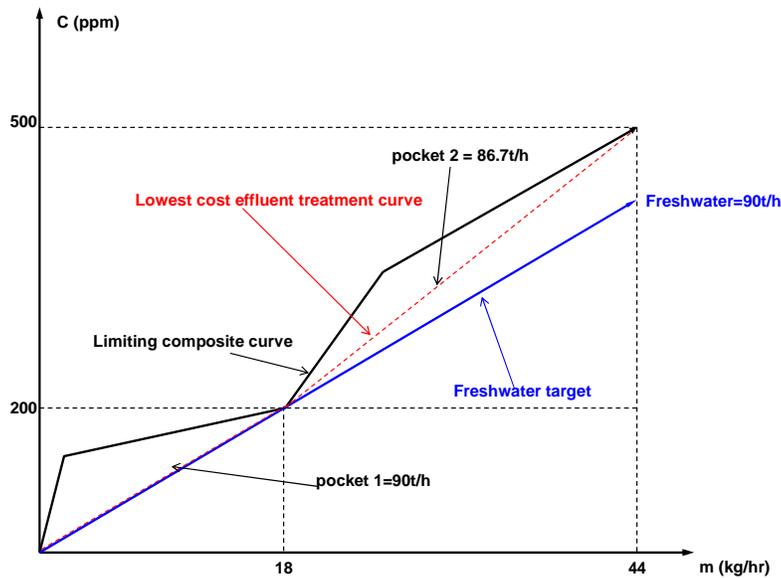


Figure 2.11 Freshwater and effluent targets

In Figure 2.11, by cutting off the local concave regions (or pockets) of the limiting composite curve, the lowest flowrate effluent curve is obtained. The effluent treatment curves provide a basis for a water network design methodology. It is assumed that there are hypothetical water mains at the beginning and end of each pocket and thus the flowrates at each end and beginning of the pockets can be calculated. Pocket one supplies pocket two with water (86.7 ton/hr) at 200 ppm level of contamination. The excess water

from pocket one (3.3 ton/hr) is discharged from the system at a concentration of 200 ppm. The water used in pocket two is discharged from the system at a higher concentration of 500 ppm. Once the water and the effluent treatment targets have been set the water network is then designed. The design method is divided into the following four steps.

- (i) Set up the design grid.
- (ii) Connect operations with water mains.
- (iii) Merge operations that cross the mains.
- (iv) Remove intermediate mains.

These four steps are discussed in detail below.

#### *Design for wastewater minimization*

The water mains method is adopted to provide the design strategy.

##### *Step 1 Set up the design grid*

The three water mains identified in the targeting stage are represented on a grid diagram, with the flowrate required for each pocket shown at the top of each water main, and the wastewater discharged from the mains shown at the bottom. The limiting flowrates, inlet and outlet concentrations of water using processes/operations are shown as indicated in Figure 2.12.

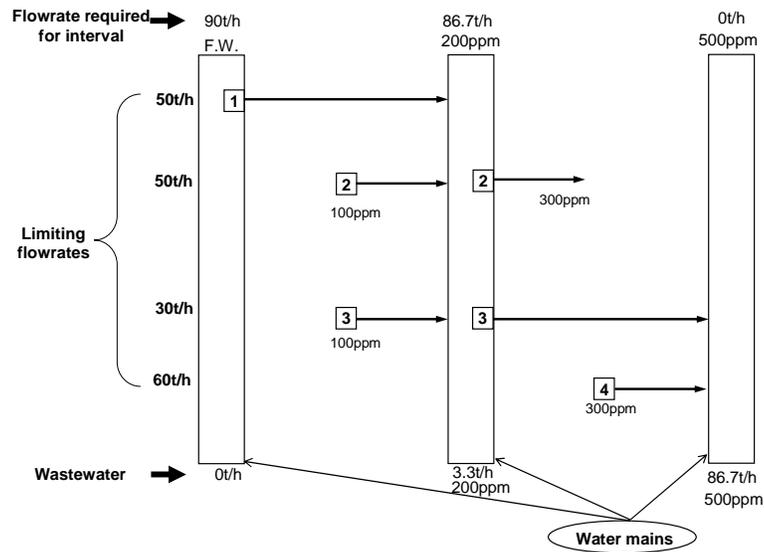


Figure 2.12 Design step 1

Step 2 Connect operations with water mains

Water using operations are connected to the water mains in order to satisfy the requirements of each operation. This is done for the interval between the first two water mains as shown in Figure 2.13.

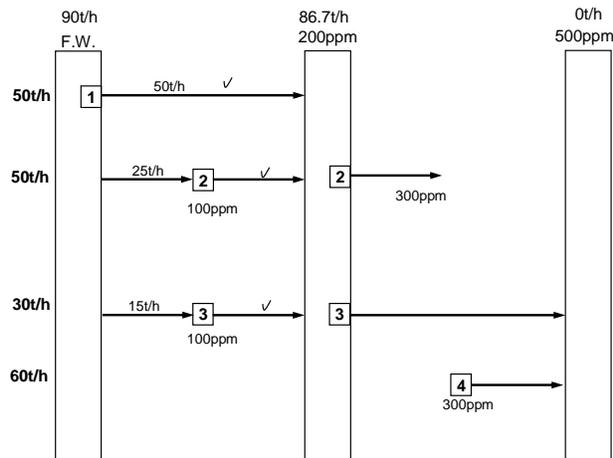


Figure 2.13 Design step 2

The ticks in Figure 2.13 show that the water requirement has been satisfied without violating any of the process constraints.

*Step 3 Merge operations crossing boundaries*

This step is for operations that cross the intermediate water mains. Merging operations this way is difficult to implement in practice or more often completely impractical because for some operations require different flowrates below and above the intermediate mains, e.g. operation 3 requires 15 ton/hr below the intermediate water mains and 30 ton/hr above the mains. However, there are ways of overcoming these problems. This design step is shown in Figure 2.14.

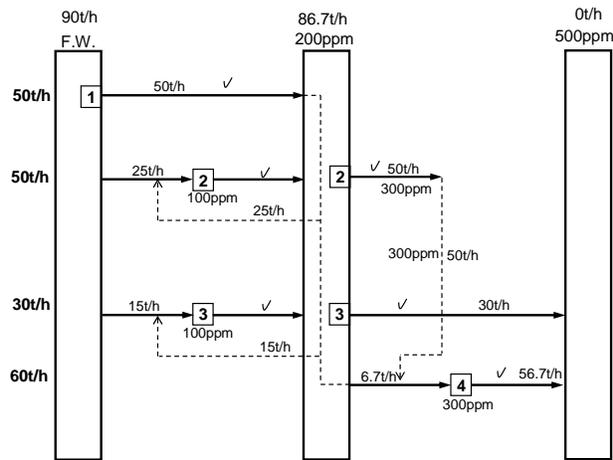


Figure 2.14 Design step 3

*Step 4 Remove intermediate mains*

The intermediate water mains acts as a source and a sink. Water is discharged to the intermediate mains from operation 1 and then it is drawn from this mains to satisfy operations 2, 3 and 4. The sources can connect with the sinks directly as long as the supplying and required flowrates are matched and process constraints, e.g. piping layout are considered. This step is shown in Figure 2.15.

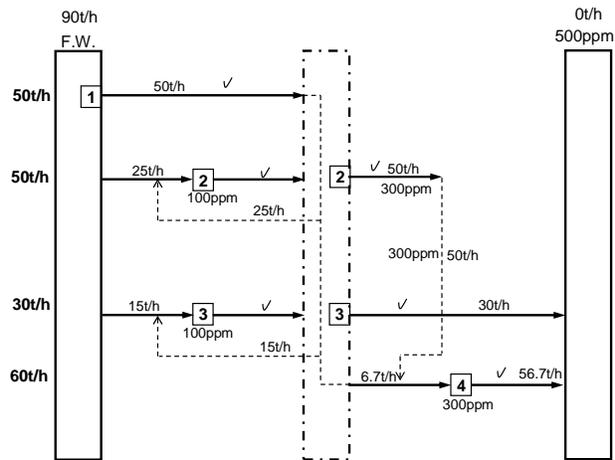


Figure 2.15 Design step 4

Once the intermediate mains have been removed, the resulting design grid (Figure 2.16(a)) can be evolved to yield the final design as shown in Figure 2.16(b).

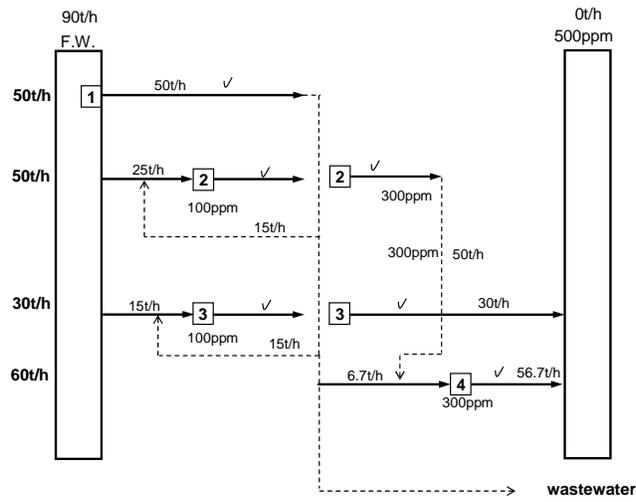


Figure 2.16(a) Final design grid

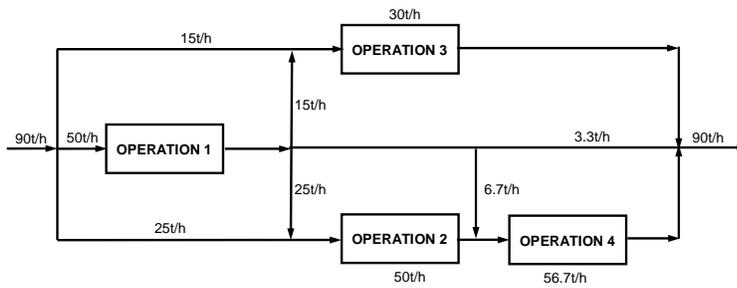


Figure 2. 16(b) Final design

This design method is much simpler than previous methods (Wang and Smith, 1994; 1995) and provides designs for water using network which favour the effluent treatment to follow. Furthermore, Kuo and Smith (1998) investigated the interactions between water minimization and regeneration systems and interactions between regeneration systems and effluent treatment systems. However, this is beyond the scope of this thesis and thus the reader is referred to Kuo and Smith (1998) for a detailed discussion.

Hallale (2002) also developed a graphical method for targeting freshwater and wastewater minimization. The technique differs from that presented by Kuo and Smith (1998) in that it is based on a representation of water composite curves and the water surplus. The construction of the water surplus is similar to that of the grand composite curve in heat Pinch Analysis. The water demand and the water sources data is required to construct the composite curves. The main advantage of this technique is that it is able to deal with a wider range of water using operations as well as having more convenient and familiar representations. Also, the approach gives a target prior to design rather than merely giving a representation of a particular design. This is achieved by automatically building in all mixing possibilities to determine the true pinch point and reuse targets. Moreover, it has the ability to handle operations that cannot be modeled as mass transfer. The network is designed either manually or using mathematical programming.

The methods presented thus far focus on the contamination level of the wastewater stream. In contrast, Kim et al. (2001) introduced a method for the design of effluent cooling water systems, focusing on reducing the temperature of the effluent stream, rather

than the contamination level. Environmental regulations restrict the temperature levels of aqueous effluent which is discharged. Thus effluent with high temperatures has to go through the cooling systems to reduce the temperature before it is discharged. The method presented looks at treatment of wastewater from the thermal perspective rather than the contaminant level.

The focus of this section of the chapter is the minimization of wastewater, particularly, chemical contaminated water. By understanding the impacts of chemical contamination, wastewater can be minimized. It is important to minimize wastewater in order to reduce overall water requirement and also to comply with environmental regulations. As mentioned above, chemically contaminated water can be regenerated in a regeneration system to reduce the contamination level before it is recycled to the chemical process or discharged to the water system. In contrast, thermally contaminated water, i.e. water leaving the system at a higher temperature, is regenerated to reduce the temperature before it is recycled to the cooling water network. Cooling towers, discussed in Section 2.2 are used to regenerate the thermally contaminated water before it is recycled back to the cooling water network. Techniques have been developed to analyse the regeneration of thermally contaminated water (Kim and Smith, 2001). They assess the cooling water system as a holistic entity. That is, the design and analysis of the cooling towers is done with consideration of the cooling water network. Section 2.5 below reviews the work that has been done on cooling water systems design.

## 2.5 Cooling water systems design

A cooling water system consists of four major components, i.e. cooling water using operations, cooling towers, circulating pipes and pumps. To optimize such a system, the system interactions must be defined and the relationships between them applied to the simultaneous design of each component. As mentioned above, recently research has been conducted to assess cooling water networks as a holistic system. Figure 2.17 shows a typical cooling water system, comprising of the two major components, i.e. the cooling tower and the cooling water network.

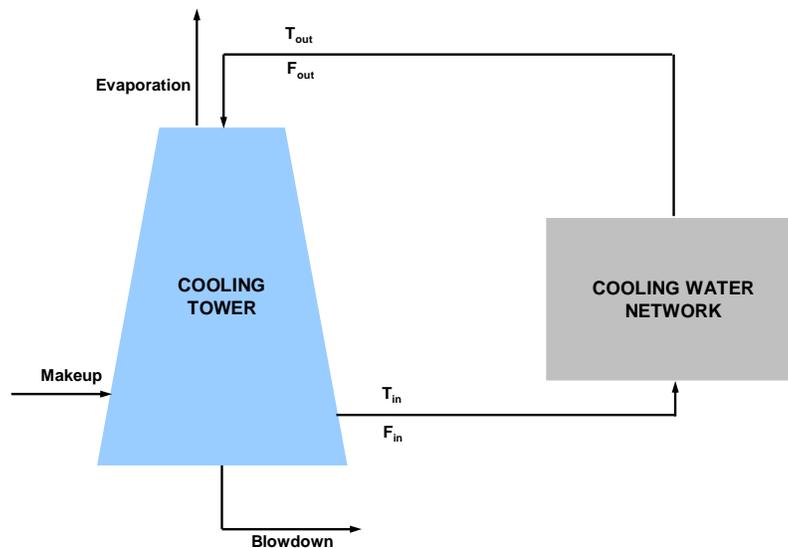


Figure 2.17 Typical system with two interactions

Figure 2.17 shows a cooling tower which supplies cooling water to a cooling water network. The cooling water network may consist of coolers and other process units that

require cooling water, e.g. absorption towers, reactors etc. One of the interactions which were identified by Crozier (1980) is between the outlet temperature of the cooling tower and the inlet temperature of the cooling water network. The tower outlet temperature is the variable with which the cooling tower designer has the least latitude, yet it is the most significant determinant of cooling tower investment and operating costs. Specifying the cooling tower outlet temperature is difficult because it is bound on the lower side by the wet bulb temperature in the cooling tower and on the upper bound by the return temperature from the cooling water network. Thus, it is important to design the cooling water system as a whole, i.e. considering the impacts of the design on both the cooling tower and the cooling water network.

In view of the drawback caused by designing cooling water system components separately, Kim and Smith (2001) suggested that a combined water and energy analysis should be used to investigate the interaction for the overall system. A cooling tower model was developed as well as a method for the design of cooling water systems that accounts for the interactions and process constraints. This cooling tower model as well as those developed by several other authors was discussed in section 2.2 above. The method for the design of cooling water systems is an adaptation of the two-part design methodology by Kuo and Smith (1998) for water and wastewater minimization which took into account the interactions between water minimization, regeneration systems and effluent treatment systems. The limiting concentration is replaced by the limiting temperature, mass load by the heat duty and water flowrate is replaced by the heat capacity flowrate. A graph of temperature against heat duty is drawn using the limiting

data. Then a cooling water supply line is matched against the limiting cooling water composite curve as explained before. The gradient of this supply line represents the inverse of the heat capacity flowrate.

This methodology assumes fixed inlet and outlet water conditions for the cooling water and that the heat capacity of cooling water is constant throughout the temperature range. To develop the systematic method, the concept of the limiting water profile (Wang and Smith, 1994) is taken from water pinch and shown as "limiting cooling water profile". This is constructed using the maximum inlet and outlet temperatures for the cooling water streams. The allowable temperatures are set by the minimum temperature difference ( $\Delta T_{min}$ ) between the process stream temperature and the cooling water temperature. Given the process stream data, the limiting cooling water data is obtained by subtracting  $\Delta T_{min}$  from the hot process stream temperatures. Figure 2.18 shows the representation of a heat exchanger analogy used to obtain the limiting cooling water data.

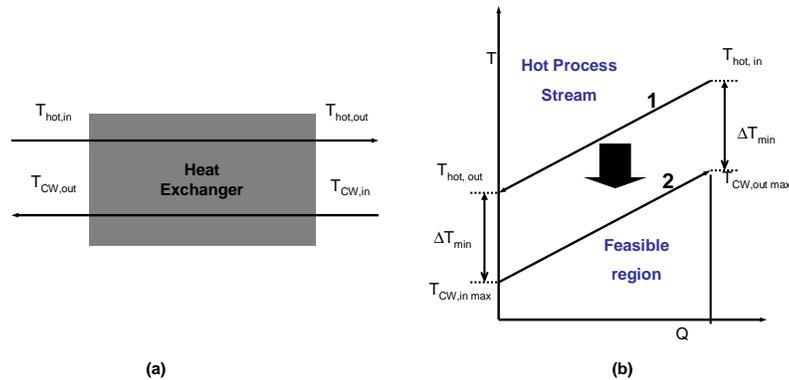


Figure 2.18 Representation of a cooling water using heat exchanger

In Figure 2.18, it is assumed that the temperature difference between the process stream and the cooling water stream at each end of the heat exchanger is equal. The cooling water data shown in this representation (**line 2**) shows the maximum inlet and outlet cooling water temperatures that are acceptable. Normally, water using operations use the cooling water at lower temperatures. Thus, this assumption ensures that the cooling requirement for the heat exchanger is not compromised. Any cooling water line below the limiting cooling water line is acceptable. An example taken from Kim and Smith (2001) is used to illustrate the design procedure. The process stream data and the limiting cooling water data are shown in Tables 2.3 and 2.4, respectively. The minimum temperature difference  $\Delta T_{min}$  for the process is  $10^{\circ}\text{C}$ .

*Table 2.3* Hot process stream data [Example 1, Kim and Smith (2001)]

Heat Exchanger	$T_{hot,in}$ (°C)	$T_{hot,out}$ (°C)	CP (kW/°C)	Q (kW)
1	50	30	20	400
2	50	40	100	1 000
3	85	40	40	1 800
4	85	65	10	200

*Table 2.4* Limiting cooling water data [Example 1, Kim and Smith (2001)]

Heat Exchanger	$T_{hot,in}$ (°C)	$T_{hot,out}$ (°C)	CP (kW/°C)	Q (kW)
1	20	40	20	400
2	30	40	100	1 000
3	30	75	40	1 800
4	55	75	10	200

The temperatures in Table 2.4 are obtained by subtracting 10°C from the temperatures given in Table 2.3, which is the minimum temperature difference ( $\Delta T_{min}$ ), from the process stream temperatures. The limiting cooling water composite curve obtained using the data in Table 2.4 is shown in Figure 2.19.

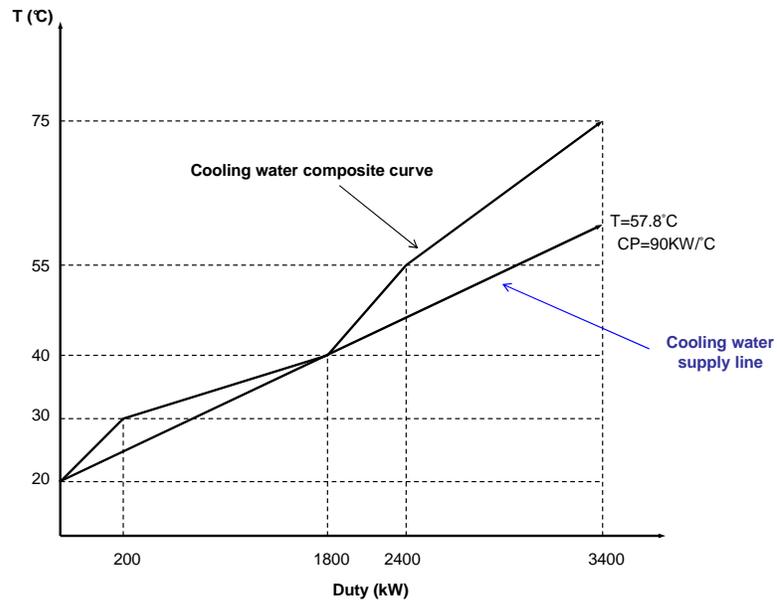


Figure 2.19 Cooling water composite curve and targeting for maximum reuse

The minimum amount of cooling water that can satisfy the cooling requirement is obtained from the cooling water supply line which forms a pinch with the cooling water composite curve as shown in Figure 2.19. Minimum cooling water means that the reuse between cooling water using operations is maximized. This increases the return temperature to the cooling tower as well as the performance of the cooling tower (Bernier, 1994 and Kim and Smith, 2001).

When the cooling water target has been set, the cooling water network is designed using the grid representation of Kuo and Smith (1998). The cooling water network is obtained in four steps.

- (i) Generate the grid diagram with the cooling water mains and the water using

operations as shown in Figure 2.20.

- (ii) Connect the water using operations to the water mains.
- (iii) Merge the water using operations that cross the cooling water mains.
- (iv) Remove the intermediate cooling water mains, which is normally placed in the design to simplify the design procedure.

Details of this procedure are given in section 2.4, where concentration is used rather than temperature. Figure 2.21 shows one of the final designs, which meet the target set in Figure 2.19.

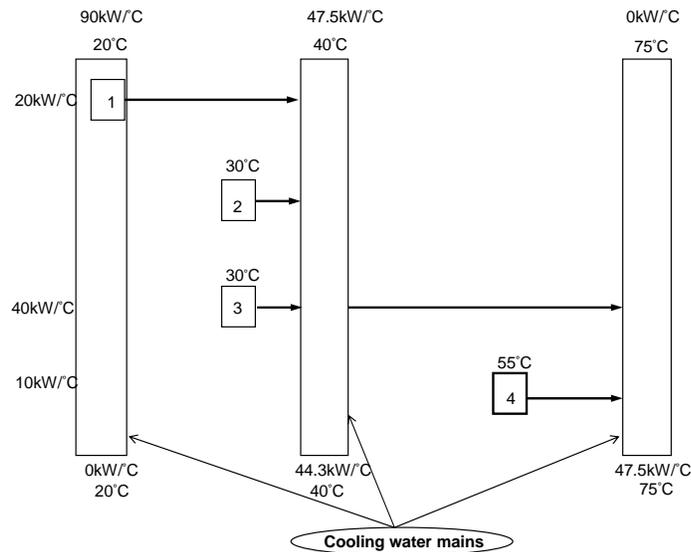


Figure 2.20 Grid representation of cooling water streams

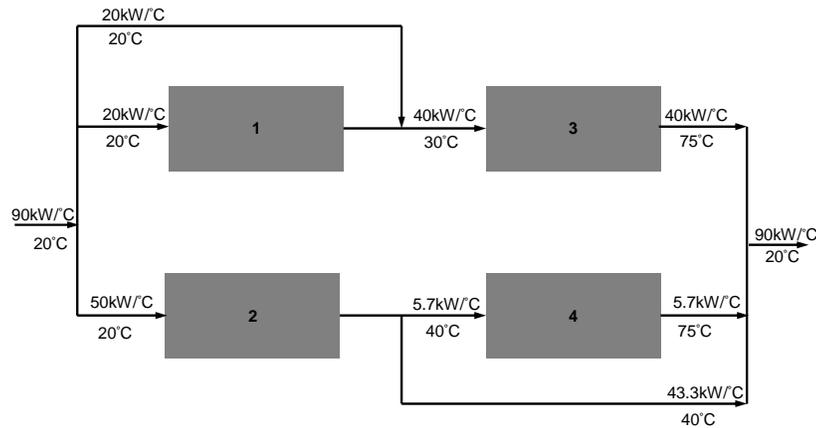


Figure 2.21 Final design for the cooling water network

If features of the design shown in Figure 2.21 are unacceptable for practical reasons such as control problems or pipework complexity, then the design can always be evolved.

Kim and Smith (2001) also looked at the interactions between the cooling water network and the cooling tower performance. A cooling tower model which incorporates equations for calculating the cooling tower makeup, blowdown and evaporation was developed. Cooling water is lost in the cooling tower due to evaporation and blowdown. Evaporation is essential for the cooling of the hot water entering the cooling tower. On the other hand, blowdown is necessary to avoid the build-up of undesirable materials in the re-circulating water as a result of evaporation. Equations 2.7, 2.8 and 2.9 were used for calculating blowdown, makeup and evaporation, respectively (Kim and Smith, 2001).

$$B = \frac{E}{CC - 1} \quad (2.7)$$

$$M = E \frac{CC}{CC - 1} \quad (2.8)$$

$$E = f(F_2, T_2, G, T_{WBT}) \quad (2.9)$$

In Equations 2.7, 2.8 and 2.9,  $B$  is the blowdown flowrate,  $E$  is the evaporation,  $M$  is the makeup,  $CC$  is the cycles of concentration,  $F_2$  is the circulating water flowrate,  $T_2$  is the return temperature to the cooling tower,  $G$  is the dry air flowrate and  $T_{WBT}$  is the wet bulb temperature.

The cycles of concentration ( $CC$ ) is defined as the ratio of the concentration of a soluble component in the blowdown to that in the makeup stream. It is a key factor in the design and operation of cooling towers.

The main advantage of the cooling water system design technique by Kim and Smith (2001) is that it investigated the interactions between the cooling tower and the cooling water network. All the major components of the cooling water system are incorporated in the design and the model gives acceptable results when applied to a cooling water network system which has one cooling water source.

Following the development of the cooling water network by Kim and Smith (2001),

several other authors have also looked at different aspects of cooling water network design. Kim et al. (2002) extended the cooling water network system to incorporate refrigeration systems. Additionally, Kim and Smith (2003) used an automated approach to investigate the interactions between cooling tower performance and the cooling water network design. A retrofit design of cooling water systems with minimum pressure drop by using an automated approach was explored. Mathematical programming was used to achieve the required goal and thus the reader is referred to the article by Kim and Smith (2003) for details as mathematical formulation is beyond the scope of this thesis.

Furthermore, Kim and Smith (2004) developed a design method aimed at the reduction of cooling water makeup. Cooling water makeup is necessary to replace the water, which is lost in the cooling tower through evaporation, blowdown and other forms of water losses including drift. Reduction in makeup is achieved by introducing water recovery between wastewater-generation processes and cooling systems. The method assumed that water using systems have abundant wastewater (chemically contaminated) enough to supply the recirculation cooling water. Two cases were considered for substituting makeup with wastewater. Firstly, when the temperature of the wastewater was lower than that of the inlet cooling water temperature to the network, the wastewater was added after the cooling tower. Alternatively, when the temperature of the wastewater was higher than that of the cooling water temperature to the cooling water network, the wastewater stream was added before the cooling tower. This ensured that the cooling water did not gain any heat before entering the cooling water network. When the cooling tower becomes debottlenecked, due to high flowrate of the wastewater added, a solution is obtained by

modifying the cooling water network. Debottlenecking is necessary when the cooling tower is required to remove more heat than it was designed for. The targeting and design procedures used for the design of the cooling water network are those developed by Kim and Smith (2001). The main advantage of the method for reducing makeup is that it used a systematic approach to identify process changes that have to be made.

Recently, other methods have been developed for energy and water management in cooling water systems. One of these methods is based on Pinch Analysis. Zhelev (2003, 2005) developed a conceptual approach for resource management in industrial cooling systems. The cooling tower is divided into two sections, the upper and lower sections. This ensures that the sensible heat and latent heat transfer are partially separated. Latent heat transfer occurs predominantly in the lower section and sensible heat is predominantly in the upper section. The division creates possibility for offering two qualities of water (a concept similar to the heating utility - low pressure (LP) and high pressure (HP) steam). Addressing the cooling water system performance this way could lead to substantial water savings associated with the seasonal control of the load of the latent heat dominated part of an oversized cooling system.

Savulescu et al. (2005) also developed a design methodology for simultaneous energy and water management. The method combines the methods by Kuo and Smith (1998) for wastewater minimization and that of Kim and Smith (2001) for cooling water system design. The main difference between this method and those presented before is that, the grid diagram used in the design stage is two-dimensional unlike the previous ones which

were one-dimensional. The grid diagram has both the temperature and concentration dimensions. The water streams that are involved in the systems are at different temperatures and concentrations. Isothermal and non-isothermal stream mixing between water streams are introduced to create separate systems between hot and cold water streams in the composite curves and provide a design basis for a better structure with fewer units for the heat exchanger network. During the design phase, the temperature of each water stream is brought to the temperature of the operation before it is used in that operation, through non-isothermal mixing of streams which are at the same concentration. Water reuse between processes reduces the water consumption and the direct mixing of water streams before using them in an operation minimizes heat losses inside the unit operation. Thus designing the network this way, allows for the simultaneous management of water and energy.

In this section, the development in the field of cooling water systems design has been discussed. There is still room for improving some of the methods presented in this section of the thesis and also those methods presented in the other sections above. In section 2.6 below, some of the limitations of the methods discussed in this chapter are discussed.

## **2.6 Limitations of methods presented**

Most of the research done thus far focuses into the different components of the cooling water system, and not the overall system as a holistic entity. Firstly, research has been done looking on cooling towers disregarding their impact on the cooling water network. On the other extreme, there are techniques that concentrate on the cooling water using

operations without considering the source of the cooling water. There are interactions between the cooling tower and the cooling water network, thus for a technique to be applied effectively in practice there is a need to design the two components simultaneously. However, most recently there are methods which have been developed to look at the interactions between the cooling water network and the source of cooling water, the cooling tower. The major drawback of these methods is that they assume that the cooling water network is supplied with cooling water from one source. In practice, it has been noted that there are some cooling water networks which are supplied by multiple cooling water sources, with different supply temperatures. Hence, there is a need to develop a method that can be applied to such cooling water systems.

## 2.7 Conclusions

A review of methodologies for cooling tower, heat exchanger networks, wastewater minimization and cooling water systems has been presented in this chapter. The main advantages and disadvantages of these models have been identified. The common disadvantage in most published methods is that, they analyse the components of the cooling water system as separate entities. That is, cooling towers, and cooling water using operations are designed separately. The main finding of research on cooling towers is that the cooling tower performance is enhanced by reducing the cooling water flowrate thus increasing the return temperature to the cooling tower. Also, this combination of operational parameters results in low cooling tower investment and reduced operating costs. Pinch Analysis is the most accepted approach in the analysis of heat exchanger networks. It uses basic thermodynamic principles and ensures that hot and cold utilities

used in a heat exchanger network are minimized, thus reducing the operating costs. Wastewater minimization methods presented a major foundation in the development of cooling water systems. Recently, methodologies have been developed for cooling water systems which also take into account the interactions between the cooling tower and the cooling water using operations. This has helped designers to come up with practical and usable cooling tower and water network designs which have been applied to real world processes. Also, work has been done in the field of water and energy management. Future work needs to concentrate on designing cooling water systems with multiple cooling water sources as well as the development of alternative cooling tower models with fewer assumptions and improved accuracy.

### 3.1 Introduction

This chapter discusses a new graphical methodology used to design cooling water systems with multiple cooling water sources. It is an extension of the technique developed by Kim and Smith (2001) for cooling water networks with a single cooling water source. It is divided into two parts, namely, targeting and design. The technique is developed and then applied to an illustrative example with two cooling water sources.

### 3.2 Targeting

Targeting involves the setting of cooling water supply targets from the cooling tower into the associated cooling water using network. The cooling water composite curve is constructed as suggested by Kim and Smith (2001) for a single cooling water source by combining all individual profiles into a single curve within temperature intervals. However, there are two scenarios that can arise in the presence of multiple cooling water sources. If the cooling water sources have very high design capacities and significantly high maximum return temperatures, all the cooling water used will be supplied by the cooling water source with the lowest supply temperature (primary source). Thus the water supply line will be similar to that for systems with a single cooling water source. This observation is demonstrated in Figure 3.1

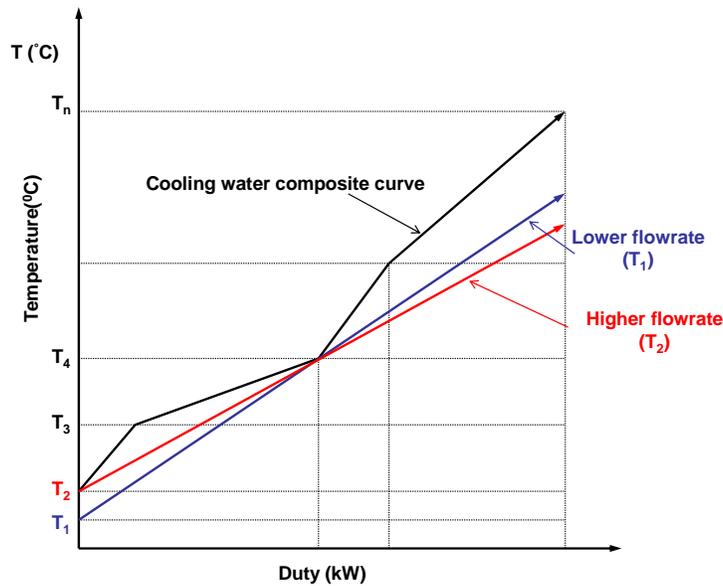


Figure 3.1 Cooling water targets for cooling water sources with unlimited capacity

Figure 3.1 shows that the flowrate for the cooling water source with a lower supply temperature ( $T_1$ ) is lower than that with a higher supply temperature. Thus less water will be required if it is supplied solely from the primary source. However, the lower flowrate is concomitant with higher return temperature for the same heat duty (Fig. 3.1). It is, therefore, evident that in a situation where the flowrates are unlimited and return temperatures not critical, the source with minimum supply temperature will always be the sole supplier. This renders the other supplies redundant. The targeting is thus performed as outlined by Kim and Smith (2001) for single cooling water sources, where the flowrate is minimized by ensuring that the water supply line forms a pinch with the limiting cooling water composite curve. Any cooling water supply line beyond that which forms a pinch with the limiting composite curve does not satisfy the cooling requirements of the system.

However, in cases where the minimum water requirement for the cooling water system is higher than the design capacity of the primary source, the cooling water from the cooling water sources with higher supply temperatures has to be used to supplement the primary cooling water supply. In this particular case, targeting is no longer straightforward. The steps followed in targeting for the cooling water supply are outlined below.

*Step 1* Primary cooling water source

Maximize the amount of cooling water used from the primary source by adjusting the gradient of the cooling water supply line until its value corresponds to the maximum flowrate. This step is illustrated in Figure 3.2. At this point, supplementary water from higher temperature sources is required in order to meet the target for the entire cooling water system.

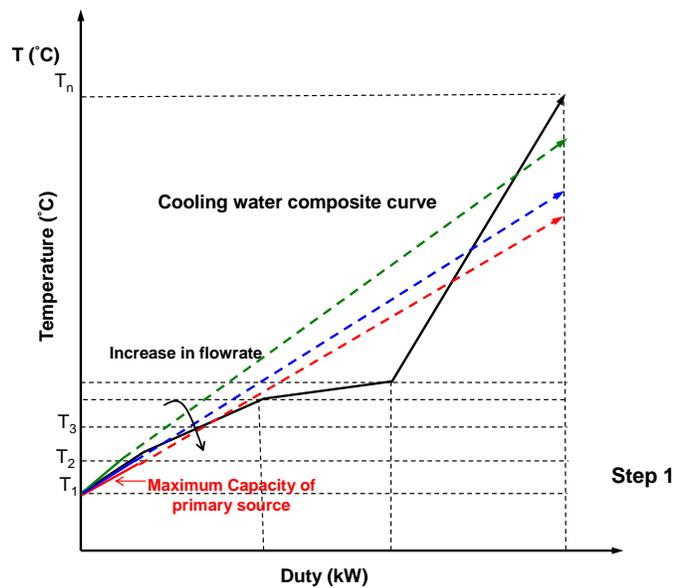


Figure 3.2 Setting the target for primary cooling water source

Step 2 Intermediate cooling water sources

All the subsequent cooling water supply lines represent the overall flowrate of the previous cooling water sources and the one being targeted at that stage. The cooling water supply line for the intermediate cooling water sources is set by either the maximum capacity of the cooling water source or the pinch point. If the maximum capacity is reached before a pinch is formed with the limiting cooling water composite curve, then the cooling water source with the next closest supply temperature is used to supplement the cooling requirement. However, if the pinch is formed before the maximum capacity is reached, the rest of the cooling water sources need not be used because the cooling water requirement will be satisfied. Thus the rest of the cooling water sources become redundant. This step is illustrated in Figure 3.3.

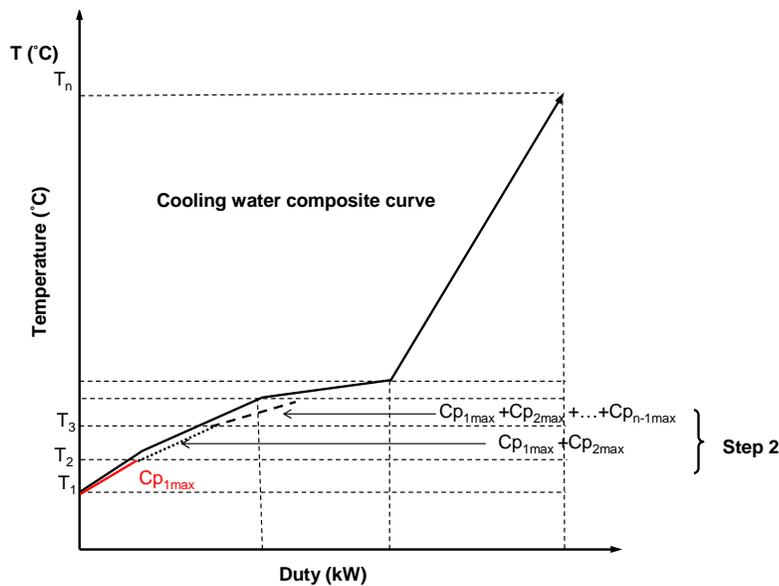


Figure 3.3 Setting the targets for intermediate cooling water sources

As shown in Fig. 3.3, the gradient of the cooling water supply line decreases with the addition of an extra cooling water source as it represents the sum of all the cooling water flowrates from all the water sources that have been used.

*Step 3* Cooling water source with the highest supply temperature

If a pinch is not formed while targeting for any of the intermediate cooling water sources, the cooling water source with the highest supply temperature has to be used. The overall amount of cooling water used by the whole system is set by minimizing the amount of cooling water from the last cooling water source. This is done by ensuring that the final supply line forms a pinch with the cooling water composite curve. The flowrate obtained from this line represents the overall cooling water requirement for the system. This is shown in Figure 3.4.

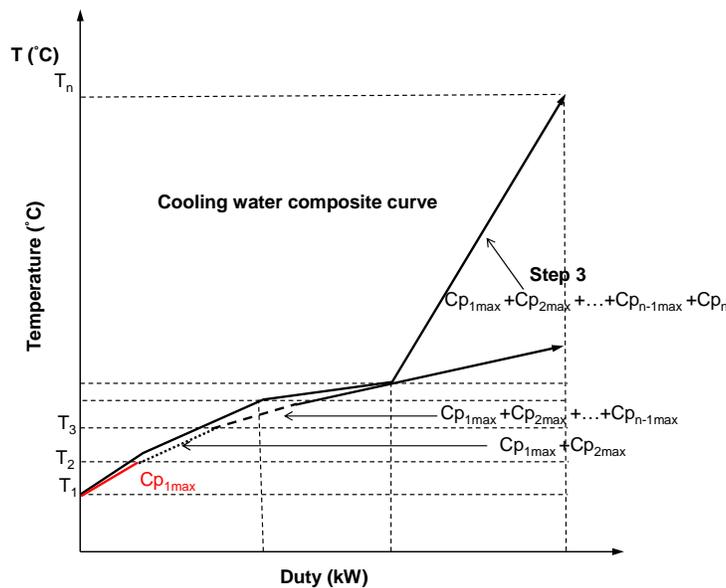


Figure 3.4 Targeting steps for systems with multiple cooling water sources

### 3.3 Design Procedure

The design procedure for systems with unlimited cooling water capacities is similar to the water mains method for single cooling water sources (Kim and Smith, 2001). The water mains on a grid diagram represent the cooling water source, the pinch point as well as the highest exit temperature of the water using operations. Other intermediate water mains are possible depending on the maximum supply and target temperatures of the cooling water. However, the design procedure for systems with limited cooling water supply from the primary cooling water source is an extension of the procedure suggested by Kim and Smith (2001). Each cooling water source is represented by a water mains and the grid diagram also has water mains representing the pinch point and the highest exit temperature. The procedure has five steps.

The first step is to generate the grid diagram consisting of the cooling water mains representing all the cooling water sources, the pinch temperature, the intermediate temperatures and the highest exit temperature. Then, the cooling water using operations are plotted in accordance with their maximum supply and target temperatures on the grid diagram. This is shown in Figure 3.5.

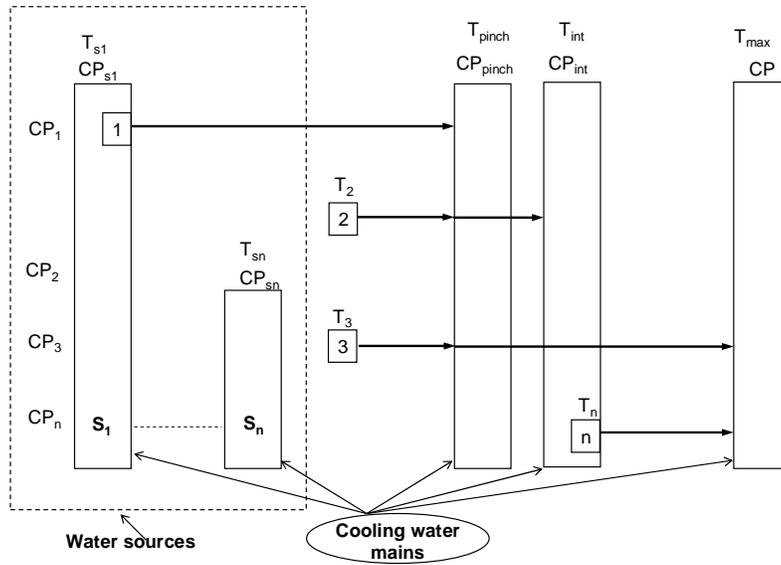


Figure 3.5 Step 1 of the design procedure

The second step is to connect the cooling water operations to the water mains. The cooling water from the source mains is used in ascending order, starting with the water supplied by the primary source. This is shown in Figure 3.6.

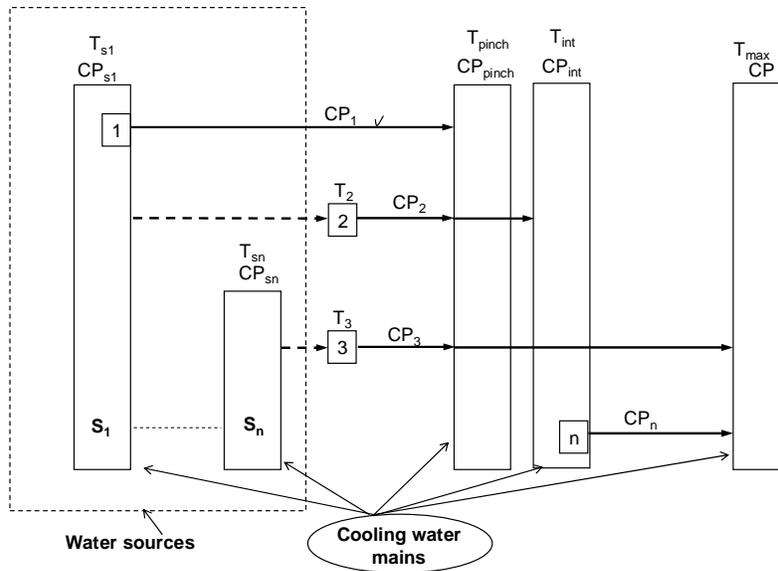


Figure 3.6 Step 2 of the design procedure

The ticked stream in Fig. 3.6 indicates that the cooling requirement for the cooling water using operation has been satisfied.

The third step is to merge operations that cross the intermediate cooling water and pinch mains. This is shown in Figure 3.7.

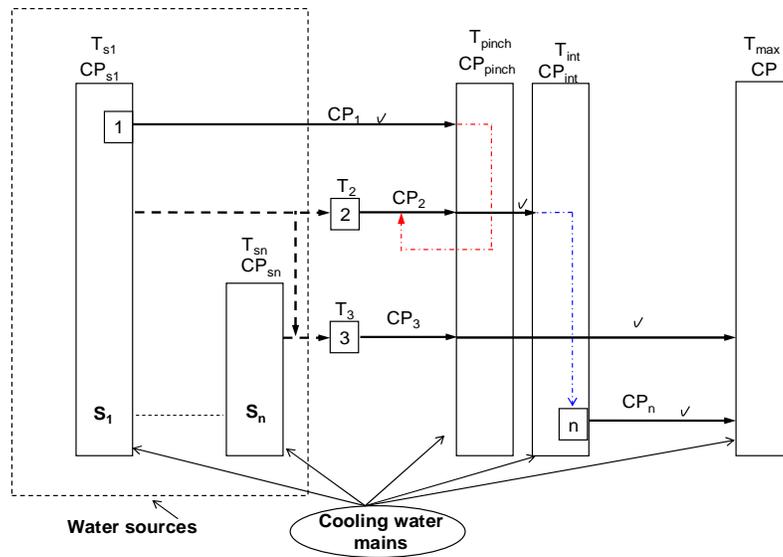


Figure 3.7 Step 3 of the design procedure

The fourth step is to remove the intermediate and pinch mains as shown in Figure 3.8.

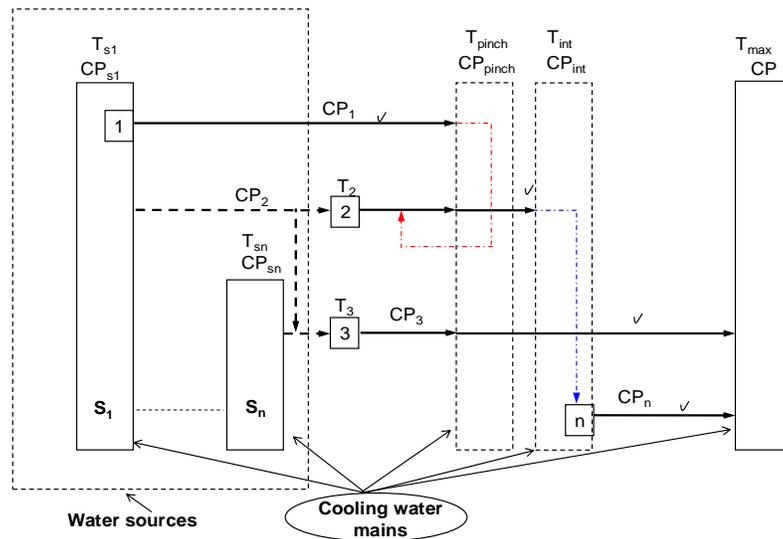
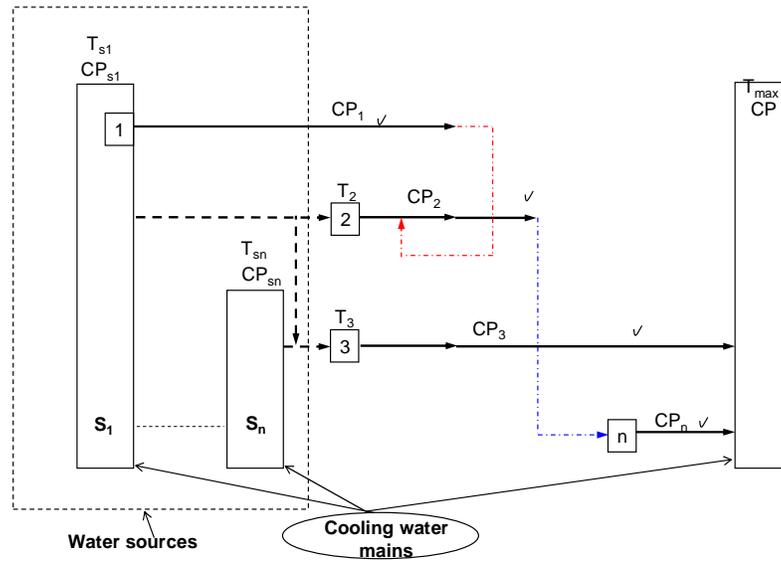
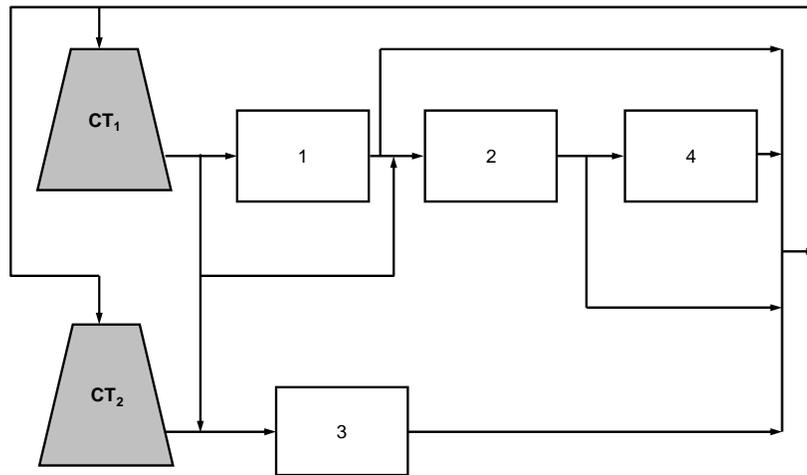


Figure 3.8 Step 4 of the design procedure

The fifth step is to connect the operations directly, which yields the final design as shown in Figures 3.9(a) and 3.9(b).



(a)



(b)

*Figure 3.9* Step 5 of the design procedure

#### APPLICATION OF METHOD TO ILLUSTRATIVE EXAMPLE

In this example, the cooling water network comprises of four cooling water using operations. These cooling water using operations are supplied by two cooling towers A and B with supply temperatures of 20°C and 25°C, respectively. The maximum design capacities for cooling tower A and B are 69 ton/hr (80 kW/°C) and 43 ton/hr (50 kW/°C), respectively. Table 3.1 below shows the limiting cooling water data used. Cooling tower A supplies heat exchangers 1 and 2 and cooling tower B supplies heat exchangers 3 and 4.

Table 3.1 Limiting cooling water data

Heat Exchanger	$T_{\text{hot,in}}$ (°C)	$T_{\text{hot,out}}$ (°C)	CP (kW/°C)	Q (kW)
1	25	40	30	450
2	35	40	160	800
3	25	75	34	1 700
4	50	75	12	300

Cooling water inlet temperature from cooling tower A = 20 °C

Cooling water inlet temperature from cooling tower B = 25 °C

Initially, the system was analyzed as two independent subsystems (case 1). Then the overall system was analyzed using the new technique for targeting for multiple cooling water sources (case 2). The targeting and design procedures are detailed in sections 3.4 and 3.5 below.

### 3.4 Targeting for illustrative example

The targeting procedure for case 1 is similar to that discussed by Kim and Smith (2001). That is, the limiting cooling water composite curves are constructed for the subsystems and the cooling water supply line is matched against them. The supply lines have the highest possible gradients to ensure that the flowrate is minimized. This is set when the water supply line forms a pinch with the limiting cooling water composite. The pinch point represents the region where the driving forces go to a minimum, but not necessarily zero (Wang and Smith, 1994). The targets for cooling tower A and cooling tower B are shown in Figure 3.10.

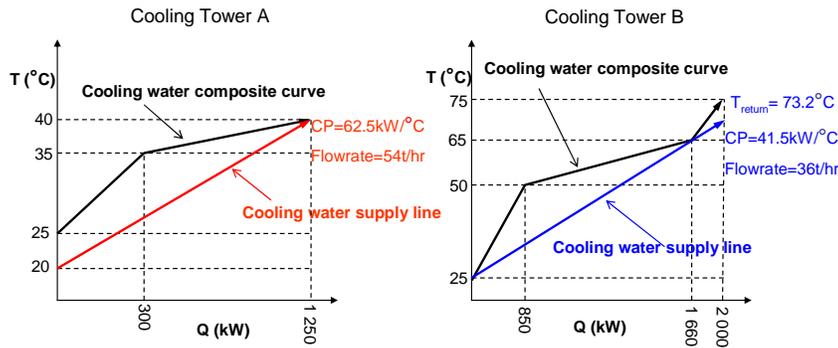


Figure 3.10 Cooling water targets for system analyzed using case 1

Fig. 3.10 shows that when the system is analyzed as separate subsystems, the cooling water requirements for cooling tower A and cooling tower B are 54 ton/hr (62.5 kW/°C) and 36 ton/hr (41.5 kW/°C). Both of these are less than the maximum design capacities for the cooling towers. The return temperatures of cooling tower A and cooling tower B are 40°C and 73.2°C, respectively. The return temperature of cooling tower B is very high and could be unacceptable due to some constraints such as fouling and corrosion. Thus there could be a need to reduce the return temperature to cooling tower B.

The targeting procedure used for case 2 has been introduced in section 3.1 above and will be discussed in detail in this section. The amount of cooling water supplied by the cooling tower with the lowest supply temperature (primary source) is maximized to ensure that the overall requirement is minimized. The maximum value is set by the

maximum capacity of the cooling tower. The cooling water used from the subsequent sources is also maximized as long as the pinch point is not reached. Otherwise the amount used from the subsequent cooling water sources is set by the pinch. However, if the pinch point is not formed when using the intermediate cooling water sources, the target for the source with the highest supply temperature is set by ensuring that the final cooling water supply line forms a pinch with the limiting cooling water composite curve. The final cooling water supply line represents the overall cooling water requirement. Targeting this way ensures that the overall cooling water requirement is optimized. In the example used in this thesis, there are only two cooling water sources (primary and secondary), thus the amount of cooling water from the primary source will be maximized and that from the secondary source will be minimized. The target set is shown in Figure 3.11.

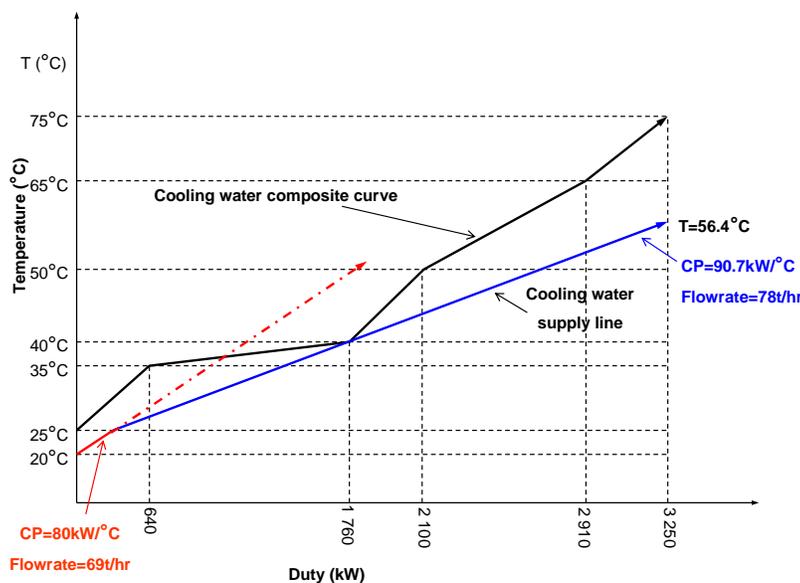


Figure 3.11 Targets for case 2

Fig. 3.11 shows that targeting holistically significantly reduces the overall cooling water requirement (from 90 ton/hr to 78 ton/hr). The overall cooling water requirement (78 ton/hr) is more than the maximum design capacity of cooling tower A (69 ton/hr) thus, cooling tower B has to be used to supplement it. Furthermore, the return temperature to cooling tower B is also significantly reduced (from 73.2°C to 56.4°C). The overall performance of the cooling towers is improved, i.e. less water is required for the removal of the same amount of heat.

### 3.5 Design Procedure for illustrative example

When designing for case 1, the subsystems are designed as independent systems using the water mains method as described in section 3.2 above. Lines representing the cooling water using operations are placed on a grid diagram, indicating the maximum inlet and maximum outlet temperatures as well as the cooling duty required in terms of the heat capacity flowrate,  $CP$ . The next step is to connect the cooling water operations which are below the pinch (those that are not connected to the water mains) to the water mains. This is followed by connecting the cooling water operations that cross the pinch mains to fulfill the cooling requirement. Then, the intermediate and pinch mains are removed. Finally the cooling water operations are connected directly. The final cooling water network design for case 1, which meets the target set in Figure 3.10, is shown in Figure 3.12.

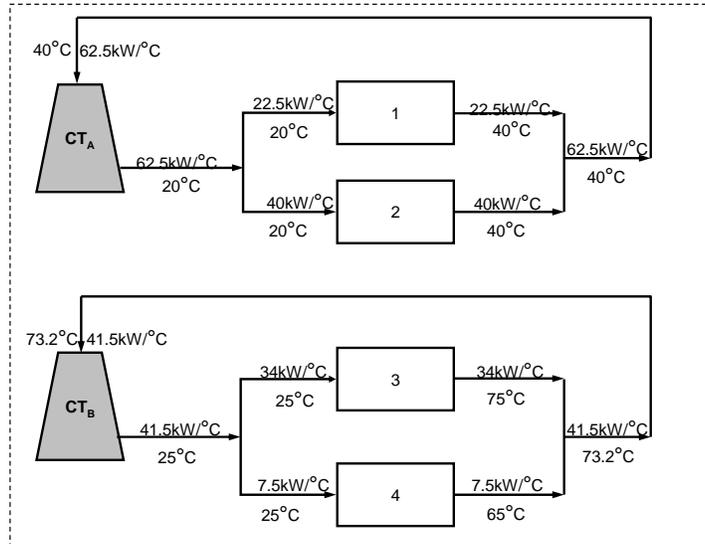


Figure 3.12 Final cooling water network design using case 1

For case 2, the system is analyzed in a holistic manner. The network is first supplied by the primary source and then the secondary source is used to fulfill the overall cooling water requirement. The steps for designing the network are shown in Figures 3.13 to 3.17.

*Step 1*

Generate the grid diagram with the water mains representing all the cooling water sources, the pinch point, the intermediate temperature(s) and the highest exit temperature.

Plot all the cooling water using operations as shown in Figure 3.13.

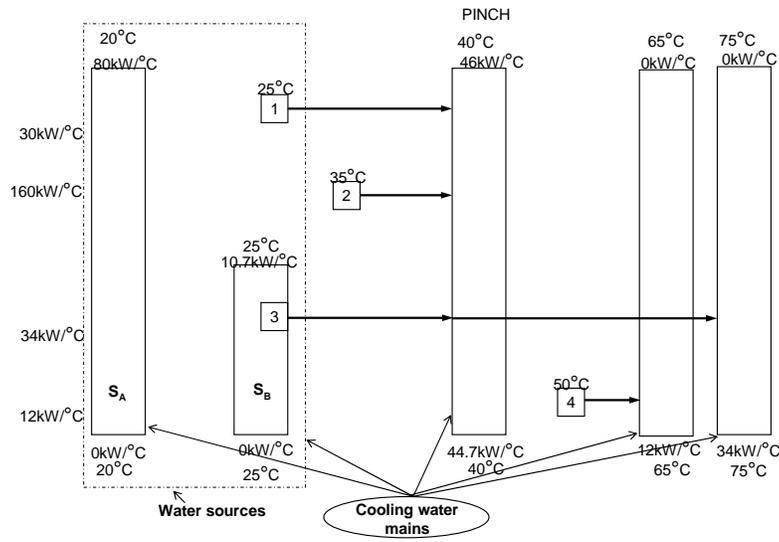


Figure 3.13 Design procedure step 1 for case 2

Step 2

Connect the operations to the water mains as shown in Figure 3.14.

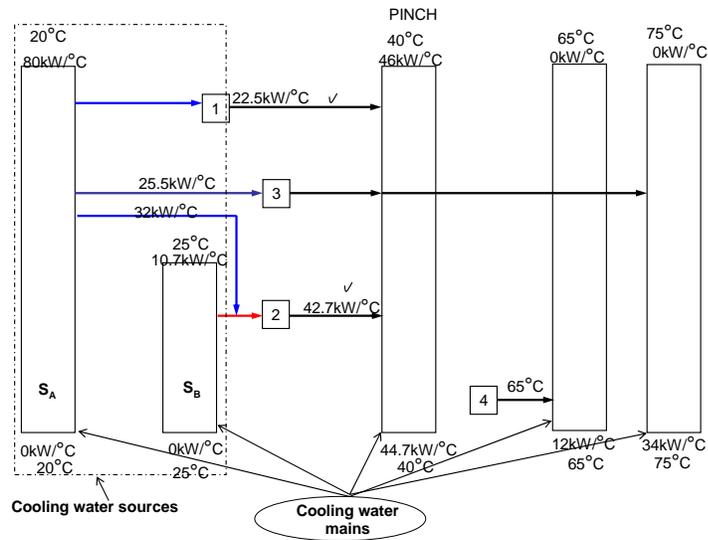


Figure 3.14 Step 2 for the design procedure for case 2

Step 3

Merge all operations that cross the pinch as shown in Figure 3.15.

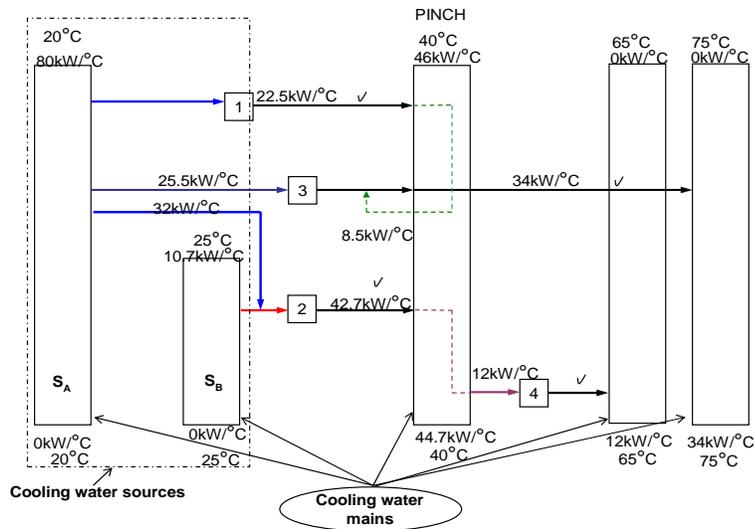


Figure 3.15 Step 3 for the design procedure for case 2

Step 4

Remove the intermediate pinch as shown in Figure 3.16.

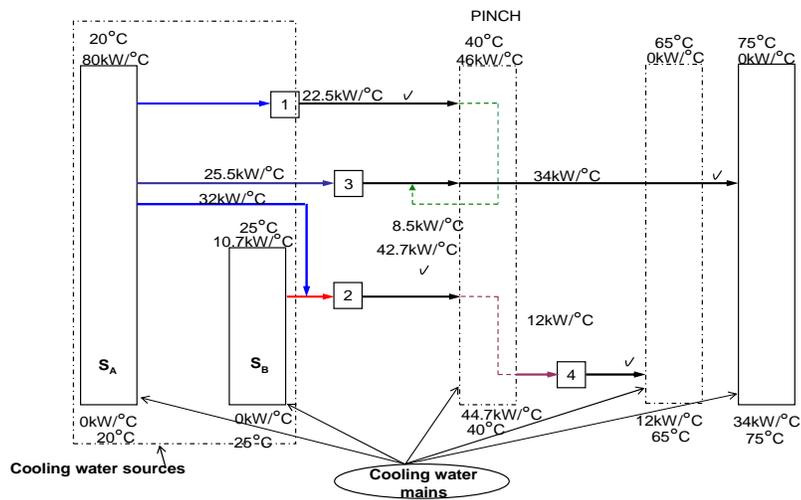


Figure 3.16 Step 4 of the design procedure for case 2

Step 5

Connect the cooling water operations directly as shown in Figure 3.17.

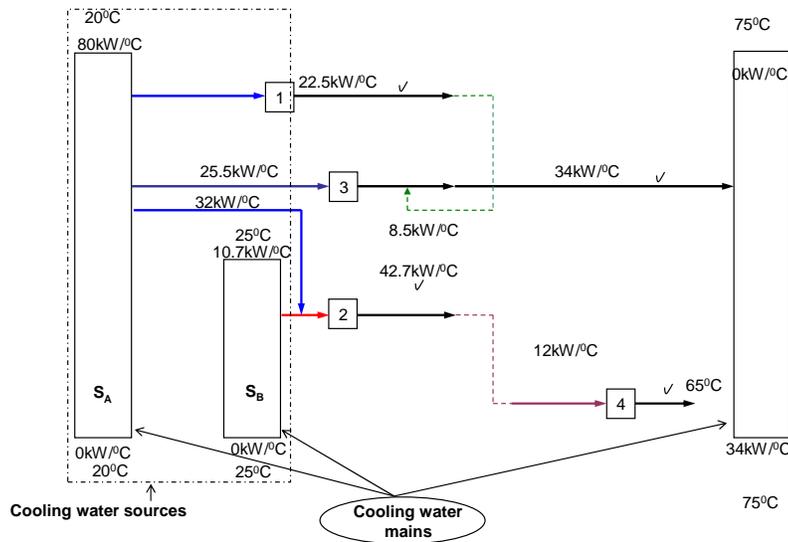


Figure 3.17 Step 5 of the design procedure for case 2

The final design obtained for case 2 which meets the target set in Figure 3.11 is shown in Figure 3.18. This shows the actual layout of the cooling water network, with the cooling towers and cooling water using operations in place. Cooling water operation 2 is supplied by both cooling tower A and cooling tower B. This forms the main interaction between cooling tower A and cooling tower B. The rest of the cooling water operations are supplied by one cooling tower or by other operations, i.e. water from other operations is reused.

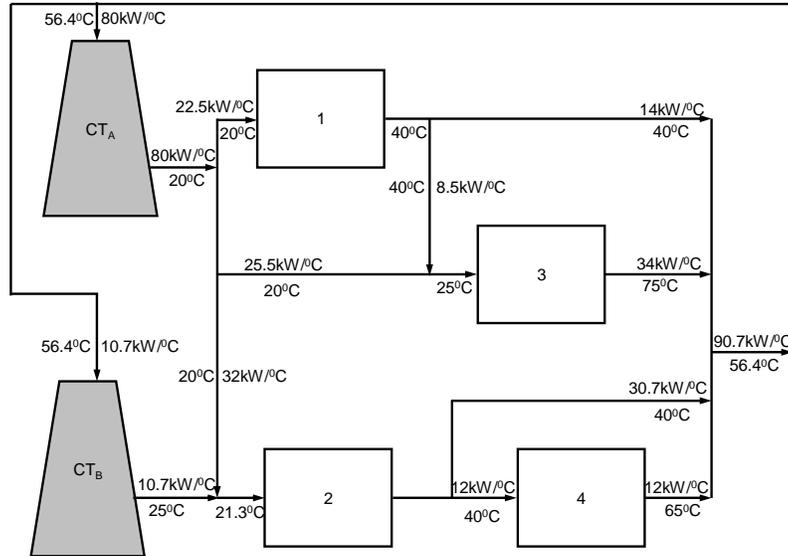


Figure 3.18 Final design for the illustrative example for case 2

### 3.6 Results and Discussion

Table 3.2 summarizes the results obtained for cases 1 and 2, which includes the overall cooling water requirements and the overall performance of the cooling towers. The overall performance of cooling tower A and cooling tower B for cases 1 and 2 was analyzed using an artificial performance factor ( $\phi$ ) represented by Equation 3.1.

$$\phi_k = \frac{\Delta T_k}{Flowrate_k}, k \in K = \{k \mid k = \text{Cooling Tower}\} \quad (3.1)$$

In Equation 3.1,  $\Delta T_k$  is the temperature difference between the return temperature and the supply temperature of cooling tower  $k$ . The flowrate is the amount of cooling water

required to cool the cooling water using operations. Since the intention of this investigation is to reduce flowrate, thereby increasing return temperature, an increase in the factor  $\phi$  is associated with improved cooling tower performance.

*Table 3. 2 Comparison of case 1 and case 2 results*

	<b>Flowrate (ton/hr)</b>	<b>Performance Factor (<math>\phi</math>) (<math>^{\circ}</math>C.s/kg)</b>
<i>Case 1</i>		
Cooling Tower A	54	1.3
Cooling Tower B	36	4.9
<b>Overall</b>	<b>90</b>	
<i>Case 2</i>		
Cooling Tower A	69	1.9
Cooling Tower B	9	12.3
	<b>78</b>	

The increase in the performance factors for both cooling towers as shown in Table 3.2, suggests an overall increase in the cooling tower performance for both cooling tower A and cooling tower B (Bernier, 1994). Furthermore, the overall cooling water requirements presented in Table 3.2, show that analyzing the system in a holistic manner reduces the overall amount of cooling water required, thus improving the performance of the cooling towers. Although the amount of cooling water required from cooling tower A is increased, the overall performance of the cooling tower is improved. When assessing the results for cooling tower B, it can be seen that the flowrate required decreases significantly and the return temperature also decreases because there is mixing between the water supplied by cooling tower A and cooling tower B when heat is removed from the cooling water using operations.

### **3.7 Conclusions**

Following the success in applying the new graphical methodology to an illustrative example, the technique was further applied to an existing process and this is discussed in the following chapter.

#### 4.1 Introduction

This chapter focuses on the application of the new graphical methodology for processes with multiple cooling water sources to an existing process. The background of the process used in the research study is given in the following section.

#### 4.2 Case Study Background

The presented industrial case study is based on a nitrates production facility. The process is supplied by one counter-current induced draft cooling tower. The cooling water network is predominantly heat exchangers with a parallel-series configuration as shown in Figure 4.1. The process stream data of the case study is shown in Table 4.1 and the current cooling water data is given in Table 4.2.

*Table 4.1* Case study process stream data

Heat Exchanger	$T_{\text{supply}}$ (°C)	$T_{\text{target}}$ (°C)	Duty (kW)
1	52	25	10 700
2	115	45	16 700
3	100	40	13 500
4	48	39	300
5	118	50	1 100
6	114	50	4 400
7	20	30	-2 000

Table 4.2 Current cooling water data for the case study

Heat Exchanger	T <sub>supply</sub> (°C)	T <sub>target</sub> (°C)	Duty (kW)
1	24	28	10 700
2	28	34	16 700
3	24	32	13 500
4	24	29	300
5	32	34	1 100
6	32	36	4 400
7	35	34	-2 000

Currently the process requires 3900 ton/hr of cooling water with about 59% (2290 ton/hr) used by the absorption tower. 41% (1610 ton/hr) of the cooling water supplied by the cooling tower is used by the rest of the heat exchangers before it is returned to the cooling tower at a higher temperature. Currently the return temperature to the cooling tower is 34°C and the supply temperature is 24°C. Some of the cooling water is lost in the cooling tower through evaporation, windage and blowdown. Blowdown is necessary for the prevention of salts and nitrates accumulation in the system. Water lost is replaced by a freshwater makeup stream.

Since most of the inlet temperatures of the process streams have temperatures above 100°C it is evident that the limiting cooling water data cannot be set by directly using the minimum temperature difference on each end of the operation. Subtracting the minimum temperature difference from the process temperatures on each end of the heat exchangers to obtain the limiting cooling water temperature is not straightforward in this case as it will result in the return temperature close to or above 100°C. Hence, engineering insight and knowledge of the process is required to obtain the limiting cooling water data. The

limiting cooling water data was thus obtained by adding 10°C to the current cooling water exit temperatures of the heat exchangers as shown in Table 4.3.

*Table 4.3* Limiting cooling water data for the case study

<b>Heat Exchanger</b>	<b>T<sub>supply</sub> (°C)</b>	<b>T<sub>target</sub> (°C)</b>	<b>Duty (kW)</b>
1	24	28	10 700
2	28	44	16 700
3	24	42	13 500
4	24	29	300
5	32	44	1 100
6	32	46	4 400
7	35	44	-2 000

The exit temperature of heat exchanger 4 was not changed due to limited information on the unit operation. Also, for practical reasons, the exit temperature of the absorption tower (water using operation 1) was not changed.

In the assessment of the network, it is evident that the cooling water network has two cooling water sources, i.e. the cooling tower (primary source) and the absorption tower (secondary source), as shown in Figure 4.2. This system is unique in that, the cooling water required by the secondary source is supplied by the primary source. The absorption tower is treated as a secondary cooling water source rather than one of the cooling water using operations due to the fact that its cooling water supply is always fixed. As a process requirement, the amount of cooling water required by the absorption tower is fixed and cannot be manipulated. Therefore, in this case, the objective is to maximize the amount of cooling water that is reused from the secondary source, whilst minimizing the amount of water from the primary source. This is the direct opposite of the case presented and

illustrated in the example in Chapter 3. The analysis is, therefore, reversed as detailed in the following sections.

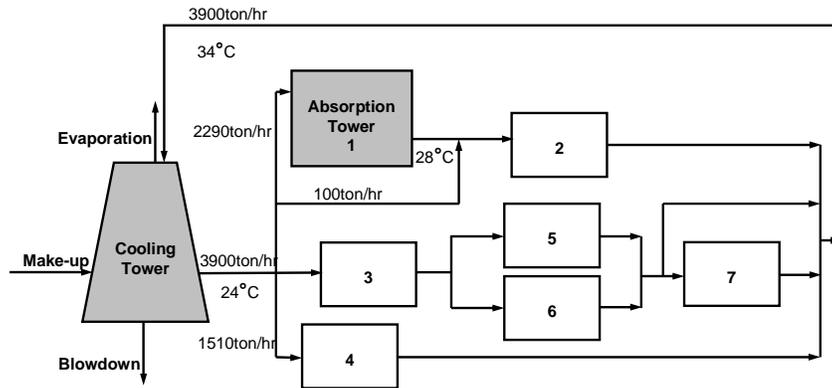


Figure 4.1 Cooling water network for a nitrates production facility

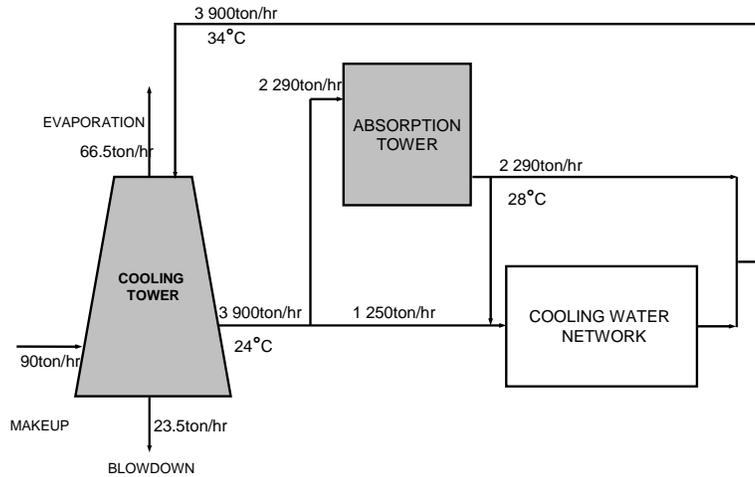


Figure 4.2 Two sources of cooling water to the cooling water network

### 4.3 Targeting for Case Study

The case study analyzed is a *special system* in that, in order to obtain an optimal solution, the amount of cooling water from the secondary cooling water source should be maximized instead of maximizing the cooling water from the primary source as required in ordinary systems presented earlier in this thesis. In this case, the secondary cooling water source has a fixed cooling water requirement and this is supplied by the primary cooling water source, as shown in Figures 4.1 and 4.2. In order to minimize the overall amount of cooling water required from the cooling tower the amount of cooling water supplied directly from the cooling tower to the other cooling water using operations should be minimized, since the stream to the absorption tower is fixed. This can only be achieved by maximizing the amount of cooling water reused from the secondary cooling

water source, i.e. the absorption tower. The procedure for constructing the cooling water supply line for this case is described below. Water using operation 7 is not included in the construction of the limiting cooling water curve, because in that unit, cooling water is used as a hot stream. This is characterized by higher inlet cooling water temperature than the exit temperature. The limiting cooling water composite curve is only constructed considering the operations where the cooling water is used as a cold stream which is heated from a lower to a higher temperature.

The amount of cooling water used from the primary source is minimized by allowing its supply line to form a pinch with the composite curve at a temperature equal to or below that of the subsequent cooling water source. Figure 4.3 illustrates targeting when two cooling water sources supply a system of cooling water using operations.

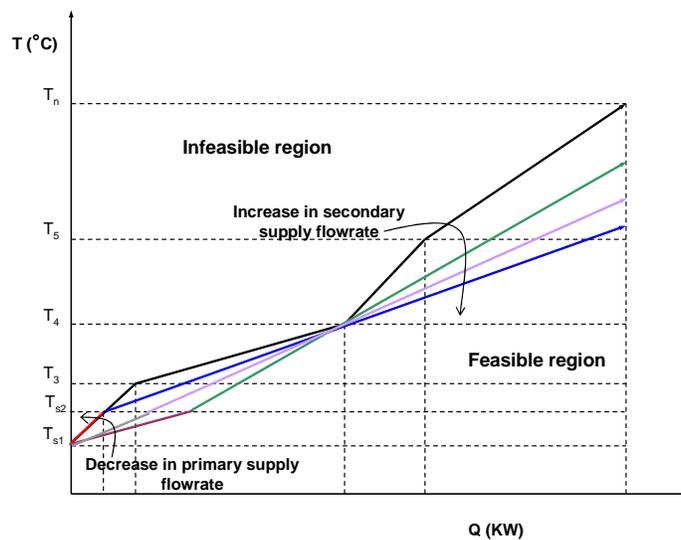


Figure 4.3 Targeting procedure for special systems

From Fig. 4.3, it can be seen that as the amount of cooling water from primary source is decreased, the amount required from secondary source is increased as shown by the arrows. The limit is set when the cooling water supply line for the primary cooling source forms a pinch with the limiting cooling water composite curve. In the illustration in Fig. 4.3, this occurs when the cooling water supply line is exactly on top of the limiting cooling water composite curve. Further decrease in primary cooling water supply would result in infeasibility as the composite curve forms the boundary between the feasible and infeasible regions. Targeting in this manner ensures that as much cooling water as possible is used from the secondary cooling water source.

The cooling water target set for the case study is shown in Figure 4.4.

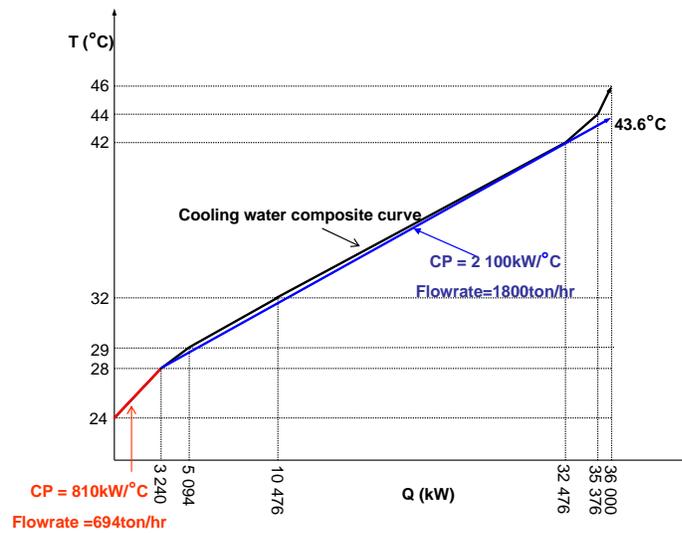


Figure 4.4 Target for case study

Fig. 4.4 shows that the supply line for the primary cooling water source is directly on top of the cooling water composite curve. The overall target shown in Fig. 4.4 for part of the network is 1800 ton/hr. This includes the cooling water obtained directly from the primary source (694 ton/hr) and part of the cooling water which is used in the secondary source (1106 ton/hr). The cooling water from the secondary source which is not reused anywhere else in the network (1184 ton/hr) is recombined with water from the rest of the cooling water network before being returned to the cooling tower (primary source). Thus, the temperature shown at the end of the cooling water supply line in this case does not reflect the return temperature to the cooling tower. The return temperature is obtained by calculating the temperature of the mixture of cooling water from the secondary source which is not reused anywhere else in the system and the cooling water from the rest of the network. In this case, the final temperature is 37°C.

#### **4.4 Design Procedure for Case Study**

The design procedure adopted is similar to that of ordinary cooling water systems with multiple cooling water sources. On the grid diagram each cooling water source is represented by water mains. The pinch point and the exit temperature are also represented by water mains. The cooling water using operations are supplied by the primary cooling water source before the cooling water from the secondary source can be used. The design of the final network is performed in five steps as outlined in section 3.2 of this thesis. The final cooling water network design obtained for the case study is shown in Figure 4.5. Table 4.4 shows the current cooling water requirements as well as the reduced cooling water requirements obtained using the methodology developed.

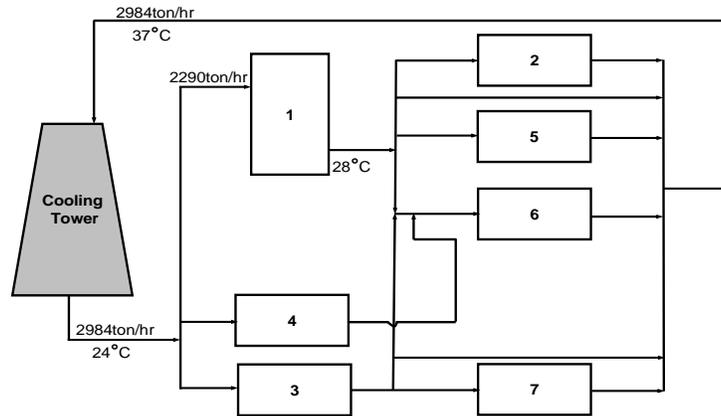


Figure 4.5 Improved cooling water network design for case study

Table 4.4 Cooling water requirements for the improved cooling water network

Heat Exchanger	$T_{\text{supply}}$ (°C)	$T_{\text{target}}$ (°C)	Flowrate (ton/hr)	New Flowrate (ton/hr)
1	24	28	2 290	2 290
2	28	44	2 390	895
3	24	42	1 450	643
4	24	29	60	51
5	32	44	450	59
6	32	46	900	269
7	35	34	1 700	214

#### 4.5 Discussion

Analysing the nitrates production facility using the new methodology results in significant reduction in the amount of cooling water required by the individual cooling water using operations as well as the overall cooling water requirement. The cooling water requirement is reduced by 23%. The return temperature is slightly increased to

37°C. This increase is insignificant compared to the benefit obtained from the reduction on the cooling water flowrate, i.e. the reduction in the utility costs of the process.

When looking at Figures 4.1 and 4.5 there are no major changes in the overall layout of the process. There are a few additional pipes that will need to be added. Considering the benefit of the reduced utility requirements, it could be worthwhile to make the necessary changes. However, the effects of the pressure drop will have to be investigated before any decision is made. This does not form part of the presentation made in this thesis.

#### **4.6 Conclusions**

This chapter and the preceding chapter focus on the design of the cooling water network without consideration of the implications of the design parameters on the performance of the cooling water source, particularly, the cooling tower connected to the network. The following chapter discusses the application of the cooling tower model developed by Kim and Smith (2001) to the illustrative example and the case study presented in this chapter. The implications of changing the overall cooling water flowrate used in the network and the temperature of the cooling water leaving the cooling water network are investigated.

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**Cooling Tower Model Application**

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**5.1 Introduction**

Cooling towers are arguably the largest heat and mass transfer devices that are in common use in process industries. They are used to reject waste heat from the systems via a water loop which connect them to the cooling water network. Over the past decades, models have been developed to assess different characteristics of cooling towers, e.g. thermal performance. Some of these models where discussed in Chapter 2 of this thesis. In this chapter, the cooling tower model developed by Kim and Smith (2001) was used to analyse the thermal performance of a case study cooling tower in order to ascertain that the supply temperature to the absorption tower is not adversely affected by the proposed changes.

This chapter is structured as follows.

- (i) Section 5.2 focuses on the description of the cooling tower model.
- (ii) Section 5.3 discusses the verification of the literature results as well as the application of the cooling tower model to a case study.
- (iii) Section 5.4 presents the conclusions.

**5.2 Cooling Tower Model**

The model was developed for a mechanical draft countercurrent cooling tower, with air entering at the bottom and leaving at the top and cooling water entering at the top and leaving at the bottom of the cooling tower. The main assumption of the model was that

the flowrate of the cooling water remains constant from the top to the bottom of the tower. The information that is required for the model is as follows. The inlet conditions of water, i.e. temperature and flowrate, which corresponds to the exit conditions from the cooling water network.

- (i) The exit cooling water conditions, which corresponds to the inlet conditions to the cooling tower network.
- (ii) The inlet air conditions, which includes temperature, flowrate and humidity.

The cooling tower model equations are shown below.

$$T_i = f(T_G, T_L, W, G) \quad (5.1)$$

$$T_L = f(T_i, L, G, T_G) \quad (5.2)$$

$$T_G = f(T_i, G) \quad (5.3)$$

In Equations 5.1, 5.2 and 5.3,  $T_i$  is the interface temperature,  $T_L$  is the cooling water temperature,  $W$  is the humidity,  $L$  is the cooling water flowrate and  $G$  is the dry air flowrate.

The detailed equations used in the model are given in Appendix A. Microsoft Excel was used to develop the model, and the third order Runge-Kutta method was used to solve the ordinary differential equations. Using the third order Runge-Kutta method ensured that the cooling tower was divided into four equal segments. Equations 5.1 to 5.3 above show that  $T_i$ ,  $T_G$  and  $T_L$  are interrelated. Therefore, two of the three variables must be specified

to determine the third. The calculations were started at the bottom of the cooling tower where the inlet air and exit cooling water conditions were known. An initial value of  $T_i$  at the bottom of the cooling tower was assumed and used to calculate the change of the air humidity, air and cooling water temperatures with the cooling tower height. Then, these values were used to calculate the interface temperature ( $T_{i,cal}$ ) and this value was compared to the initial value assumed ( $T_i$ ). When the absolute difference between the two temperatures was greater than  $0.01^\circ\text{C}$ ,  $T_i$  was replaced by a new value of  $T_i$ , i.e.  $T_{i,cal}$ , and calculation redone until the convergence criterion was satisfied. When the absolute difference was less than  $0.01^\circ\text{C}$ , then calculations for the conditions at the end of the segment were calculated using the linearised differential equations for humidity ( $W$ ), air temperature ( $T_G$ ) and cooling water temperature ( $T_L$ ). These values were then used as the initial conditions of the subsequent segment.

The procedure was repeated until the conditions at the end of the fourth segment at the top of the cooling tower were predicted. This process is represented by the inner loop in Figure A.2 in Appendix A. When the conditions at the top of the tower were established, the calculated inlet cooling water temperature ( $T_{L2,cal}$ ) was compared with the initial inlet cooling water temperature ( $T_{L2}$ ) used. When the absolute difference between the two temperatures was above  $0.05^\circ\text{C}$ , a new value of the exit cooling water temperature ( $T_{L1}$ ) was assumed. The calculations were then restarted at the bottom of the cooling tower predicting the new conditions at the end of each segment, until the convergence criterion was reached.

Moreover, the model also included Equations 5.4, 5.5 and 5.6 for calculating evaporation ( $E$ ), blowdown ( $B$ ) and makeup ( $M$ ), respectively (Perry, 1997).

$$E = 0.00085(1.8)F_2(T_2 - T_1) \quad (5.4)$$

$$B = \frac{E}{CC - 1} \quad (5.5)$$

$$M = E + B \quad (5.6)$$

The results obtained using this model are discussed in the next section of this chapter.

### 5.3 Discussion

#### *Application to illustrative example*

The example used by Kim and Smith (2001) was adapted from Bernier (1994). The cooling tower model was for a laboratory size cooling tower. However with the necessary information it can be easily adapted to full scale cooling towers. The data used in the model is shown in Table 5.1 below.

*Table 5.1* Illustrative example cooling tower data

Parameter	Value
Cooling tower height ( $z$ )	0.5 m
Cooling tower cross sectional area ( $A$ )	0.2 m <sup>2</sup>
Humidity of air ( $W$ )	0.01 kg of water /kg of air
Wet Bulb temperature ( $T_{WB}$ )	15.8 °C
Cooling water inlet temperature ( $T_{L2}$ )	36.7 °C
Cooling water outlet temperature ( $T_{L1}$ )	19.83 °C
Cooling water flowrate ( $m_L$ )	0.2 kg/s
Air flowrate ( $m_G$ )	0.67 kg/s

Given the above information, the first step was to obtain  $T_{L2,cal}$  using the inner loop of model as shown in Figure A.2. When the exit cooling water temperature ( $T_{L1}$ ) at the bottom of the cooling tower was set at  $19.83^{\circ}\text{C}$ , the calculated value of the inlet temperature  $T_{L2, cal}$  was  $38^{\circ}\text{C}$ . This was 3.6% higher than the initial inlet cooling water temperature, ( $T_{L2}=36.7^{\circ}\text{C}$ ) given in literature. (Refer to Appendix B1 for the model). Considering the outer loop in Figure A.2, iterations using different values of exit cooling water temperature ( $T_{L1}$ ) indicated that a  $T_{L1}$  value equal to  $19.59^{\circ}\text{C}$  corresponded to an inlet cooling water temperature ( $T_{L2}$ ) value of  $36.7^{\circ}\text{C}$ . The error in the predicted exit cooling water value was 1.2% less than the actual value given in literature. (Refer to Appendix B2 for the model.)

Considering results from the literature example, the model was deemed reasonably accurate and was thus used to predict the air and cooling water conditions of a case study cooling tower. This is discussed below.

#### *Application to case study*

The cooling tower modeled is part of the cooling water system of unit 11 at AEL, Modderfontein. It is connected to the cooling water network discussed in Chapter 4 of this thesis. The cooling water system has two cooling towers that are operated individually. The cooling water and the air in the cooling tower are in countercurrent flow. The water lost in the cooling tower due to evaporation, blowdown and drift is replaced by a cooling water makeup stream. The cooling tower is currently running at 6

cycles of concentration ( $CC$ ). The data which was available for the cooling towers is shown in Table 5.2 below.

Table 5.2 Case study cooling tower data

Parameter	Value
Air humidity ( $W$ )	0.012 kg water/kg air
Cooling water inlet temperature ( $T_{L2}$ )	34 °C
Cooling tower exit temperature ( $T_{L1}$ )	24 °C
Cooling water flowrate ( $F$ )	3 900 ton/hr

The information shown in Table 5.2 above is insufficient to model the cooling tower thus several assumptions were made to obtain the missing data. Firstly, the heat and mass transfer coefficients of the cooling tower were not available thus it was not possible to model the cooling tower accurately using its actual dimensions since the heat transfer coefficients are dependent on the cooling tower dimensions. The heat and mass transfer equations given in literature are for a laboratory size cooling tower (0.5 m high) which is much smaller than the case study cooling tower (14 m high). Heat and mass transfer coefficients are normally obtained experimentally (Coulson and Richardson, 1996). It was thus assumed that the two cooling towers were geometrically similar and the dimensions of the literature example were used to model the case study cooling tower. Since the same dimensions were used in both the literature example and the case study models, the same equations for predicting the heat and mass transfer coefficients were used. Secondly, the air flowrate was not known and thus the model was used to calculate the optimum air flowrate using the original cooling tower data available. The optimum air flowrate was that for which, when the inlet cooling water temperature ( $T_{L2}$ ) at the top of

the cooling tower was 34°C, the exit temperature at the bottom of the tower ( $T_{LI}$ ) was 24°C. These are the current cooling water conditions of the cooling tower as shown in Table 5.2. The optimum air flowrate obtained was 4 175 ton/hr. (Refer to Appendix B3). The results from the optimized cooling water network presented in Chapter 4 were applied to the cooling tower model to assess the effect of the reduced cooling water flowrate on the exit and inlet cooling water temperatures. The optimized cooling water network showed there is a potential for reducing the overall cooling water requirement from 3900 ton/hr to 2984 ton/hr with a slight increase in the inlet temperature to the cooling tower ( $T_{L2}$ ) from 34°C to 37°C. The new cooling water flowrate and temperature were used in the model. When using the inner loop of the model, the results showed that when  $T_{LI}$  was 24°C,  $T_{L2}$  obtained at the top of the cooling tower was 39.3°C. This was 46.3% higher than the initial inlet cooling water temperature ( $T_{L2} = 37^\circ\text{C}$ ). (Refer to Appendix B4). Further iteration using the outer loop of the model showed that when  $T_{LI}$  was 23.4°C,  $T_{L2}$  was 37°C. The exit cooling water temperature at the bottom of the tower was 2.5% less than the one given initially ( $T_{LI} = 24^\circ\text{C}$ ). (Refer to Appendix B5).

The effects of the reduced cooling water flowrate and increased inlet temperature on the evaporation, blowdown, makeup streams was also assessed. The results from the model are shown in Table 5.3 below.

*Table 5.3* Evaporation, blowdown and makeup flowrates

	<b>Current</b>	<b><math>T_{L1}=24^\circ\text{C}</math>, <math>T_{L2}=39.3^\circ\text{C}</math></b>	<b><math>T_{L1}=23.4^\circ\text{C}</math>, <math>T_{L2}=37^\circ\text{C}</math></b>
E (ton/hr)	60	69.9	62.6
B ( ton/hr)	23.5	14.0	12.5
M (ton/hr)	83.5	83.9	75.2

The results in Table 5.3 indicate that when the cooling water outlet temperature ( $T_{LI}$ ) is  $24^{\circ}\text{C}$  and the inlet temperature to the cooling tower is  $39.3^{\circ}\text{C}$  (inner loop of the model), the evaporation rate increases by 16.5% and the blowdown rate is reduced by 40%. Thus the overall makeup stream required is reduced by 3.6% due to the lower blowdown rate. When using the optimum results ( $T_{LI}=23.4^{\circ}\text{C}$  and  $T_{L2} = 37^{\circ}\text{C}$ ), the evaporation rate is increased slightly (4%) and the blowdown rate is reduced by 47%. This implies that the makeup stream is reduced by 10%. Thus the overall cooling water effluent produced and cooling water consumption are both reduced by using the lower flowrate. Further analysis of the blowdown rate, based on the current flowrate and temperature conditions indicated that the cooling tower has a much higher blowdown rate than what it is supposed to be. According to Equation 5.5 at 6 cycles of concentration, the blowdown rate is supposed to be 12 ton/hr.

#### 5.4 Conclusions

The results indicate that the model is a fair representation of what takes place in a cooling tower in reality. The optimum case study model results show that when the inlet cooling water temperature ( $T_{L2}$ ) is  $37^{\circ}\text{C}$ , the exit temperature ( $T_{LI}$ ) is reduced slightly from  $24^{\circ}\text{C}$  to  $23.4^{\circ}\text{C}$ , which implies there is more cooling and thus the cooling tower performance is increased. The current blowdown rate at the facility is much higher than what it is supposed to be. There is a potential to reduce the amount of effluent by 47% and cooling water makeup by 10%. The results of this model must be verified using the actual cooling tower dimensions and the actual heat and mass transfer coefficients before this model is applied in practice.

The accuracy of the results presented in this thesis are dependent on the accuracy of the limiting cooling water data used. The systematic technique for extracting the limiting cooling water data from the hot process stream data could not be used as explained in Chapter 4 of this thesis. Based on the information that was made available, the results in this thesis are fairly accurate.

Although the actual dimensions of the cooling tower where not used, the results presented in this thesis are a fair representation of what actually takes place in the cooling tower. For cooling towers which are geometrically similar, it would be easy to scale up from the laboratory size results to the full scale cooling tower without any problems.

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*Conclusions and Recommendations*

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The conclusions that can be drawn from the research study conducted are discussed below.

1. Since the introduction of Pinch Analysis in the late 1970s, it has been applied to situations beyond energy savings. Its success in heat exchanger network design led to its application in mass exchanger networks, then to wastewater minimization and most recently to cooling water system design.
2. The major drawback in most of the research work that has been conducted in the field of cooling water system design is that the components of the system are designed as separate entities. Recently, research has been done to combat this drawback and the most significant work in this regard was done by Kim and Smith, (2001). Since then, more work has been done to improve the design of cooling water systems as a holistic entity. The work has concentrated on cooling water systems which have one cooling water source. However, in reality one almost always encounters a situation where there are multiple cooling water sources supplying a set of cooling water using operations.
3. Analyzing a system with multiple cooling water sources discretely results in higher cooling water requirements. A graphical technique for setting targets in systems comprising multiple cooling towers has been developed. Its performance has been

demonstrated using an illustrative example system with two cooling water sources and four cooling water using operations whereby it reduced the cooling water requirement by 13%. Although this method has been demonstrated on systems with two cooling water sources, it can be readily applied to more complex systems with more than two cooling water sources. The adaptation of the methodology to a special system has also been demonstrated through a case study, where the cooling water requirement was reduced by 23%.

4. To obtain the optimum solution when using multiple cooling towers with different supply temperatures, all the cooling water from the primary source should be used first before using water from any other cooling water source. The target for the cooling tower with the highest supply temperature is set by the pinch.
5. When the new methodology was applied to an existing nitric acid production facility, results showed that there exists a potential to reduce the overall cooling water requirement from 3900 ton/hr to 2984 ton/hr, i.e. 23% reduction. This reduction is concomitant with a slight increase in the return temperature from 34°C to 37°C.
6. The cooling tower model developed by Kim and Smith (2001) was used to demonstrate that the high return temperature of 37°C obtained with the new cooling water network would not adversely affect the supply temperature to the cooling water network. The results from the model indicated that when the return temperature was 37°C, the inlet cooling water temperature to the cooling water

network was 23.4°C. This is lower than the current value of 24°C, which shows that more heat is removed by the cooling tower, thus the performance of the cooling tower is improved.

7. The model was also used to investigate the impact of the new cooling water flowrate on the effluent production and the requirement of cooling water makeup. The results obtained showed that there exists a potential to reduce the blowdown rate by 47% and the freshwater makeup by 10%.

Based on the conclusions given above, the following recommendations can be made.

1. Heat exchanger network design (HEN) should be done prior to designing the cooling water network, to investigate the possibility of reducing the overall amount of external utilities that are required by the process thus saving energy and reducing operating costs.
2. The controllability and pressure drop implications of the new cooling water network design should be investigated before the design is implemented.
3. The cycles of concentration of the cooling tower have a significant impact on the amount of effluent produced, thus the optimal value should be investigated as another way of reducing the amount of effluent produced.

4. The graphical technique presented in this thesis is such that the return temperature is not fixed, i.e. there is no limit to the value of the return temperature. In reality, one finds that the maximum return temperature is set by either fouling considerations, corrosion or design considerations of the cooling tower packing. In these instances, the final water supply line is set by the maximum acceptable return temperature. It is possible that this line would not form a pinch with the limiting cooling water composite curve, thus it will not be possible to obtain the minimum cooling water requirement directly. The water mains method presented is based on the concept of the pinch point and can not be readily applied to cases where there is no pinch. In this case, the pinch migration method suggested by Kim and Smith (2001) can be adopted. In this method, the limiting cooling water composite curve is allowed to move along the temperature axis until a new pinch is formed. The details of how to find the new pinch point and how to modify the composite curve are given in Kim and Smith (2001). The pinch migration and temperature shift method enables design with any target temperature (Kim and Smith, 2001). The cooling water flowrate obtained this way may be minimum but not necessarily optimal.
  
5. The graphical technique as presented in Chapter 3 of this thesis assumes that premixing and post mixing are acceptable. Premixing refers to a situation where, cooling water from different cooling water sources is mixed before it is used in any water using operation. Post mixing refers to a situation where cooling water which has been used in the cooling water using operations is mixed before it is returned to the cooling water sources. There may exist situations where premixing is not

acceptable due to geographical constraints or maximum supply temperature acceptable. Moreover, there may be situations where post mixing is not allowed due to the maximum return temperatures acceptable for the various cooling water sources or due to the process layout. For these reasons, there is a need to investigate a way of incorporating these constraints to the graphical technique. However, it is possible to set these constraints when mathematical formulation is used.

6. To improve on the cooling tower model, the effects of loss of water via evaporation and drift should be incorporated in the model. This could mean striking a balance between a representation close to what actually takes place inside the cooling tower and a complex model. The principles used in the models by Milosavljevic and Heikkilä (2001) and Khan and Zubair (2001) could be used as the starting point.

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**Cooling Tower Model**

The cooling tower model used was adapted from Kim and Smith (2001). The equations used were derived based on the control volumes shown in Figure A.1 below.

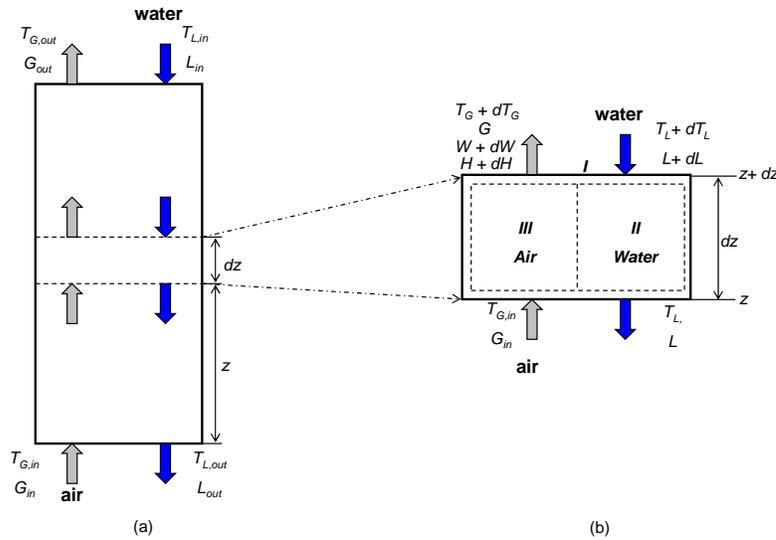


Figure A.1 Cooling tower control volume

The one dimensional model was developed to illustrate the working principles and to predict the cooling tower efficiency. The model is simple and reasonably accurate. The main assumptions of the cooling tower model are as follows.

1. Adiabatic operation in the cooling tower.
2. Dry air and water flowrate are constant.
3. Drift and leakage losses are negligible.
4. The location of the air fans has no effect.
5. Interfacial areas are equal for heat and mass transfer.
6. No influence of temperature on the transfer coefficient

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7. Thermodynamic properties are constant across the cross section of the tower.

Figure A.1(b) shows the three control volumes used to derive the equations. The phenomenon of mass and heat transfer was modeled as the product of transfer coefficients and the driving force based on interface temperature. To find the interface temperature, heat balances are set up for overall control volume (I), water (II) and airside (III).

Control volume (I)

$$\underline{\text{Enthalpy in}} = GH + C_{PL}(L + dL)(T_L + dT_L - T_0)$$

$$\underline{\text{Enthalpy out}} = LC_{PL}(T_L - T_0) + G(H - dH)$$

In the above equations:

$$\underline{dH = C_s dT_G + (C_{PA}(T_G - T_0) + l_0) dW}$$

$$\underline{LC_{PL}dT_L = GC_s dT_G + G(C_{PA}(T_G - T_0) - C_{PL}(T_L - T_0) + \lambda_0) dW} \quad \text{(A.1)}$$

Control volume (II)

$$\underline{\text{Enthalpy in}} = C_{PL}(L + dL)(T_L + dT_L - T_0) - GdWC_{PL}(T_i - T_0)$$

$$\underline{\text{Enthalpy out}} = LC_{PL}(T_L - T_0)$$

$$\underline{\text{Heat transfer}} = h_L a (T_i - T_L) dz$$

In the above equations:

$$dWdT_L \approx 0$$

$$LC_{PL}dT_L = (GC_{PL}dW - h_Ladz)(T_i - T_L) \quad (A.2)$$

Control volume (III)

$$\text{Enthalpy in} = GH \quad \text{,}$$

$$\text{Enthalpy out} = G(H + dH) - GdW(C_{PA}(T_G - T_0) + \lambda_0) \quad \text{,}$$

$$\text{Heat transfer} = h_Ga(T_i - T_G)dz$$

$$GC_SdT_G = h_Ga(T_i - T_G)dz \quad (A.3)$$

When the above equations are rearranged, the equation of the interface temperature is obtained.

$$T_i - T_L = \frac{GC_S \left( \frac{dT_G}{dz} \right) + G(C_{PA}(T_G - T_0) - C_{PL}(T_L - T_0) + \lambda_0) \left( \frac{dW}{dz} \right)}{GC_S \left( \frac{dW}{dz} \right) - h_La} \quad (A.4)$$

From Equation A.4 above it can be seen that, to determine the interfacial temperature, the differential value of the humidity and air temperature is required. Air humidity, which represents mass transfer of water vapour from the interface to the air, is obtained using Equation A.5 below.

$$\frac{dW}{dz} = \frac{k_Ga}{G}(W_i - W) \quad (A.5)$$

Water and air temperatures are also represented in a similar way as shown in Equation A.6 and A.7, respectively.

$$\frac{dT_L}{dz} = \frac{h_L a}{LC_{PL}} (T_L - T_i) \quad \text{(A.6)}$$

$$\frac{dT_G}{dz} = \frac{h_G a}{GC_s} (T_i - T_G) \quad \text{(A.7)}$$

Equation A.6 represents heat transferred from water to the interface and Equation A.7 represents heat transferred from the interface to the air. These differential equations need the value of interface temperature. But the differential increments of humidity and air are also needed to calculate the interface temperature in Equation A.4. This means an iterative method is necessary to obtain the value of the interface temperature in the model. Furthermore, additional information was used to obtain the absolute humidity at the interface as well as the vapour pressure.

$$W_i = \frac{M_w p_s}{M_a (P - p_s)} \quad \text{(A.8)}$$

$$p_s = e^{\left\{ A_0 - \frac{B_0}{C_0 + T} \right\}} \quad \text{(A.9)}$$

$A_0 = 23.7093, B_0 = 4111, C_0 = 237.7$  for  $0^\circ\text{C} < T < 57^\circ\text{C}$

$A_0 = 23.1863, B_0 = 3809.4, C_0 = 226.7$  for  $57^\circ\text{C} < T < 135^\circ\text{C}$

The heat and mass transfer coefficients used for the air water system, are presented as a function of air and water flowrates as shown in Equations A.10 to A.12.

$$h_G a + 3.0L^{0.26} G'^{0.72} C_S \tag{A.10}$$

$$h_L a = 10400L^{0.51} G'^{1.00} \tag{A.11}$$

$$k_G a = 2.95L^{0.26} G'^{0.72} \tag{A.12}$$

Figure A.2 shows the flowchart for the model.

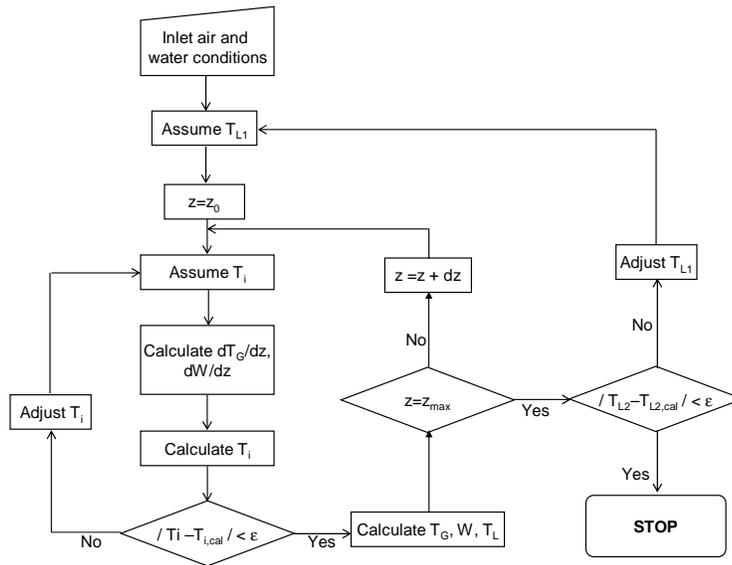


Figure A.2 Flowchart for the cooling tower model

This model finds conditions of the exit water and air when the inlet air and water conditions are given. First, the exit water temperature ( $T_{L1}$ ) is assumed and then numerically integrated from the bottom to the top of the tower. The third order Runge-Kutta method is used to solve the ordinary differential equations. The role of the inside loop in Figure A.2 is to find the interface temperature at every differential increment. The

calculated inlet temperature ( $T_{L2,cal}$ ) is compared with the real inlet temperature ( $T_{L2}$ ). The value of the exit temperature ( $T_{L1}$ ) is updated if the condition is not satisfied. The whole procedure is repeated until the convergence criterion is satisfied. The additional equations used to calculate the evaporation, blowdown and makeup are shown in Equations A.13 to A.15 (Perry, 1997).

$$E = 0.00085(1.8)F_0(T_{L2} - T_{L1}) \quad \text{(A.13)}$$

$$B = \frac{E}{CC - 1} \quad \text{(A.14)}$$

$$M = E + B + D \quad \text{(A.15)}$$

In Equation A.15,  $D$  represents drift loss.

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## Mathematical modelling for cooling towers

### Assumptions

1. Adiabatic operation in the cooling tower
2. Dry air and water flowrate are constant
3. No drift or leakage loss
4. The location of the air fan has no effect
5. Interfacial areas are equal for heat and mass transfer
6. No influence of temperature on the transfer coefficients
7. Thermodynamic properties are constant across the cross section of the tower

## Changes should be made on this part of the model

### Notation

$m_G$	flow rate of air, kg/s
$m_L$	flow rate of water, kg/s
$G$	dry air flowrate, kg/s.m <sup>2</sup>
$L$	water flowrate, kg/s.m <sup>2</sup>
$C_s$	humid heat capacity of air, kJ/kg.°C
$T_{G1}$	inlet temperature of air, °C
$T_0$	reference temperature, °C
$T_{L1}$	exit(from cooling tower) temperature of water, °C
$T_{L2}$	inlet(into cooling tower) temperature of the water, °C
$T_i$	temperature at the interface, °C
$z$	height of cooling tower, m
$C_{PA}$	heat capacity of air, kJ/kg.°C
$C_{PL}$	heat capacity of water, kJ/kg.°C
$W$	air humidity, kg water/kg air
$W_i$	air humidity at the interface, kg water/kg air
$h_L$	heat transfer coefficient of water, kW/m <sup>2</sup> .°C
$a$	interfacial area per unit volume of column, m <sup>2</sup> /m <sup>3</sup>
$\lambda_0$	latent heat of vapourisation, kJ/kg
$k_G$	mass transfer coefficient of air, m/s
$M_W$	molecular weight of water, kg/kgmole
$M_{Air}$	molecular weight of air, kg/kgmole
$P$	total Pressure, (Pa)
$Z$	Tower height, m
$A$	Tower cross section area, m <sup>2</sup>

## No editing on this part of the model

### MODEL

Assumed value of  $T_{L1}$

Assumed value of  $T_i$

Assumed value of  $W$

$\varepsilon$

$C_s$

$\lambda_0$

$C_{PL}$

$C_{PA}$

$A_0$

$B_0$

$C_0$

$P$

$M_W$

$M_{air}$

$G$

$L$

$$h_L a = 1.04 \times 10^4 L^{0.51} G^1$$

$$k_G a = 2.95 L^{0.26} G^{0.72}$$

$$h_G a = 3 L^{0.26} G^{0.72}$$

$$p_s = \exp(A_0 - (B_0 / (C_0 + T_i)))$$

$$W_i = M_W p_s / (M_{air} (P - p_s))$$

$$dT_G/dz = h_G a (T_i - T_{G1}) / GC_s$$

$$dW/dz = k_G a / G^* (W_i - W)$$

$$dT_L/dz = h_L a (T_{L1} - T_i) / LC_{PL}$$

$$T_{i,cal} = T_{L1} + (GC_s (dT_G/dz) + G \{ C_{PA} (T_{G1} - T_0) - C_{PL} (T_{L1} - T_0) + \lambda_0 \} (dW/dz)) / [GC_{PL} (dW/dz) - h_L a]$$

$$T_i - T_{i,cal}$$

Calculations of  $T_G$ ,  $W$ ,  $T_L$  done by solving the ordinary differential equations using Runge-Ku  
Third Order Runge Kutta Method

$dT_G/dz = h_G a (T_i - T_G) / GC_s$  - Calculation of  $T_G$

$$dT_G/dz = f(T_G)$$

$h$

Step 4

$T_{G3}$

$$k_0 = hf(T_{G3})$$

$$k_1 = hf(T_{G3} + 1/2 k_0)$$

$$k_2 = hf(T_{G3} + 2k_1 - k_0)$$

$$T_{G4} = T_{G3} + 1/6 (k_0 + 4k_1 + k_2)$$

$dW/dz = k_G a / G^* (W_i - W)$ , - Calculation of  $W$

$$dW/dz=f(W)$$

$h_1$

Step 4

$W_3$

$$x_0=h_1f(W_3)$$

$$x_1=h_1f(W_3+1/2x_0)$$

$$x_2=h_1f(W_3+2x_1-x_2)$$

$$W_4=W_3+1/6(x_0+4x_1+x_2)$$

$$dT_L/dz=h_L a(T_L - T_i)/LC_{PL} \text{ - Calculation of } T_L$$

$$dT_L/dz=h_L a(T_L - T_i)/LC_{PL}$$

$$dT_L/dz=f(T_L)$$

$h_2$

Step 4

$T_{L0}$

$$y_0=h_2f(T_{L3})$$

$$y_1=h_2f(T_{L3}+1/2y_0)$$

$$y_2=h_2f(T_{L3}+2y_1-y_0)$$

$$T_{L4}=T_{L3}+1/6(y_0+4y_1+y_2)$$



Error in the model (%)

### Calculation of z using the number of steps in Runge-Kutta method

n

h

z=nh

### Calculations of z done by integration

Using  $dT_G/dz$

$$\frac{dT_G}{dz} = \frac{h_G a}{GC_s} (T_i - T_G)$$

k

$$k = \frac{h_G a}{GC_s}$$

$$\int \frac{1}{T_i - T_G} dT_G = \int 2.138 dz$$

$$\Rightarrow -LN(T_i - T_G) = 2.138z + c$$

Using initial conditions to get c

$T_G$

$T_i$

$z_0$

$$c = -LN(T_i - T_G)$$

$$\Rightarrow -LN(T_i - T_G) = 2.138z - 2.070$$

Using final conditions to get z

$T_G$

$T_i$

$T_i - T_G$

$$z = \frac{2.070 - \ln(T_i - T_G)}{2.138}$$



$z$

### Using dW/dz

$$\frac{dW}{dz} = \frac{k_G a}{G} (W_i - W)$$

$$\frac{k_G a}{G}$$

$$\int \frac{1}{W_i - W} dW = \int 2.103 dz$$

$$\Rightarrow -\ln(W_i - W) = 2.103z + c$$

Using initial conditions to get c

$W$

$W_i$

$z_0$

$c$

$$-\ln(W_i - W) = 2.103z + 4.73$$

$$\Rightarrow$$

Using final conditions to get z

$W$

$W_i$

$W_i - W$

$z$

$$z = \frac{-\ln(W_i - W) - 4.73}{2.103}$$



**Using  $dT_L/dz$**

$$\frac{dT_L}{dz} = \frac{h_L a}{LCp_L} (T_L - T_i)$$

$$k = \frac{h_L a}{LCp_L}$$

$$\int \frac{1}{(T_L - T_i)} = \int 8.295 dz$$

$$\Rightarrow \ln(T_L - T_i) = 8.295z + c$$

Using initial conditions to get  $c$

$T_L$

$T_i$

$z_0$

$c$

$$\Rightarrow c = \ln(T_L - T_i)$$

$$\Rightarrow \ln(T_L - T_i) = 8.295z + 1.408$$

Using final conditions to get  $z$

$T_L$

$T_i$

$T_L - T_i$

$z$

$\Rightarrow$

$$z = \frac{(\ln(T_L - T_i) - 1.408)}{8.295}$$



one dimensional steady state

0.67  
0.2  
3.35  
1.00  
1.17 from coulson  
18.7  
25  
30.8  
36.7  
26.7  
0.5 from Bernier  
1.06 from perry  
4.2 from perry  
0.013

1233

18  
29  
1.01E+05  
0.5 from Bernier  
0.2 from Bernier

30.8

26.7
0.013
0.01
1.17
1233
4.2
1.06
23.7
4111
237.7
101325
18
29
3.35
1.00
34.84
7.04
8.38
3459
0.022
17.08
0.019
34.18
26.65
0.000
increase $T_i$
calculate TG W TL

\*divided by 1000 to convert to kW/m<sup>2</sup>.°C

Assumed T <57°C

Using the Assumed G in C18

Using the Assumed W in C25

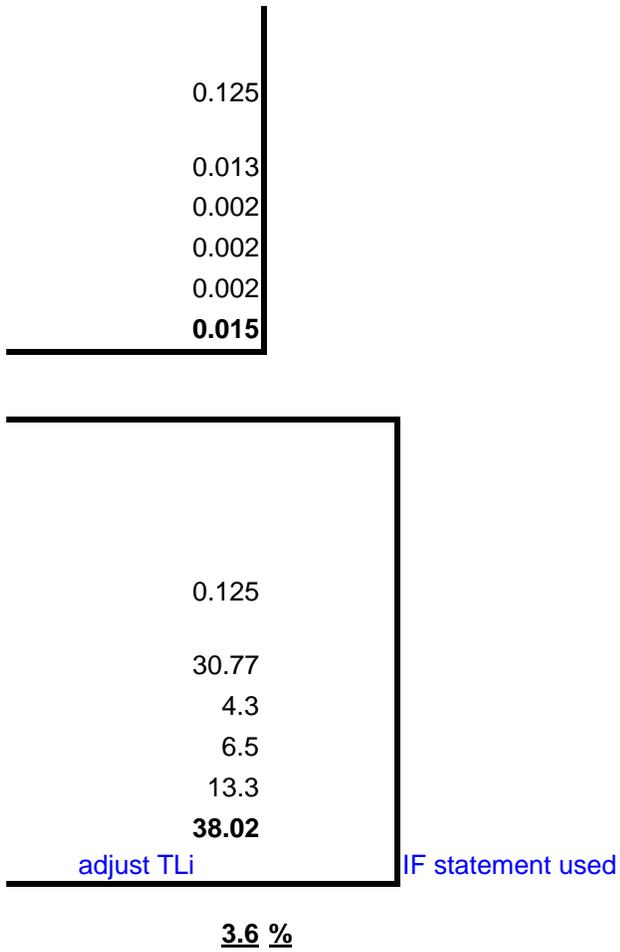
IF statement used

IF statement used

Itta method

0.125
18.7
2.135
1.850
1.717
<b>20.54</b>

--



$z_1$	$z_2$	$z_3$	$z_4$
1	2	3	4
0.125	0.125	0.125	0.125
<b>0.125</b>	<b>0.250</b>	<b>0.375</b>	<b>0.500</b>



18.7  
26.6525  
0  
-2.078

20.54  
26.6525  
6.11

0.125

2.103

0.013  
0.022  
0  
4.72

0.0151  
0.0219

0.0069

0.125

8.295

30.8

26.6525

0

1.416

38.02

26.6525

11.37

0.122



## Mathematical modelling for cooling towers

### Assumptions

1. Adiabatic operation in the cooling tower
2. Dry air and water flowrate are constant
3. No drift or leakage loss
4. The location of the air fan has no effect
5. Interfacial areas are equal for heat and mass transfer
6. No influence of temperature on the transfer coefficients
7. Thermodynamic properties are constant across the cross section of the tower

## Changes should be made on this part of the model

### Notation

$m_G$	flow rate of air, kg/s
$m_L$	flow rate of water, kg/s
$G$	dry air flowrate, kg/s.m <sup>2</sup>
$L$	water flowrate, kg/s.m <sup>2</sup>
$C_s$	humid heat capacity of air, kJ/kg.°C
$T_{G1}$	inlet temperature of air, °C
$T_0$	reference temperature, °C
$T_{L1}$	exit(from cooling tower) temperature of water, °C
$T_{L2}$	inlet(into cooling tower) temperature of the water, °C
$T_i$	temperature at the interface, °C
$z$	height of cooling tower, m
$C_{PA}$	heat capacity of air, kJ/kg.°C
$C_{PL}$	heat capacity of water, kJ/kg.°C
$W$	air humidity, kg water/kg air
$W_i$	air humidity at the interface, kg water/kg air
$h_L$	heat transfer coefficient of water, kW/m <sup>2</sup> .°C
$a$	interfacial area per unit volume of column, m <sup>2</sup> /m <sup>3</sup>
$\lambda_0$	latent heat of vapourisation, kJ/kg
$k_G$	mass transfer coefficient of air, m/s
$M_W$	molecular weight of water, kg/kgmole
$M_{Air}$	molecular weight of air, kg/kgmole
$P$	total Pressure, (Pa)
$Z$	Tower height, m
$A$	Tower cross section area, m <sup>2</sup>

## No editing on this part of the model

### MODEL

Assumed value of  $T_{L1}$

Assumed value of  $T_i$

Assumed value of  $W$

$\varepsilon$

$C_s$

$\lambda_0$

$C_{PL}$

$C_{PA}$

$A_0$

$B_0$

$C_0$

$P$

$M_W$

$M_{air}$

$G$

$L$

$$h_L a = 1.04 \times 10^4 L^{0.51} G^1$$

$$k_G a = 2.95 L^{0.26} G^{0.72}$$

$$h_G a = 3 L^{0.26} G^{0.72}$$

$$p_s = \exp(A_0 - (B_0 / (C_0 + T_i)))$$

$$W_i = M_W p_s / (M_{air} (P - p_s))$$

$$dT_G/dz = h_G a (T_i - T_{G1}) / GC_s$$

$$dW/dz = k_G a / G^* (W_i - W)$$

$$dT_L/dz = h_L a (T_{L1} - T_i) / LC_{PL}$$

$$T_{i,cal} = T_{L1} + (GC_s (dT_G/dz) + G \{ C_{PA} (T_{G1} - T_0) - C_{PL} (T_{L1} - T_0) + \lambda_0 \} (dW/dz)) / [GC_{PL} (dW/dz) - h_L a]$$

$$T_i - T_{i,cal}$$

Calculations of  $T_G$ ,  $W$ ,  $T_L$  done by solving the ordinary differential equations using Runge-Ku  
Third Order Runge Kutta Method

$dT_G/dz = h_G a (T_i - T_G) / GC_s$  - Calculation of  $T_G$

$$dT_G/dz = f(T_G)$$

$h$

Step 4

$T_{G3}$

$$k_0 = hf(T_{G3})$$

$$k_1 = hf(T_{G3} + 1/2 k_0)$$

$$k_2 = hf(T_{G3} + 2k_1 - k_0)$$

$$T_{G4} = T_{G3} + 1/6 (k_0 + 4k_1 + k_2)$$

$dW/dz = k_G a / G^* (W_i - W)$ , - Calculation of  $W$

$$dW/dz=f(W)$$

$h_1$

Step 4

$W_3$

$$x_0=h_1f(W_3)$$

$$x_1=h_1f(W_3+1/2x_0)$$

$$x_2=h_1f(W_3+2x_1-x_2)$$

$$W_4=W_3+1/6(x_0+4x_1+x_2)$$

$$dT_L/dz=h_L a(T_L - T_i)/LC_{PL} \text{ - Calculation of } T_L$$

$$dT_L/dz=h_L a(T_L - T_i)/LC_{PL}$$

$$dT_L/dz=f(T_L)$$

$h_2$

Step 4

$T_{L0}$

$$y_0=h_2f(T_{L3})$$

$$y_1=h_2f(T_{L3}+1/2y_0)$$

$$y_2=h_2f(T_{L3}+2y_1-y_0)$$

$$T_{L4}=T_{L3}+1/6(y_0+4y_1+y_2)$$



Error in the model (%)

### Calculation of z using the number of steps in Runge-Kutta method

n

h

z=nh

### Calculations of z done by integration

#### Using $dT_G/dz$

$$\frac{dT_G}{dz} = \frac{h_G a}{GC_s} (T_i - T_G)$$

$$k = \frac{h_G a}{GC_s}$$

k

$$\int \frac{1}{T_i - T_G} dT_G = \int 2.138 dz$$

$$\Rightarrow -LN(T_i - T_G) = 2.138z + c$$

Using initial conditions to get c

$T_G$

$T_i$

$z_0$

$$c = -LN(T_i - T_G)$$

$$\Rightarrow -LN(T_i - T_G) = 2.138z - 2.070$$

Using final conditions to get z

$T_G$

$T_i$

$T_i - T_G$

$$z = \frac{2.070 - \ln(T_i - T_G)}{2.138}$$



$z$

### Using dW/dz

$$\frac{dW}{dz} = \frac{k_G a}{G} (W_i - W)$$

$$\frac{k_G a}{G}$$

$$\int \frac{1}{W_i - W} dW = \int 2.103 dz$$

$$\Rightarrow -\ln(W_i - W) = 2.103z + c$$

Using initial conditions to get c

$W$

$W_i$

$z_0$

$c$

$$-\ln(W_i - W) = 2.103z + 4.73$$

$$\Rightarrow$$

Using final conditions to get z

$W$

$W_i$

$W_i - W$

$z$

$$z = \frac{-\ln(W_i - W) - 4.73}{2.103}$$



**Using  $dT_L/dz$**

$$\frac{dT_L}{dz} = \frac{h_L a}{LCp_L} (T_L - T_i)$$

$$k = \frac{h_L a}{LCp_L}$$

$$\int \frac{1}{(T_L - T_i)} = \int 8.295 dz$$

$$\Rightarrow \ln(T_L - T_i) = 8.295z + c$$

Using initial conditions to get  $c$

$T_L$

$T_i$

$z_0$

$c$

$$\Rightarrow c = \ln(T_L - T_i)$$

$$\Rightarrow \ln(T_L - T_i) = 8.295z + 1.408$$

Using final conditions to get  $z$

$T_L$

$T_i$

$T_L - T_i$

$z$

$\Rightarrow$

$$z = \frac{(\ln(T_L - T_i) - 1.408)}{8.295}$$



one dimensional steady state

0.67  
0.2  
3.35  
1.00  
1.17 from coulson  
18.5  
25  
29.9  
36.7  
26.1  
0.5 from Bernier  
1.06 from perry  
4.2 from perry  
0.013

1233

18  
29  
1.01E+05  
0.5 from Bernier  
0.2 from Bernier

29.9

26.1
0.013
0.01
1.17
1233
4.2
1.06
23.7
4111
237.7
101325
18
29
3.35
1.00
34.84
7.04
8.38
3341
0.021
16.17
0.017
32.10
26.0622
0.000
decrease $T_i$
calculate TG W TL

\*divided by 1000 to convert to kW/m<sup>2</sup>.°C

Assumed T <57°C

Using the Assumed G in C18

Using the Assumed W in C25

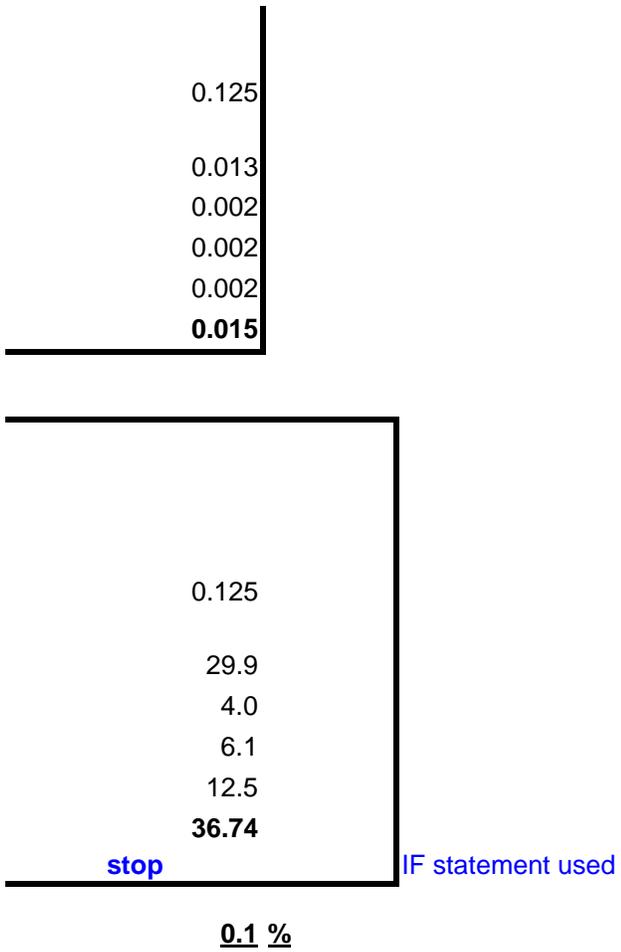
IF statement used

IF statement used

Itta method

0.125
18.5
2.021
1.751
1.626
<b>20.3</b>

--



$z_1$	$z_2$	$z_3$	$z_4$
1	2	3	4
0.125	0.125	0.125	0.125
<b>0.125</b>	<b>0.250</b>	<b>0.375</b>	<b>0.500</b>



18.5  
26.0626  
0  
-2.023

20.28  
26.0626  
5.79

0.125

2.103

0.013  
0.021  
0  
4.79

0.0148  
0.0212

0.0064

0.125

8.295

29.9  
26.0626  
0

1.353

36.74  
26.0626  
10.68

0.122



## Mathematical modelling for cooling towers

### Assumptions

1. Adiabatic operation in the cooling tower
2. Dry air and water flowrate are constant
3. No drift or leakage loss
4. The location of the air fan has no effect
5. Interfacial areas are equal for heat and mass transfer
6. No influence of temperature on the transfer coefficients
7. Thermodynamic properties are constant across the cross section of the tower

## Editing should be done from these cells

### Notation

$m_G$	flow rate of air, kg/s
$m_L$	flow rate of water, kg/s
$G$	dry air flowrate, kg/s.m <sup>2</sup>
$L$	water flowrate, kg/s.m <sup>2</sup>
$C_s$	humid heat capacity of air, kJ/kg.°C
$T_{G1}$	inlet temperature of air, °C
$T_0$	reference temperature, °C
$T_{L1}$	exit(from cooling tower) temperature of water, °C
$T_{L2}$	inlet(into cooling tower) temperature of the water, °C
$T_i$	temperature at the interface, °C
$z$	height of cooling tower, m
$C_{PA}$	heat capacity of air, kJ/kg.°C
$C_{PL}$	heat capacity of water, kJ/kg.°C
$W$	air humidity, kg water/kg air
$W_i$	air humidity at the interface, kg water/kg air
$h_L$	heat transfer coefficient of water, kW/m <sup>2</sup> .°C
$a$	interfacial area per unit volume of column, m <sup>2</sup> /m <sup>3</sup>
$\lambda_0$	latent heat of vapourisation, kJ/kg
$k_G$	mass transfer coefficient of air, m/s
$M_W$	molecular weight of water, kg/kgmole
$M_{Air}$	molecular weight of air, kg/kgmole
$P$	total Pressure, (Pa)
$Z$	Tower height, m
$A$	Tower cross section area, m <sup>2</sup>
$Q_{HEN}=mC_p(T_{L2}-T_{L1})$	

## No editing on this part of the model

### MODEL

Assumed value of  $T_{L1}$

Assumed value of  $T_i$

Assumed value of  $W$

$\varepsilon$

$C_s$

$\lambda_0$

$C_{PL}$

$C_{PA}$

$A_0$

$B_0$

$C_0$

$P$

$M_W$

$M_{air}$

$G$

$L$

$$h_L a = 1.04 \times 10^4 L^{0.51} G^1$$

$$k_G a = 2.95 L^{0.26} G^{0.72}$$

$$h_G a = 3 L^{0.26} G^{0.72}$$

$$p_s = \exp(A_0 - (B_0 / (C_0 + T_i)))$$

$$W_i = M_W p_s / (M_{air} (P - p_s))$$

$$dT_G / dz = h_G a (T_i - T_{G1}) / GC_s$$

$$dW / dz = k_G a / G^* (W_i - W)$$

$$dT_L / dz = h_L a (T_{L1} - T_i) / LC_{PL}$$

$$T_{i,cal} = T_{L1} + (GC_s (dT_G / dz) + G \{ C_{PA} (T_{G1} - T_0) - C_{PL} (T_{L1} - T_0) + \lambda_0 \} (dW / dz) / [GC_{PL} (dW / dz) - h_L a])$$

$$T_i - T_{i,cal}$$

Calculations of  $T_G$ ,  $W$ ,  $T_L$  done by solving the ordinary differential equations using Runge-Kutta method  
Third Order Runge Kutta Method

$dT_G / dz = h_G a (T_i - T_G) / GC_s$  - Calculation of  $T_G$

$$dT_G / dz = f(T_G)$$

$h$

Step 1

$T_{G0}$

$$k_0 = hf(T_{G0})$$

$$k_1 = hf(T_{G0} + \frac{1}{2}k_0)$$

$$k_2 = hf(T_{G0} + 2k_1 - k_0)$$

$$T_{G1} = T_{G0} + \frac{1}{6}(k_0 + 4k_1 + k_2)$$

$dW / dz = k_G a / G^* (W_i - W)$  - Calculation of  $W$

$$dW/dz=f(W)$$

$h_1$

Step 1

$W_0$

$$x_0=h_1f(W_0)$$

$$x_1=h_1f(W_0+1/2x_0)$$

$$x_2=h_1f(W_0+2x_1-x_2)$$

$$W_1=W_0+1/6(x_0+4x_1+x_2)$$

$dT_L/dz=h_L a(T_L - T_i)/LC_{PL}$  - Calculation of  $T_L$

$$dT_L/dz=h_L a(T_L - T_i)/LC_{PL}$$

$$dT_L/dz=f(T_L)$$

$h_2$

Step 1

$T_{L0}$

$$y_0=h_2f(T_{L0})$$

$$y_1=h_2f(T_{L0}+1/2y_0)$$

$$y_2=h_2f(T_{L0}+2y_1-y_0)$$

$$T_{L1}=T_{L0}+1/6(y_0+4y_1+y_2)$$



Calculation of  $z$  using the number of steps in Runge-Kutta method

$n$

$h$

$$z=nh$$

Calculations of  $z$  done by integration

Using  $dT_G/dz$

$$\frac{dT_G}{dz} = \frac{h_G a}{GC_s} (T_i - T_G)$$

$k$

$$k = \frac{h_G a}{GC_s}$$

$$\int \frac{1}{T_i - T_G} dT_G = \int 2.138 dz$$

$$\Rightarrow -LN(T_i - T_G) = 2.138z + c$$

Using initial conditions to get  $c$

$T_G$   
 $T_i$   
 $z_0$

$$c = -LN(T_i - T_G)$$

$$\Rightarrow -LN(T_i - T_G) = 2.138z - 0.94$$

Using final conditions to get z

$T_G$   
 $T_i$   
 $T_i - T_G$

$$z = \frac{0.94 - \ln(T_i - T_G)}{2.138}$$



$z$

### Using $dW/dz$

$$\frac{dW}{dz} = \frac{k_G a}{G} (W_i - W)$$

$$\frac{k_G a}{G}$$

$$\int \frac{1}{W_i - W} dW = \int 2.103 dz$$

$$\Rightarrow -\ln(W_i - W) = 2.103z + c$$

Using initial conditions to get c

$W$   
 $W_i$   
 $z_0$   
 $c$

$$\Rightarrow -\ln(W_i - W) = 2.103z + 5.73$$

Using final conditions to get z

$W$   
 $W_i$   
 $W_i - W$

$$z = \frac{-\ln(W_i - W) - 5.73}{2.103}$$



$z$

**Using  $dT_L/dz$**

$$\frac{dT_L}{dz} = \frac{h_L a}{LCp_L} (T_L - T_i)$$

$$k = \frac{h_L a}{LCp_L}$$

= >

$$\int \frac{1}{(T_L - T_i)} = \int 8.295 dz$$

$$\ln(T_L - T_i) = 8.295z + c$$

Using initial conditions to get c

$T_L$

$T_i$

$z_0$

c

= >

$$c = \ln(T_L - T_i)$$

= >

$$\ln(T_L - T_i) = 8.295z + 0.365$$

Using final conditions to get z

$T_L$

$T_i$

$T_L - T_i$

z

= >

$$z = \frac{(\ln(T_L - T_i) - 0.365)}{8.295}$$



1.40	
1.08	
7.016	
5.417	
1.17	from coulson
17.45	assumed
25	
24	from AEL information data
34	from AEL information data
22.65	
0.5	
1.06	from perry
4.2	from perry
0.012	from AEL information data

1233

18	
29	
1.01E+05	Assumed
0.5	from AEL information data
0.20	from AEL information data
45.5	kW



24
22.65
0.012
0.01
1.17
1233
4.2
1.06
23.7
4111
237.7
101325
18
29
7.02
5.42
172.72
18.61
22.15
2723
0.017
14.02
0.014
10.26
22.65
0.000
decrease $T_i$
calculate TG W TL

\*divided by 1000 to convert to kW/m<sup>2</sup>.°C

Assumed T < 57°C

Using the assumed G in C18

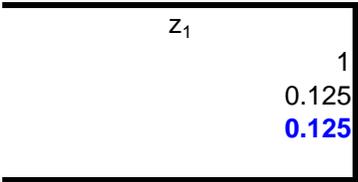
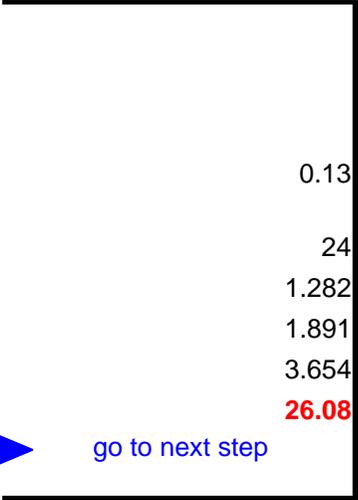
Using the assumed W in C25

IF statement used

IF statement used

ethod

0.13
17.45
1.753
1.458
1.361
<b>18.9</b>



17.45  
22.65  
0  
-1.648

18.9  
22.65  
3.71

**0.125**

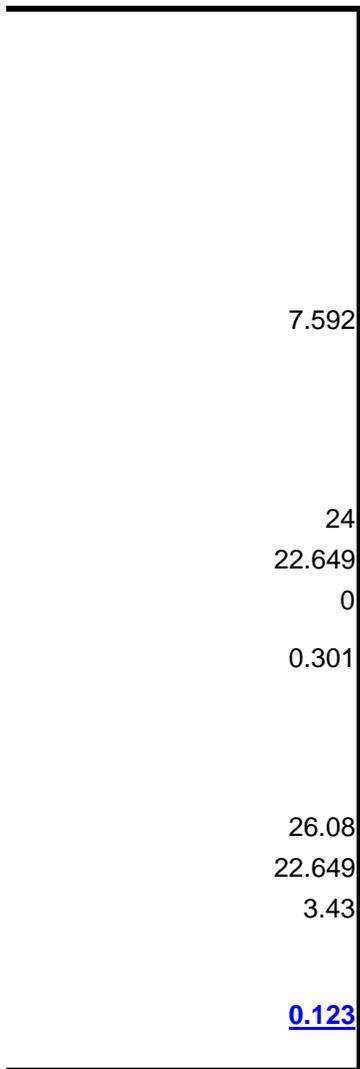
2.653

0.010  
0.017  
0  
4.94

0.0135  
0.0171  
0.0037

**0.249**





**Calculation of z using the number of steps in Runge-Kutta method**

	z1		z2
n	1		2
h		0.125	0.125
z=nh		0.125	0.25

**Calculations of z done by integration**

**Using  $dT_G/dz$**

	z1		z2
n		1	2
h		0.125	0.125
z=nh		0.125	0.250

**Using  $dW/dz$**

	z1		z2
n		1	2
h		0.260	0.147
z=nh		0.260	0.407

**Using  $dT_L/dz$**

	z1		z2
n		1	2
h		0.122	0.122
z=nh		0.122	0.244

**Calculation of evaporation, blowdown and makeup**

$F_0$	Flowrate of water in kg/hr	2984
$T_{L1}$	Exit temperature from the cooling tower	24
$T_{L2}$	Inlet temperature to the cooling tower	39.3
CC	Cycles of concentration	6

**Calculation of Evaporation loss**

$E = 0.00085 \times 1.8 F_0 (T_{L2} - T_{L1})$
$E$ <span style="float: right;"><b>69.9</b></span>

**Calculation of the Blowdown**

$$B = \frac{E}{CC - 1}$$

*B*

14.0

**Calculation of Makeup**

$$M = E + B$$

*M*

83.9

z3	z4
3	4
0.125	0.125
0.375	0.5

z3	z4
3	4
0.125	0.125
0.376	0.501

z3	z4
3	4
0.147	0.125
0.554	0.679

z3	z4
3	4
0.122	0.122
0.366	0.489

## Mathematical modelling for cooling towers

### Assumptions

1. Adiabatic operation in the cooling tower
2. Dry air and water flowrate are constant
3. No drift or leakage loss
4. The location of the air fan has no effect
5. Interfacial areas are equal for heat and mass transfer
6. No influence of temperature on the transfer coefficients
7. Thermodynamic properties are constant across the cross section of the tower

## Changes should be made on this part of the model

### Notation

$m_G$	flow rate of air, kg/s
$m_L$	flow rate of water, kg/s
$G$	dry air flowrate, kg/s.m <sup>2</sup>
$L$	water flowrate, kg/s.m <sup>2</sup>
$C_s$	humid heat capacity of air, kJ/kg.°C
$T_{G1}$	inlet temperature of air, °C
$T_0$	reference temperature, °C
$T_{L1}$	exit(from cooling tower) temperature of water, °C
$T_{L2}$	inlet(into cooling tower) temperature of the water, °C
$T_i$	temperature at the interface, °C
$z$	height of cooling tower, m
$C_{PA}$	heat capacity of air, kJ/kg.°C
$C_{PL}$	heat capacity of water, kJ/kg.°C
$W$	air humidity, kg water/kg air
$W_i$	air humidity at the interface, kg water/kg air
$h_L$	heat transfer coefficient of water, kW/m <sup>2</sup> .°C
$a$	interfacial area per unit volume of column, m <sup>2</sup> /m <sup>3</sup>
$\lambda_0$	latent heat of vapourisation, kJ/kg
$k_G$	mass transfer coefficient of air, m/s
$M_W$	molecular weight of water, kg/kgmole
$M_{Air}$	molecular weight of air, kg/kgmole
$P$	total Pressure, (Pa)
$Z$	Tower height, m
$A$	Tower cross section area, m <sup>2</sup>

## No editing on this part of the model

### MODEL

Assumed value of  $T_{L1}$

Assumed value of  $T_i$

Assumed value of  $W$

$\varepsilon$

$C_s$

$\lambda_0$

$C_{PL}$

$C_{PA}$

$A_0$

$B_0$

$C_0$

$P$

$M_W$

$M_{air}$

$G$

$L$

$$h_L a = 1.04 \times 10^4 L^{0.51} G^1$$

$$k_G a = 2.95 L^{0.26} G^{0.72}$$

$$h_G a = 3 L^{0.26} G^{0.72}$$

$$p_s = \exp(A_0 - (B_0 / (C_0 + T_i)))$$

$$W_i = M_W p_s / (M_{air} (P - p_s))$$

$$dT_G/dz = h_G a (T_i - T_{G1}) / GC_s$$

$$dW/dz = k_G a / G^* (W_i - W)$$

$$dT_L/dz = h_L a (T_{L1} - T_i) / LC_{PL}$$

$$T_{i,cal} = T_{L1} + (GC_s (dT_G/dz) + G \{ C_{PA} (T_{G1} - T_0) - C_{PL} (T_{L1} - T_0) + \lambda_0 \} (dW/dz)) / [GC_{PL} (dW/dz) - h_L a]$$

$$T_i - T_{i,cal}$$

Calculations of  $T_G$ ,  $W$ ,  $T_L$  done by solving the ordinary differential equations using Runge-Ku  
Third Order Runge Kutta Method

$dT_G/dz = h_G a (T_i - T_G) / GC_s$  - Calculation of  $T_G$

$$dT_G/dz = f(T_G)$$

$h$

Step 4

$T_{G3}$

$$k_0 = hf(T_{G3})$$

$$k_1 = hf(T_{G3} + 1/2 k_0)$$

$$k_2 = hf(T_{G3} + 2k_1 - k_0)$$

$$T_{G4} = T_{G3} + 1/6 (k_0 + 4k_1 + k_2)$$

$dW/dz = k_G a / G^* (W_i - W)$ , - Calculation of  $W$

$$dW/dz=f(W)$$

$h_1$

Step 4

$W_3$

$$x_0=h_1f(W_3)$$

$$x_1=h_1f(W_3+1/2x_0)$$

$$x_2=h_1f(W_3+2x_1-x_2)$$

$$W_4=W_3+1/6(x_0+4x_1+x_2)$$

$$dT_L/dz=h_L a(T_L - T_i)/LC_{PL} \text{ - Calculation of } T_L$$

$$dT_L/dz=h_L a(T_L - T_i)/LC_{PL}$$

$$dT_L/dz=f(T_L)$$

$h_2$

Step 4

$T_{L0}$

$$y_0=h_2f(T_{L0})$$

$$y_1=h_2f(T_{L0}+1/2y_0)$$

$$y_2=h_2f(T_{L0}+2y_1-y_0)$$

$$T_{L4}=T_{L0}+1/6(y_0+4y_1+y_2)$$



Error in the model (%)

### Calculation of z using the number of steps in Runge-Kutta method

n

h

z=nh

### Calculations of z done by integration

Using  $dT_G/dz$

$$\frac{dT_G}{dz} = \frac{h_G a}{GC_s} (T_i - T_G)$$

k

$$k = \frac{h_G a}{GC_s}$$

$$\int \frac{1}{T_i - T_G} dT_G = \int 2.138 dz$$

$$\Rightarrow -LN(T_i - T_G) = 2.138z + c$$

Using initial conditions to get c

$T_G$

$T_i$

$z_0$

$$c = -LN(T_i - T_G)$$

$$\Rightarrow -LN(T_i - T_G) = 2.138z - 2.089$$

Using final conditions to get z

$T_G$

$T_i$

$T_i - T_G$

$$z = \frac{2.089 - \ln(T_i - T_G)}{2.138}$$



$z$

### Using dW/dz

$$\frac{dW}{dz} = \frac{k_G a}{G} (W_i - W)$$

$$\frac{k_G a}{G}$$

$$\int \frac{1}{W_i - W} dW = \int 2.103 dz$$

$$\Rightarrow -\ln(W_i - W) = 2.103z + c$$

Using initial conditions to get c

$W$

$W_i$

$z_0$

$c$

$$-\ln(W_i - W) = 2.103z + 4.69$$

$$\Rightarrow$$

Using final conditions to get z

$W$

$W_i$

$W_i - W$

$z$

$$z = \frac{-\ln(W_i - W) - 4.69}{2.103}$$



**Using  $dT_L/dz$**

$$\frac{dT_L}{dz} = \frac{h_L a}{LCp_L} (T_L - T_i)$$

$$k = \frac{h_L a}{LCp_L}$$

$$\int \frac{1}{(T_L - T_i)} = \int 8.295 dz$$

$$\Rightarrow \ln(T_L - T_i) = 8.295z + c$$

Using initial conditions to get  $c$

$T_L$

$T_i$

$z_0$

$c$

$$\Rightarrow c = \ln(T_L - T_i)$$

$$\Rightarrow \ln(T_L - T_i) = 8.295z + 1.437$$

Using final conditions to get  $z$

$T_L$

$T_i$

$T_L - T_i$

$z$

$\Rightarrow$

$$z = \frac{(\ln(T_L - T_i) - 1.437)}{8.295}$$



one dimensional steady state

1.40  
0.83  
7.02  
4.14  
1.17 from coulson  
22.0  
25  
32.4  
37  
30.0  
0.5 from Bernier  
1.06 from perry  
4.2 from perry  
0.017

1233

18  
29  
1.01E+05  
0.5 from Bernier  
0.2 from Bernier

32.4

30.0
0.017
0.01
1.17
1233
4.2
1.06
23.7
4111
237.7
101325
18
29
7.02
4.14
150.68
17.36
20.66
4190
0.027
20.02
0.025
21.56
29.95
0.000
increase Ti
calculate TG W TL

\*divided by 1000 to convert to kW/m<sup>2</sup>.°C

Assumed T <57°C

Using the Assumed G in C18

Using the Assumed W in C25

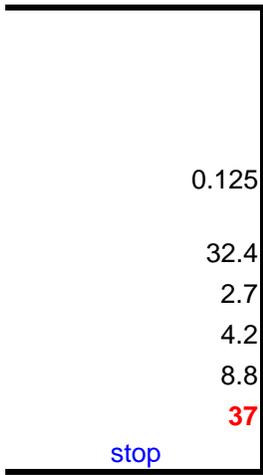
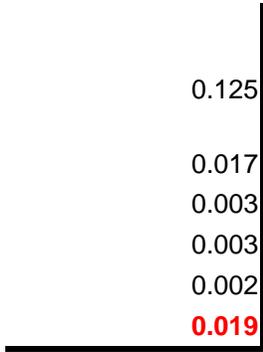
IF statement used

IF statement used

Itta method

0.125
22.0
2.502
2.108
1.962
<b>24.1</b>

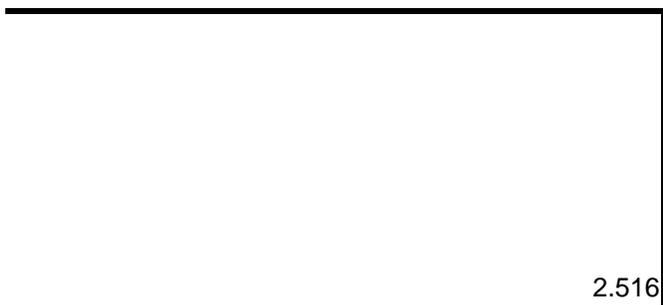
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IF statement used

0.32

$z_1$	$z_2$	$z_3$	$z_4$
1	2	3	4
0.125	0.125	0.125	0.125
<b>0.125</b>	<b>0.250</b>	<b>0.375</b>	<b>0.500</b>



22.0  
29.9503  
0  
-2.074

24.15  
29.9503  
5.80

0.125

2.474

0.017  
0.027  
0  
4.60

0.0194  
0.0268

0.0074

0.125

8.656

32.4  
29.9503  
0

0.913

37.12  
29.9503  
7.17

0.122

