# Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 9 (10): 1847-1858, 2009
ISSN 1812-5654

# Application of an Optimum Design of Cooling Water System by Regeneration Concept and Pinch Technology for Water and Energy Conservation

[1]A. Ataei, [2]M.H. Panjeshahi, [3]R. Parand and [4]N. Tahouni
[1]Department of Energy Engineering, Graduate School of the Environment and Energy,
Science and Research Branch, Islamic Azad University, Tehran, Iran
[2]Department of Chemical and Petroleum Engineering, University of Calgary, Calgary, Alberta, Canada
[3]Department of Energy Engineering, KN Toosi University of Technology, Tehran, Iran
[4]Department of Chemical Engineering, University of Tehran, Tehran, Iran

**Abstract:** In this study, using a combination of Pinch Technology and Mathematical Programming, a new technique is presented in order to grass-root design for a cooling water system to achieve minimum total annual cost. The presented technique is further improved by using patterns from the concept of regeneration recycling in water systems: in a sense that cooling water is regenerated locally by an air cooler. Moreover, in the proposed method, optimum design of cooling tower has been achieved through a mathematical model. Related coding in MATLAB version 7.3 was used for the illustrative example to get optimal values in the proposed cooling water design method computations. The result of the recently introduced design methodology was compared with the conventional and Kim and Smith design methods. The outcomes indicate that by using this new design method, more water and energy can be saved and a lower level of total annual cost can be reached.

**Key words:** Cooling tower, heat exchanger network, water reuse, mathematical programming, air cooler

## INTRODUCTION

Once-through and Re-circulating Cooling Water Systems (RCWSs) are used for the rejection of waste heat to the environment. Of these methods, RCWSs are by far the most common method, because it can conserve freshwater and reduce thermal pollution compared to once-through systems. The re-circulative cooling water system consists of the cooling tower and heat exchanger network which usually has a parallel configuration. The cooling water used in the heat exchanger network returns to the cooling tower where the hot return cooling water is cooled. Blow-down is necessary to avoid the build-up of undesirable materials in the re-circulating water as a result of evaporation. The water flowrate loss caused by evaporation and blow-down is compensated by make-up (Kim and Smith, 2001). Amount of the blow-down and make-up in each of cooling water systems are function of the evaporation loss and cycles of concentration (Kim and Smith, 2001; Smith, 2005; Kim *et al*., 2000; Panjeshahi and Ataei, 2008; Evans, 1979; Castro *et al*., 2000).

In industrial situations, not all water is fully reused or recycled in processes, even though its quality of them is good enough for reuse. For example, in steam generation systems, steam condensate loss occurs. Not all the condensate is usually recovered. The steam condensate not recovered is a good water source to reuse.

While valuable water is not recovered, the quality requirements for cooling water make-up are not generally as high as for other industrial processes. Therefore, cooling tower make-up can be changed from freshwater to reused water or wastewater, if the quality of the water is relatively good. Water consumption and wastewater generation can be reduced simultaneously when wastewater before discharge or treatment is used for cooling tower make-up. When the wastewater is added, the overall flowrate of cooling water is increased for tower operation. If the temperature of the wastewater is higher than that of the inlet cooling water, the tower may not remove the desired cooling load. When wastewater is added to the main cooling water header, cooling water systems become bottlenecked. A solution for debottlenecking can be obtained by modifying the cooling water network from the observation that the heat removal of the cooling tower is increased when reuse opportunities between coolers are increased (Fig. 1). This design methodology of cooling water networks enables an increase in the operating range of the cooling tower

---

**Corresponding Author:** Dr. Abtin Ataei, Department of Energy Engineering, Graduate School of the Environment and Energy, Science and Research Branch, Islamic Azad University, P.O. Box 14515-775, Tehran, Iran
Tel: 0098-912-5980104 Fax: 0098-21-44465383

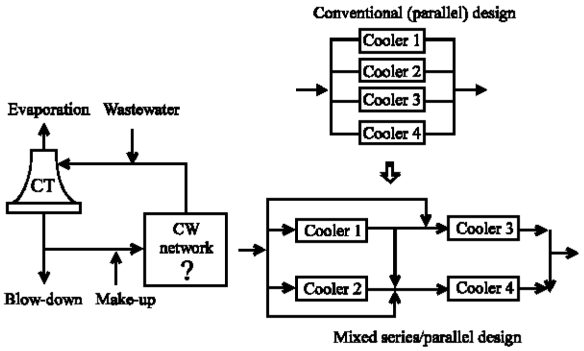

Fig. 1: New cooling water network design for wastewater minimization

and provides systematic procedures to deal with cooling tower overloading. As reuse design of cooling systems allows cooling towers to take wastewater as make-up, substituting make-up with wastewater can yield water savings, as well as reduction in aqueous emissions without overloading problems in the tower.

Water Pinch Technology, as the most common design tool, can be used for the design and synthesis of water consumption systems to achieve minimum fresh water flowrate and total annual cost. This technology is based on targeting prior to design and exploits conceptual understanding (Kim and Smith, 2001). Pinch design method has been developed through principle concepts to make opportunities for water and energy saving and reducing environmental unconstructive effects in process industries (Panjeshahi and Ataei, 2008). Earlier researches on RCWS focused on the cooling system components individually, not the system as a whole. However, a simultaneous integration of RCWS components provides opportunity to achieve the optimum design. Kim and Smith (2001) developed a systematic design methodology of RCWS, which accounts for the interactions between the cooling tower and heat exchanger network. The Kim and Smith's design method allowed the minimum cooling water flowrate to be participated in the performance parameters calculation and network configuration design, considering fix approach temperature value as the cooling tower design variable (Kim and Smith, 2001). However, the minimum cooling water flowrate through the fix approach value does necessarily ensure neither optimum value, nor the minimum cost of system. Furthermore, in this design method, only reuse of cooling water between different cooling duties was considered and another technique such as cooling water regeneration recycling by some equipment like an air cooler was not addressed. In other words, using the Kim and Smith's design method, only leads to energy saving but no water can be conserved in the RCWS.

The objective of this study was to introduce and develop a modern methodology to RCWS design, regarding the interaction between cooling tower performance and the heat exchanger network configuration, not the cooling system components individually. In this study, the Kim and Smith's design method has been modified in two stages to get optimal heat exchanger network configuration, maximum water and energy conservation and minimum cost. In the first stage, using a combination of Pinch Technology and Mathematical Programming, a technique for the integrated design of such systems was presented so that optimum flowrate with inlet and outlet temperatures of the cooling tower were adjusted to obtain minimum total annual cost. The heat exchanger network has been synthesized and designed according to the Kim and Smith's (2001) methodology. For this purpose, the objective function has been achieved through the inclusion of operational and capital cost and after applying constraints resulting from the Pinch Technology concepts in order to obtain the optimum amount of operational parameters. In the second stage, by adopting patterns from the regeneration recycling concept, presented by Smith (2005) for water systems, the local regeneration of cooling water by an air cooler was taken into account. It should be asserted that in Pinch design method, the regeneration technique has been used in mass exchanger networks plans but has not been considered in designing of heat transfer systems yet. Using this modern technique in designing of a RCWS, an air cooler is placed in the heat exchanger network, equal to a regeneration system in a mass exchanger network, to reduce the load of cooling tower. It is evident that by adding an air cooler to the elements of a RCWS, its purchase, installation and used electricity costs are added to the total annual cost. However, with proper placement of an air cooler in the heat exchanger network, the operational cost would be reduced. Consequently, the total annual cost would decline dramatically. This modern RCWS design method accounts for optimal heat exchanger network configuration, maximum water and energy conservation and minimum cost.

The result of the recently introduced design methodologies were compared with the conventional and Kim and Smith design methods through an illustrative example.

## MATERIALS AND METHODS

**Objective function:** In design targeting, the objective is to minimize the total annual cost (Kim and Smith, 2001). Consequently, the defined objective function of the introduced design methodology was to determine total annual cost of the cooling tower including operational and capital costs (Panjeshahi and Ataei, 2008). The capital cost of cooling tower is as follows:

$$CC = CC1\times1237(F_{in})^{0.79}(R)^{0.57}(A)^{-0.9924}(0.022T_{wb}+0.79)^{2.441} \tag{1}$$

As shown in Eq. 1, the capital cost in \$ year$^{-1}$, including chemical engineering index and animalization factor, a function of water flowrate in t h$^{-1}$. The approach, range and wet bulb temperature are in °C.

The design variables for the cooling tower construction are usually temperature range, approach temperature and water flowrate (Panjeshahi and Ataei, 2008). The approach is more important than the flowrate and the range in achieving a high driving force for cooling. This is because the driving force becomes more limiting as the approach becomes narrow. Since cooling performance is influenced by the water flowrate as well as other factors, a cooling water system should be targeted by considering the effect of tower performance on cooling cost (Kim and Smith, 2001; Kim *et al*., 2000).

The relationship between flowrate, approach and range in the integrated RCWS has been shown in Fig. 2. The operation cost includes the terms cooling water pumping cost, air fan operation cost, make-up water cost, cycle cooling water chemical treatment and blow-down treatment cost. For the water pumping cost, the terms pumping power, electricity cost coefficient and conversion factor are considered in the model. Air fan operation cost depends on air flowrate, electricity cost coefficient and related conversion factor. Make-up water cost is a function of water flowrate. Cooling water treatment cost also varies according to flowrate. Operating cost consists of blow-down treatment cost as well. As a matter of fact, the cooling tower wastewater should be treated to meet the environmental standard specification. The cost of blow-down treatment depends on the amount of blow-down flowrate and the cost coefficient.

Pump electricity cost is (Panjeshahi and Ataei, 2008):

$$PC = PC1\times C_{WP}\times P_P \tag{2}$$

where, PC1 represents the cost coefficient for electricity, $C_{WP}$ represents the conversion factors, and $P_p$ represents the pumping power, which is expressed as follows (Evans, 1979);

$$P_p = \frac{F_{in}h\rho}{\eta_p} \tag{3}$$

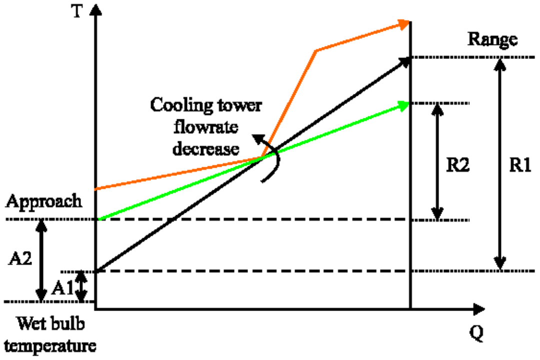

Fig. 2: The relationship between flowrate, approach and range in the integrated RCWS

As shown in Eq. 3, pumping power is in direct relation with water flowrate and with a decline in water flowrate, pump power and related electricity cost decline.

Fan electricity cost is (Panjeshahi and Ataei, 2008; Castro *et al*., 2000):

$$FC = FC1\times C_{fan}\times F_a \tag{4}$$

where, FC1 represents the cost coefficient for electricity, $C_{fan}$ represents the conversion factors and $F_a$ represents air flowrate which is expressed as follows (Kim *et al*., 2000; Panjeshahi and Ataei, 2008):

$$F_a = \frac{E}{W_{out} - W_{in}} \tag{5}$$

where, E represents evaporation loss, and $W_{in}$ and $W_{out}$ represent the absolute inlet and outlet air humidity of the cooling tower, respectively. Temperature and also outlet air humidity given by the average of the inlet and outlet temperature of water.

Evaporation loss is calculated as follows (Kim *et al*., 2000; Panjeshahi and Ataei, 2008; Evans, 1979):

$$E = 0.00153\ F_{in}\ (T_{in} - T_{out}) \tag{6}$$

Therefore, fan electricity cost is also a function of water flowrate with inlet and outlet water temperature. In an integrated RCWS, as the cooling flowrate is decreased, the range increases (Fig. 2). But as the amount of water flowrate reduction is greater than the amount of range increase; in general, with a decline in water flowrate, the fan electricity cost will decrease, resulting in cooling systems becoming bottlenecked, and requiring more air.

Chemical treatment cost of water is given by the following Eq. 7 (Panjeshahi and Ataei, 2008):

$$CHTC = CHTC1\times F_{in} \tag{7}$$

where, CHTC1 represents the annual cost of chemical treatment materials and $F_{in}$ represents inlet water flowrate to tower.

Make-up water cost and blow-down treatment cost are defined as follows (Parker, 1998):

$$CW = CW1 \times M \quad (8)$$

$$BTC = BTC1 \times B \quad (9)$$

where, CW1 and BTC1 represent, respectively, the annual cost of providing water and purchase cost of blow-down treatment materials, and M and B represent the flowrates of make-up water and blow-down.

These two parameters in series arrangement of heat exchangers do not change in relation to parallel one. But with proper placement of an air cooler in the heat exchanger network, as a reduction occurs in the load of cooling tower, the amounts of these two parameters decreases dramatically and reduce the operational cost.

In the above mentioned cost functions, the coefficient price of each term and conversion factors are regarded so that operational cost (\$ year$^{-1}$) is obtained using air flowrate, water flowrate, make-up water flowrate and blow-down flowrate (t ha$^{-1}$) and fan and pump power in kW.

The function of operational cost is as follows:

$$OC = PC+FC+CHTC+CW+BTC \quad (10)$$

Ultimately, the objective function is defined as the total annual cost. The optimization problem can be stated as follows:

$$\text{Min } TC = CC+OC \quad (11)$$

The operating cost and capital cost of the cooling tower differently affect the overall cost of cooling water systems, as shown in Fig. 3. The problem of targeting cooling water systems becomes an optimization problem to search for the optimal cooling line.

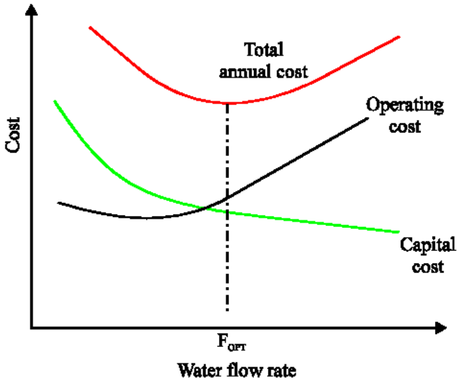

Fig. 3: Water flowrate changes and its effect on tower cost

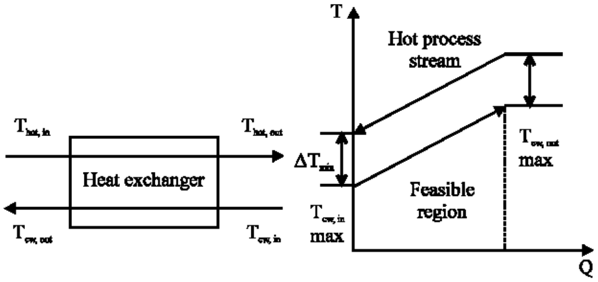

Fig. 4: Representation of heat exchangers in cooling water system design

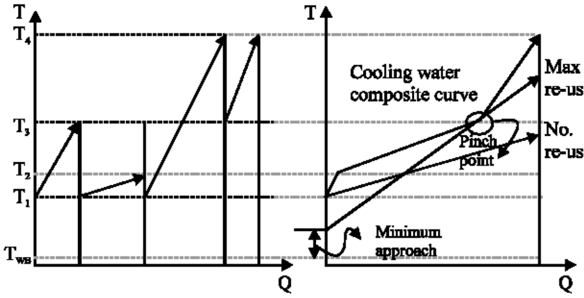

Fig. 5: Composite curve and targeting lines with minimum and maximum flowrate

**Constraints:** To establish the model constraints, first, the cooling water composite curve should be drawn. Cooling water streams depend on the heat load and the temperatures were graphed. In the cooling water network analysis, it was assumed that any cooling-water-using operation can be represented as a counter-current heat exchanger operation with minimum temperature difference (Fig. 4). All the cold streams are then summed up to figure out the composite curve (Kim *et al*., 2000). The cooling water supply line is shown for the maximum reuse of water, which means the possible series configuration of heat-exchangers. Figure 5 shows the procedure for the composite curve graph and the targets for the maximum reuse of water flowrate. The point where the target supply line touches with the composite curve creates a pinch point. The interpretation of the pinch does not imply zero driving force for the heat transfer, but it is only a minimum driving force. Upon introducing constraints, the pinch point that will not cross the composite curve should be considered. The cooling tower cannot operate at temperatures above a specific water temperature due

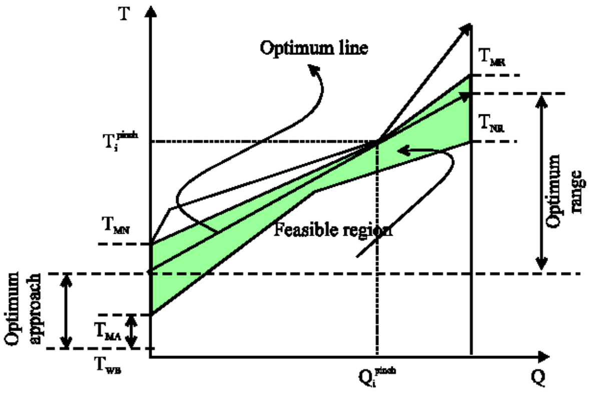

Fig. 6: Introducing feasible region and constraints

to operational problems related to cooling tower performance, such as packing decomposition. Therefore, temperature constraints should be imposed on the model. Figure 6 shows the feasible region for cooling water systems, using the optimum cooling target line located between two limits. One limit is the minimum flowrate target and the other is the maximum flowrate target line, representing a parallel configuration. The slope and inlet/outlet temperature of the target cooling line are limited by the temperature conditions and the composite curve. It should be considered that for maximum water reuse cooling supply line construction i.e., a minimum approach ($T_{MA}$), is necessary.

Heat load of cooling system is (Panjeshahi and Ataei, 2008):

$$Q = F_{in}\, C_p(T_{in} - T_{out}) \tag{12}$$

The heat load of the system does not change with the altering or the arrangement of exchangers from parallel to series: only water flowrate and inlet and outlet temperatures of the tower are changed. As seen, the relationship between heat load and temperature range is linear, the heat load of the system is fixed, an increase in temperature range is formed together with a decline in flowrate or with an increase in line slope (Fig. 6).

It should be noted that even by utilizing an air cooler as a local regenerator, the total heat load of the cooling system does not decrease but some of this load is tolerated by the air cooler instead of the tower.

Absolute inlet humidity is fixed and depends on the ambient temperature and wet bulb temperature as Eq. 13:

$$\text{Win} = \text{const} = f\,(T_{WB}, T_{amb}) \tag{13}$$

The air exiting the tower is saturated and its temperature is equal to the average of the inlet and outlet water temperature.

Outlet air temperature of the tower is defined as follows:

$$T_{air,out} = \frac{T_{in} + T_{out}}{2} \tag{14}$$

Saturation pressure of outlet air is (Lyderson, 1983):

$$P^s = \exp\left[23.71 - \frac{4111}{237.7 + T}\right] \tag{15}$$

Absolute humidity of air that leaves the tower is found by the following equation:

$$W_{out} = 0.622 \times \frac{P^s}{P - P^s} \tag{16}$$

where, P is atmosphere pressure. By placing the outlet air temperature in Eq. 15, saturation pressure of outlet air can be obtained. By placing it in Eq. 16, absolute outlet air humidity will be found.

Temperature range and approach temperature definition (Panjeshahi and Ataei, 2008):

$$R = T_{in} - T_{out} \tag{17}$$

$$A = T_{out} - T_{WB} \tag{18}$$

Blow-down and make-up are calculated as below (Mann and Liu, 1999):

$$M = E\frac{\pi_C}{(\pi_C - 1)} \tag{19}$$

$$B = \frac{E}{(\pi_C - 1)} \tag{20}$$

where, E is the evaporation loss which is found by Eq. 6 and $\pi_C$ represents cycle of concentration which is fixed and depends on the quality of make-up water. As E is in direct relation with Q, after changing the exchangers' arrangement from parallel to series, the load on the tower does not alter and amounts of blow-down and make-up water do not change.

However, by introducing an air cooler in the heat exchanger network, some of this load decreases and the afore-mentioned amounts decreases dramatically.

Equation 12 to 20 are equally constraints of the system. Now, inequality constraints are taken into account.

Feasibility constraints to avoid pinch crossing is:

$$T_{out} + R\left(\frac{Q_i^{Pinch}}{Q}\right) \le T_i^{Pinch} \tag{21}$$

Feasibility constraint on the inlet and outlet temperatures of cooling tower is:

$$T_{NR} \le T_{in} \le Min\ \{T_{MR}, T_{TL}\} \qquad (22)$$

Cooling tower water outlet temperature varies between minimum approach value, considering wet bulb temperature and the minimum temperature of water stream at heat exchanger network:

$$(T_{WB} + T_{MA}) \le T_{out} \le T_{MN} \qquad (23)$$

where, $T_{MN}$ is the minimum temperature of heat exchanger network with respect to $\Delta T_{min}$ of the network and $T_{MA}$ is the minimum cooling tower approach.

$$T_{MN} = THEN_{Min} - \Delta T_{Min} \qquad (24)$$

Feasibility constraints on the cooling water flowrate is:

$$F_{in}^{l} \le F_{in} \le F_{in}^{u} \qquad (25)$$

where, $F_{in}^{l}$ and $F_{in}^{u}$ are the upper and lower limits of the water flowrate which are expressed at water temperature feasibility area of cooling tower.

**Optimum cooling tower design model:** In a counter-flow cooling tower, the process consists of a gas phase (air) flowing upward and a liquid phase (water) flowing downwards, and a large interface between these two phases (Ataei *et al*., 2009). Figure 7 shows the cooling tower control volume. It has noted that the rate of energy transferred from the water is equal to the rate of energy gained by air (Eq. 26).

$$Q = m_a\ (h_{a,\ out} - h_{a,\ in}) \qquad (26)$$

The air flowrate of the tower can be achieved through Eq. 27:

$$m_a = \frac{m_w c_{pw}}{c_{pa}} \qquad (27)$$

The air humidity is represented by Eq. 28:

$$\frac{dw}{dz} = \frac{K_a A_{cr}}{m_a}(w_i - w) \qquad (28)$$

The absolute humidity at the interface $w_i$ is given by Eq. 29:

$$w_i = 0.622 \frac{P^s}{(P - P^s)} \qquad (29)$$

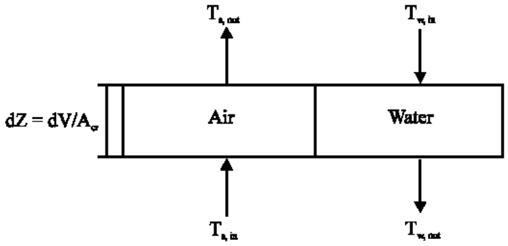

Fig. 7: Control volume of cooling tower

The air and water temperatures are given in Eq. 30 and 31 (Kim and Smith, 2001):

$$\frac{dT_w}{dz} = \frac{h_w A_{cr}}{m_w C_{pw}}(T_w - T_i) \qquad (30)$$

$$\frac{dT_a}{dz} = \frac{h_a A_{cr}}{m_a C_{pa}}(T_i - T_a) \qquad (31)$$

For the air-water system, heat and mass transfer coefficients are represented as a function of air and water flowrates. The related coefficients are given in Eq. 32-34 (Coulson *et al*., 1991):

$$K_a A_{cr} = a_1 m_a^{b1} m_w^{c1} \qquad (32)$$

$$h_w A_{cr} = a_2 m_a^{b2} m_w^{c2} \qquad (33)$$

$$h_a A_{cr} = a_3 m_a^{b3} m_w^{c3} \qquad (34)$$

The optimum heat and mass transfer area can be calculated by Eq. 35 (Söylemez, 2001; Ataei *et al*., 2009).

$$A_{i,\ opt} = \sqrt{\frac{C_E P_i m_a^3 a^3 H^2 S[6.5 + K + 2(A_{cr} / A_f)^2]}{\rho^2 \eta_f \eta_m C_v}} \qquad (35)$$

The optimum cross sectional area is given by Eq. 36:

$$A_{cr,opt} = \frac{A_{i,opt}}{aZ} \qquad (36)$$

To achieve the optimum cooling tower design, an iterative calculation is required. The computation procedure is shown in Fig. 8.

**Regeneration recycling method in water systems:** By introducing regeneration of waste water in water systems, Smith (2005) showed that the flowrate of fresh water and operational cost in these systems decrease. Three water-using operations are shown in Table 1. As it is shown in Fig. 9, the fresh water flowrate is 60 t h$^{-1}$ only if water is

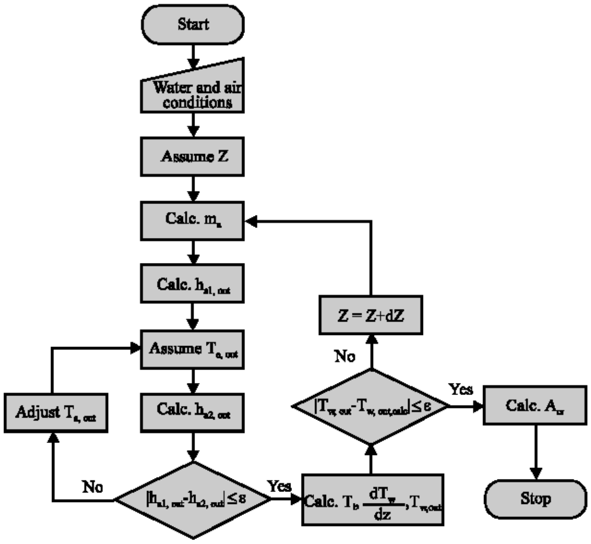

Fig. 8: Flowchart of optimum cooling tower design

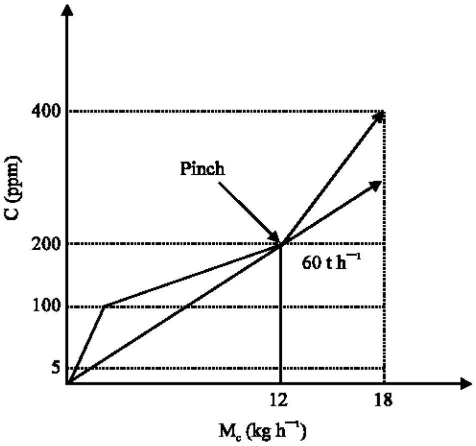

Fig. 9: Targeting of flowrate only by reusing water

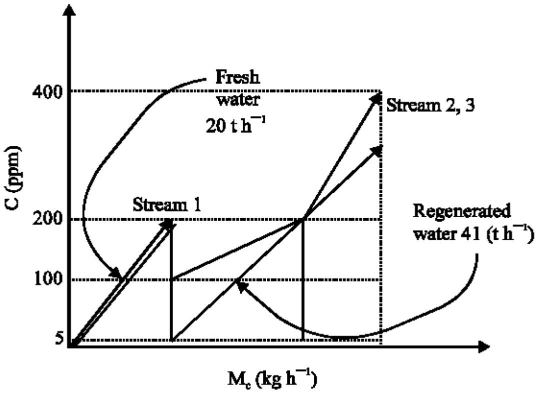

Fig. 10: Targeting of flowrate by using regeneration recycling method

Table 1: Water-using operations data

| Stream No. | $C_{in}$ (ppm) | $C_{out}$ (ppm) | Water flowrate (t h$^{-1}$) | Contaminant mass flowrate (g h$^{-1}$) |
|---|---|---|---|---|
| 1 | 0 | 200 | 20 | 4000 |
| 2 | 100 | 200 | 50 | 5000 |
| 3 | 100 | 400 | 30 | 9000 |

reused. A regeneration process is available with a performance that can achieve an outlet concentration of 5 ppm. When targeting for regeneration, the objective is to divide the water-using operations in two groups.

The first group represents the streams that require water with lower concentration than regeneration can achieve; as stream 1 is in this group. The second group includes streams that can accept a concentration greater than regeneration can achieve. In this example, streams No. 2 and 3 fall into this group. Targeting for regeneration is shown in Fig. 10. As shown, the flowrate of fresh water decreases from 60 to 20 t h$^{-1}$.

The regeneration recycling concept can be used for targeting an air cooler in the RCWS because the air cooler works without water and with air. The result of the proposed simple and hybrid RCWS design methods were shown through an illustrative example. Related coding in MATLAB version 7.3 was used for the illustrative example to get optimal values in the proposed design methods computations.

## RESULTS AND DISCUSSION

**Illustrative example:** The hot process streams data in Table 2 was examined as an illustrative example for optimum design of the RCWS, using the proposed design methods. The following parameters were used for the illustrative example:

Wet bulb temperature of air (15°C)
Ambient air temperature (25°C)
Minimum approach temperature (5°C)
Pump efficiency (60%)
Pumping head (10.67 m)
Operating time (8600 h year$^{-1}$)
Interest rate (15%)
Payback period (3 years)
$\Delta T_{min}$ (10°C)
Temperature limitation (57°C)

Also, the following cost parameters were considered for the illustrative example:

Cost of electricity (0.1 \$ kWh$^{-1}$)
Cost of fresh water (0.26 \$ t$^{-1}$)
Cost of chemical treatment (0.013 \$ t$^{-1}$)
Cost of blow-down treatment (0.13 \$ t$^{-1}$)

Table 2: Hot process streams data

| Heat exchanger | Inlet hot temperature (°C) | Outlet hot temperature (°C) | Heat capacity (kW °C$^{-1}$) | Total heat load (kW) |
|---|---|---|---|---|
| 1 | 50 | 40 | 40 | 400 |
| 2 | 55 | 45 | 100 | 1000 |
| 3 | 70 | 45 | 50 | 1250 |
| 4 | 70 | 65 | 100 | 500 |
| 5 | 75 | 70 | 50 | 250 |

Table 3: Cold process streams data

| Heat exchanger | Inlet hot temperature (°C) | Outlet hot temperature (°C) | Heat capacity (kW °C$^{-1}$) | Total heat load (kW) |
|---|---|---|---|---|
| 1 | 30 | 40 | 40 | 400 |
| 2 | 35 | 45 | 100 | 1000 |
| 3 | 35 | 60 | 50 | 1250 |
| 4 | 55 | 60 | 100 | 500 |
| 5 | 60 | 65 | 50 | 250 |

Cooling water data extracted from hot process streams data and was shown in Table 3.

If interest rate is 15% and payback period is 3 years, the animalization factor, which is expressed as Eq. 37, will be 0.438. The engineering index is equal to 1.24 for year 2008 (Garret, 1989).

$$AF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{37}$$

In this example, the capital and operational costs functions of cooling tower can be found via Eq. 1 and 10 and simplified as follows:

$$CC = 301.356(F_{in})^{0.79}(T_{in} - T_{out})^{0.57}(T_{out} - 15)^{-0.9924} \tag{38}$$

$$OC = 44(F_{air}) + 131.639(F_{in}) + 227.513(M) + 1138(B) \tag{39}$$

It should be noted that M, B and $F_{air}$ have a relationship with $F_{in}$, $T_{in}$ and $T_{out}$, so passive parameters are water flowrate, inlet and outlet water temperature of the tower. Cycle concentration ranges between 2 to 8 (Kermmer, 1979) as it is dependent on the quality of make-up water, and, in this instance, it is assumed 2. After defining capital and operational cost and drawing the composite curve, the constraints and feasible region are found (Fig. 11).

By defining the objective function and applying constraints, the optimum operational parameters are counted as follows:

Water flowrate, 85.10 t h$^{-1}$, inlet temperature to the cooling tower, 60.18°C, outlet temperature from the cooling tower, 25.77°C (Fig. 11). The line introduced by Kim and Smith for targeting flowrate in the cooling system design is also shown in Fig. 11. As it is shown in Fig. 11, the flowrate of optimum line is less than the flowrate of proposed line by Kim and Smith (2001).

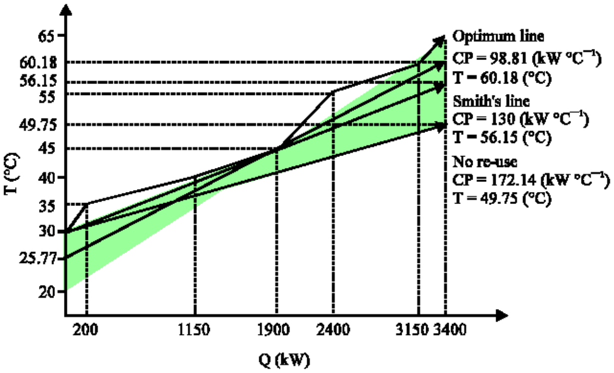

Fig. 11: Determining the feasible region and targeting lines

It is true that the capital cost increases when approach decreases, but the operational cost is reduced to an extent that it compensates for the increases in capital cost. All calculations in this regard are done using MATLAB Software.

After determining operational parameters, heat exchanger network should be designed. For this purpose, the Kim and Smith's design method is used an elaborated upon. To design exchanger network, the composite curve is divided into several pockets. In each pocket, the consumption flowrate should be minimized (Kim and Smith, 2001). For this reason, as shown in Fig. 12A, the slope of spotted lines in each pocket is maximized.

As shown in Fig. 12B, there are water mains at primary points (25.77°C), end points (65°C) and pinch points (45 and 60°C). Water flows are illustrated along the grid diagram. Stated numbers up and down of the water mains represent the consumption flowrate and the amount of returned flowrate to the tower in each pocket (Fig. 12B). This method outlined in four steps:

The first step is to generate a grid diagram with cooling water mains and plot cooling-water-using operations. The second stage is to connect the operations with cooling water mains. The third stage is to merge operations which cross mains. The final stage is to eliminate intermediate (pinch) cooling water mains. The first three stages are shown in Fig. 12B.

After eliminating intermediate water mains, the optimum arrangement of exchangers can be obtained (Fig. 13). The arrangement of heat exchanger network in Kim and Smith's design method is shown in Fig. 14 for comparison. As observed, there might be no alteration in the structure of the modified network in comparison to the Kim and Smith's network, but cooling water flowrate in exchangers of the modified method are decreased.

Now, using the method of cooling water regeneration recycling, placement of an air cooler in the heat exchanger network is discussed.

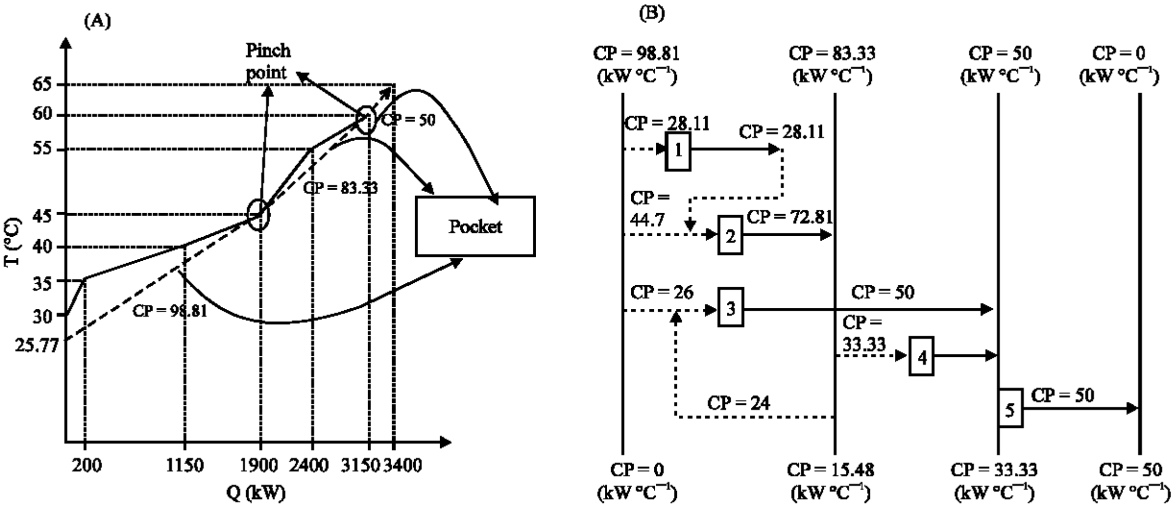

Fig. 12: Heat exchanger network synthesis

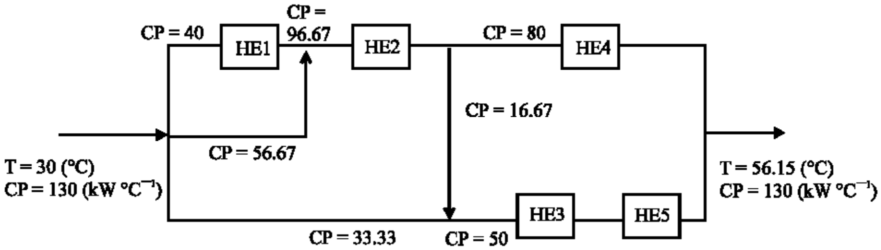

Fig. 13: The arrangement of exchangers in the modified method

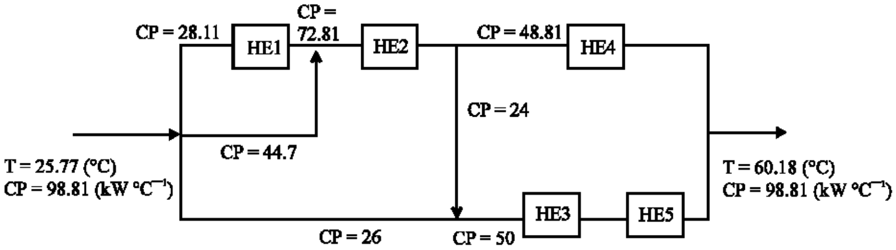

Fig. 14: The arrangement of exchangers in Kim and Smith's design method

If we assume the out temperature of the air cooler to be 30°C, according to what has been asserted so far, only heat exchanger number (1) requires water with an outlet temperature from the cooling tower and the rest of the exchangers can be satisfied with the temperature of outlet water from the air cooler. At first, according to Fig. 15, a target is set. As a result of using an air cooler, the flowrate of fresh water (outlet water from the tower) decreases from 85.10 to 24.21 t $h^{-1}$. A decrease in the flowrate leads to a decrease in operational cost. As the amount of used electricity of the pump and fan has a direct relationship with water flowrate, as the flowrate decreases, used electricity decreases accordingly and this results in saving energy. By making use of an air cooler, the load on the cooling tower is moderated, and the use of fresh water and production of blow-down accordingly decreases operational cost. After targeting, the exchanger network should be designed. For this reason, each region of the network (before and after the air cooler) is designed separately according to the presented network synthesis method and then connected to each other. The arrangement of exchangers using the modified design

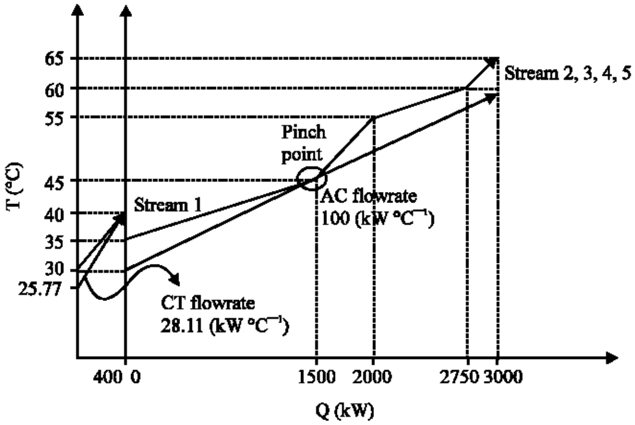

Fig. 15: Targeting in order to use an air cooler in the cooling water system's network.

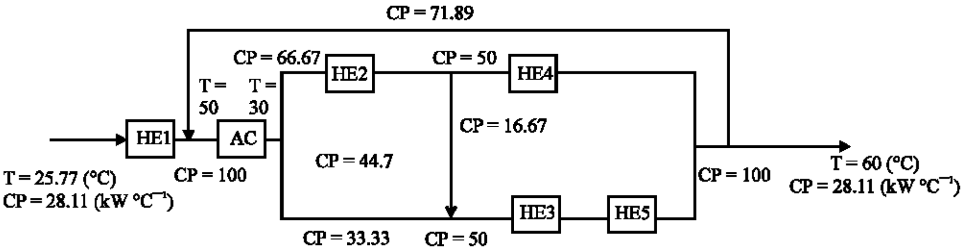

Fig. 16: The arrangement of heat exchangers in the modified design method with an air cooler.

method with an air cooler is shown in Fig. 16. As demonstrated, inlet and outlet temperatures of the network is exactly the same as the pre-determined target.

A comparison of operating conditions, the tower parameters and related costs are shown in Table 4-6, respectively. As shown in Table 6, the capital cost of the modified method using an air cooler is by far more than other methods because of the purchase cost of the air cooler. However, through the proper installation of the air cooler, the load on the tower decreases, and the capital cost of the tower decreases from 8.06 to 2.98 k$ year$^{-1}$. Further, operational cost decrease dramatically. To calculate capital cost of air cooler, Aspen Software has been used. The related air cooler was designed by this software and the estimated capital cost was 21.09 k$ year$^{-1}$.

Comparing the modified design method to the Kim and Smith's design method shows a decrease in flowrate and energy due to fixed load of cooling tower. However, no change occurs in the consumption of water and production of blow-down. With proper use of an air cooler in heat exchanger network, as the load of cooling water decreases, both the use of energy and water as well as production of blow-down decrease. The water and energy saving of modified design methods in comparison with Kim and Smith's design method are shown in Table 7.

Table 4: Performance parameters using various design methods

| Design method | Inlet water temperature to the tower (°C) | Outlet water temperature of the tower (°C) | Inlet water flowrate (t h$^{-1}$) |
|---|---|---|---|
| Conventional | 49.75 | 30.00 | 148.25 |
| Kim and Smith | 56.15 | 30.00 | 111.96 |
| Modified | 60.18 | 25.77 | 85.10 |
| Modified with an air cooler | 60.00 | 25.77 | 24.21 |

Table 5: Cooling tower design parameters

| Design condition | $Q_{rej}$ (kW) | E (t h$^{-1}$) | $A_f$ (m$^2$) | Z (m) | $A_{cr}$ (m$^2$) |
|---|---|---|---|---|---|
| Tower parameters in conventional design method | 3400 | 4.48 | 3.60 | 4.50 | 15.25 |
| Tower parameters in Kim and Smith's design method | 3400 | 4.48 | 3.10 | 3.82 | 12.10 |
| Tower parameters in modified design method | 3400 | 4.48 | 3.30 | 3.88 | 12.40 |
| Tower parameters in modified design method with an air cooler | 400 | 1.20 | 0.94 | 1.24 | 4.23 |

Table 6: Cost comparison of various design methods

| | Cost (k$ year$^{-1}$) | | |
|---|---|---|---|
| Design method | Capital | Operational | Total |
| Conventional | 6.56 | 34.47 | 41.03 |
| Kim and Smith | 6.16 | 28.03 | 34.19 |
| Modified | 8.06 | 23.96 | 32.02 |
| Modified with an air cooler | 24.04 | 6.80 | 30.87 |

Table 7: Water and energy saving of modified method in comparison with Kim and Smith's method

| Design method | Saving (%) Water | Blow-down | Energy |
|---|---|---|---|
| Modified | 0 | 0 | 13 |
| Modified with an air cooler | 72 | 72 | 20 |

## CONCLUSIONS

RCWS provides greater conservational opportunities relative to the other cooling system types. This cooling water system should be designed and operated with consideration of all the cooling system components because of the interactions between cooling water network and the cooling tower performance. Also, to achieve maximum water and energy conservation in RCWS, reuse and regeneration of cooling water between different cooling duties in heat exchanger network side should be considered. This will result in performance improvement, increased cooling tower capacity, minimum total cost and environmental impacts.

Using Pinch Technology together with the method of cooling water regeneration recycling in RCWS design, would result in a decrease in fresh water consumption, production of blow-down and energy consumption. In order to find the optimum design of RCWS, it is necessary to simultaneously integrate and consider all main elements of the system, including the heat exchanger network and the cooling tower. The present study, is intended to show that first, in order to obtain a lower total annual cost in comparison with Kim and Smith's design method, Pinch Technology and Mathematical Programming are used in RCWS design and second, by applying cooling water regeneration concept by using an air cooler, the total annual cost decreases significantly. Moreover, in the proposed design method, optimum design of cooling tower can be achieved through a mathematical iterational procedure.

Results on the presented illustrative example show that the total annual cost using the Kim and Smith's RCWS design method is 34.19 k\$ year$^{-1}$ while the modified method shows an annual cost of 32.02 k\$ year$^{-1}$, in which a combination of Pinch Technology and Mathematical Programming in addition to an air cooler using local regeneration of water, the total annual cost decreases to 30.87 k\$ year$^{-1}$. The energy saving in the modified design method when compared to the Kim and Smith's is 13%. Also the energy saving in the modified design method with an air cooler is 20% and water saving in this method is 72%. Consequently, applying these design methodologies to industrial large-scale problems provides more water and energy conservational opportunities.

## NOMENCLATURE

$A$ : Approach (°C)
$A_{cr}$ : Cross section area (m$^2$)
$A_f$ : Fan area (m$^2$)
$A_i$ : Heat and mass transfer area (m$^2$)
$a$ : Eliminator characteristic (m$^{-1}$)
$a_{1,2,3}$, $b_{1,2,3}$, $c_{1,2,3}$ : Constant value of mass transfer coefficient
AC : Air cooler
AF : Annualisation factor (year$^{-1}$)
B : Blow-down flowrate (t h$^{-1}$)
BTC : Blow-down treatment cost (\$ year$^{-1}$)
BTC1 : Cost of blow-down treatment materials in a year (\$ t$^{-1}$ year$^{-1}$)
C : Waste water concentration (ppm)
CC : Capital cost (\$ year$^{-1}$)
CC1 : Multiplication of the engineering index by annualisation factor (year$^{-1}$)
$C_E$ : Electricity cost (\$ kWh$^{-1}$)
CHTC : Chemical treatment cost (\$ year$^{-1}$)
CHTC1 : Cost of chemical treatment materials in a year (\$ t$^{-1}$)
CP : Heat capacity (kW °C$^{-1}$)
CT : Cooling tower
CW : Make-up water cost (\$ year$^{-1}$)
CW1 : Cost of water in a year (\$ t$^{-1}$)
$C_{WP}$ : Pump conversion factor
$C_{fan}$ : Fan conversion factor
E : Evaporation loss (t h$^{-1}$)
$F_a$ : Air flowrate (t h$^{-1}$)
$F_{in}$ : Inlet flowrate to cooling tower (t h$^{-1}$)
$F_{in}^{l}$ : Minimum inlet cooling water flowrate to cooling tower (t h$^{-1}$)
$F_{in}^{u}$ : Maximum inlet cooling water flowrate to cooling tower (t h$^{-1}$)
$F_{opt}$ : Optimum cooling water flowrate (t h$^{-1}$)
FC : Fan operational cost (\$ year$^{-1}$)
FC1 : Fan electricity cost in a year (\$ kWh$^{-1}$)
h : Pump head (m)
$h_a$ : Heat transfer coefficient of air (kW m$^{-2}$ °C$^{-1}$)
$h_w$ : Heat transfer coefficient of water (kW m$^{-2}$ °C$^{-1}$)
HE : Heat exchanger
i : Interest rate
K : Eliminator coefficient
$K_a$ : Mass transfer coefficient of air (m sec$^{-1}$)
M : Make-up flowrate (t h$^{-1}$)
m : Flowrate at control volume
n : Pay back period
OC : Operational cost (\$ year$^{-1}$)

PC : Pump operational cost (\$ year$^{-1}$)
PC1 : Pump electricity cost in a year (\$ kWh$^{-1}$)
$P_P$ : Pumping power (kW)
P : Atmosphere pressure (bar)
$P_i$ : Economic factor
$P^s$ : Saturation pressure (bar)
Q : Total heat load (kW)
$Q^i_{pinch}$ : Pinch point heat load (kW)
R : Range (°C)
S : Total annual operating time (h)
T : Temperature (°C)
$T_{in}$ : Inlet cooling water temperature to cooling tower (°C)
$T_{out}$ : Outlet cooling water temperature of cooling tower (°C)
$T_{MR}$ : Maximum inlet cooling water temperature to cooling tower (°C)
$T_{NR}$ : Minimum inlet cooling water temperature to cooling tower (°C)
$T_{TL}$ : Packing temperature limitation of cooling tower (°C)
$T_{MN}$ : Maximum outlet cooling water temperature of cooling tower (°C)
$T_{MA}$ : Minimum approach (°C)
$T_{WB}$ : Wet bulb temperature (°C)
$T_i^{pinch}$ : Pinch point temperature (°C)
$T_{amb}$ : Ambient temperature (°C)
$T_{air,out}$ : Outlet air temperature of cooling tower (°C)
W : Air humidity (t.water/t.air)
Z : Cooling tower height (m)

**Greek symbols**

$\rho$ : Density (kg m$^{-3}$)
$\eta_P$ : Pump efficiency
$\pi_C$ : Cycle of concentration
$\Delta t_{min}$ : Minimum temperature difference (°C)

**Subscripts**

a : Air
f : Fan
i : Initial condition
in : Inlet condition
m : Motor
out : Outlet condition
v : Vapour
w : Water

**Superscripts**

$l$ : Lower limit
u : Upper limit

## REFERENCES

Ataei, A., M.H Panjeshahi and M. Gharaie, 2009. A new algorithm for optimum design of mechanical draft wet cooling towers. J. Applied Sci., 9: 561-566.

Castro, M.M., T.W. Song and J.M. Pinto, 2000. Operational cost minimization in cooling water system. Chem. Eng. Res. Design, 78: 192-201.

Coulson, J.M., J.F. Richardson, J.R. Backhurst and J.H. Harker, 1991. Chemical Engineering: Fluid flow, Heat Transfer and Mass Transfer. Pergamon Press, Oxford.

Evans, F.L., 1979. Equipment Design Handbook for Refineries and Chemical Plants. Vol. 2, Gulf Publishing, Houston, ISBN: 0872012549.

Garret, D.E., 1989. Chemical Engineering Economics. Van Nostrand Reinhold, New York, ISBN: 0442318014.

Kermmer, F.N., 1979. The NALCO Water Handbook. McGraw-Hill, New York, ISBN: 0070458685.

Kim, J.K., L. Savulescu and R. Smith, 2000. Design of cooling systems for effluent temperature reduction. Chem. Eng. Sci., 56: 1811-1830.

Kim, J.K. and R. Smith, 2001. Cooling water system design. Chemical Eng. Sci., 56: 3641-3658.

Lyderson, L.A., 1983. Mass Transfer in Engineering Practice. Wiley-Interscience Publication, UK., ISBN: 0471104620.

Mann, J.G. and Y.A. Liu, 1999. Industrial Water Reuse and Waste Water Minimization. 1st Edn., McGraw-Hill Inc., New York, USA., ISBN: 13: 978-0071348553, pp: 235-238.

Panjeshahi, M.H. and A. Ataei, 2008. Application of an environmentally optimum cooling water system design to water and energy conservation. Int. J. Environ. Sci. Tech., 5: 251-262.

Parker, S.A., 1998. The US Department of Energy. Ozone Treatment for Cooling Tower. Federal Technology Alert Journal, New York.

Smith, R., 2005. Chemical Process Design and Integration. 1st Edn., John Wiley and Sons Ltd., USA., ISBN: 0471486809, pp: 513-516.

Söylemez, M.S., 2001. On the optimum sizing of cooling towers. Energ. Convers. Manage., 42: 783-789.