

New Method for Designing an Optimum Distributed Cooling System for Effluent Thermal Treatment

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ABSTRACT: Temperature restrictions on aqueous effluents dictate that streams with a temperature higher than the permitted level needed to pass through cooling systems to reduce the effluent temperature before discharge. In this study, by considering the grouping design rules based on pinch technology, an optimum design for a distributed effluent cooling system, has been developed. A counter-flow wet cooling tower, with a mechanical air draft, is also assumed as an effluent thermal treatment facility in predicting the exit water and air conditions of the tower in the system. In this new design method, an optimum inlet flow rate to cooling tower has been achieved by exploring the feasible region. Also, the evaporation loss effect, flexible design variables, and physical properties have been incorporated in targeting the optimal conditions for the cooling tower. A case study is presented to illustrate the design methodology and the optimization model of cooling systems.

Key words: Grouping Design Rules, Pinch Technology, Targeting, Wet Cooling Tower

INTRODUCTION

While chemical, physical or biological treatment processes can be used for controlling the chemical pollution problems of effluents (Sarparastzadeh *et al.*, 2007), the thermal treatment system is required for effluent temperature reduction problems when the temperature of the effluent streams is too high to be discharged directly to the receiving water. The thermal treatment of effluents in processing industries is most often carried out in a central cooling facility (Kim *et al.*, 2001). However, because of the inefficient performance of such cooling systems, an alternative policy, such as a distributed cooling system, should be considered. The design of an effluent thermal treatment should be based on sustainable development to improve the quality of human life and keep the natural environment clean. Sustainable development provides a framework for the integration of

ecosystems with industrial activities and systematic ways to enhance process efficiency (Ataei, 2008).

Because discharge regulations have driven up effluent thermal treatment costs (Mtethiwa *et al.*, 2008), process integration techniques have emphasized the reduction of the temperature of the effluent and the design of cost-efficient temperature reduction systems as a means of pollution prevention. Pinch analysis is the tool most commonly used for integration purposes. This technology is based on defining the targeting before generating the design, and exploits conceptual understanding. Various systematic methods based on pinch analysis have played key roles in saving energy and water in process design (Linnhoff and Smith, 1994; Smith, 2005). This technology has been used to design distributed effluent temperature reduction systems.

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Kim, Savulescu and Smith (2001) established a design methodology for distributed systems for effluent cooling. In the Kim, Savulescu and Smith Design Method (KSSDM), which is based on the grouping design rules, a minimum inlet effluent flow rate to the cooling tower is achieved with mathematical programming. Several assumptions are made in the KSSDM, but these assumptions make the design inaccurate. Some of these assumptions are (Ataei, 2008):

1. Fixed evaporative loss at constant heat rejection;
2. Fixed cooling tower exit temperature while increasing in effluent flow rate to account effect of evaporation loss;
3. Fixed physical properties;

It has been noted that the amount of evaporation loss is dependent on the changes of the temperature and flow rate of inlet conditions and a constant heat rejection value does not necessarily ensure a fixed evaporation rate (Panjeshahi and Ataei, 2008). In the KSSDM, because of the evaporative loss effect, the inlet effluent flow rate is increased. However, this will affect the cooling tower size and performance, accordingly, the targeted values such as cost and operational parameters cannot be achieved at the synthesis stage. The temperature of the tower exit water changes with variations in the inlet water conditions (flow rate and temperature). Therefore, the fixed temperature of the exit water (fixed approach value) cannot guarantee a minimum cost of cooling or its optimality (Panjeshahi and Ataei, 2008). The physical properties of the system also change under different design supply conditions. To achieve accurate results in water–air systems, it is necessary to consider the governing conditions, when calculating the system properties. Hence, the targets in KSSDM could not be met in practice. Moreover, with the KSSDM, the targets are set regardless of the model. However, a detailed model allows us to simultaneously consider the effects of the related aspects of the whole system. Furthermore, a method for designing the wet cooling tower to achieve the targeted total cost of cooling tower is not addressed in the KSSDM. In this study, a new design methodology which is called “Optimum Design method of distributed Effluent Cooling system (ODEC)” for cost-effective effluent cooling is introduced to overcome the aforementioned problems and the limitations

of the KSSDM. In the ODEC, by considering the evaporative loss effect on the cooling tower supply flow rate, the pinch technology has been improved. The presented design method, ODEC, considers the energy implications of effluent systems. In this methodology, the targets are set first and then the thermal treatment networks are designed to achieve the targeted values on the basis of the grouping design rules which proposed by Kou and Smith (1997). To achieve these objectives, a new algorithm has been developed based on a comprehensive model of a distributed cooling system. In this model, a mechanical draft counter-flow wet-cooling tower has been assumed. To achieve optimization, computations and mathematical calculations were performed with coding in Visual Studio 2003, C++. Finally, this design methodology has been used on an illustrative example and the results have been compared with the conventional design of the effluent cooling system.

MATERIALS & METHODS

Industrial processes usually produce large quantities of aqueous waste, which must be permanently removed to maintain standard operating parameters. The thermal treatment of wastewater is required to solve effluent temperature problems, to meet environmental criteria. The introduction of a cooling system is therefore necessary to reduce effluent temperatures. There are many options for cooling to satisfy environmental regulations. In this paper, wet-cooling towers will be studied among the cooling options, because this method is widely used in the process industries. Thermal treatment of effluents in the process industries is most often carried out in a central cooling facility (Fig. 1a). In conventional thermal treatment systems (centralized cooling systems), effluent streams generated from various processes and plants are collected in a common sewer before thermal treatment. After collecting all effluent streams and combining into a single effluent, the effluent stream generated is likely to have lower energy level, because the energy level of effluent with a higher temperature becomes degraded due to mixing of the effluent streams. Therefore, central cooling systems need to remove the heat from effluent streams with a lower temperature and a higher

flow rate relative to cooling systems placed on the higher temperature effluents before mixing (Kim *et al.*, 2001). If cooling systems use a cooling tower as cooling facility, central cooling systems also result in inefficient and expensive cooling. That is because cooling conditions with a high range (the temperature difference between inlet and outlet cooling water) and low flow rate are more efficient than conditions with low range and high flow rate. This results from the cooling mechanisms of cooling towers (Bedekar *et al.*, 1998). As a centralized cooling policy cannot avoid the degradation caused by mixing effluents with low temperatures, a distributed cooling policy (Fig. 1b). for cooling systems should be considered.

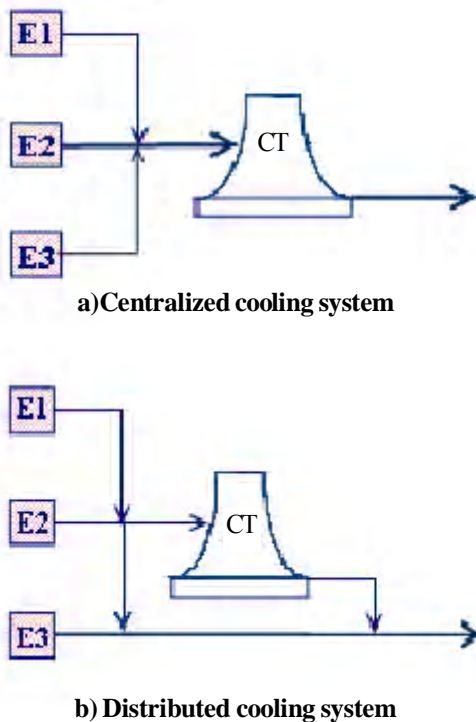


Fig. 1. Centralized and distributed effluent cooling systems

The new Optimum Design method of distributed Effluent Cooling system, which is called ODEC, for cost-efficient effluent temperature reduction was achieved using a systematic approach. With the ODEC, the optimum distributed effluent system is designed in five stages. The first stage is the construction of the effluent composite curve. The second stage is the generation of the feasible region, taking into

consideration the system limitations. The third stage targets the optimum cooling tower supply line by exploring the feasible area. The fourth stage is the design of the cooling network to achieve the target, based on the modified grouping rules and the final stage is the design of the cooling tower to achieve the targeted total cost of the cooling tower, considering targeted temperatures and flow rates of inlet and outlet conditions. Accordingly, the targeting procedure of the ODEC contains the first to third aforementioned stages and the fourth and fifth stages make the design procedure of the ODEC, see (Fig. 2).

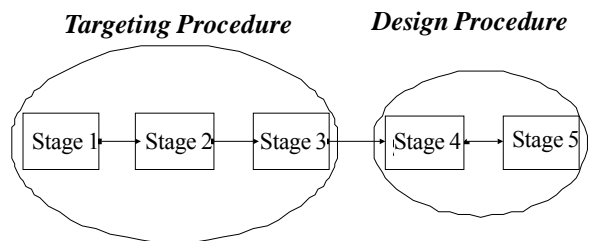


Fig. 2. Targeting and design procedures in the ODEC

In first stage of the ODEC, to construct the effluent composite curve, the environmental discharge limit for the effluent temperature is specified. The disposable heat to be removed by cooling each effluent stream is then calculated. The individual profiles are plotted on a graph of temperature versus disposable heat, as shown in (Fig. 3a). (Smith, 2005). The composite curve is constructed by combining all the individual profiles into a single curve within the temperature intervals (Fig. 3b) In second stage of the ODEC, to generate the feasible region, the upper and lower limits of the inlet effluent flow rate to cooling tower are specified. Feasibility constraints on the inlet mass flow rate to cooling tower is:

$$m_{w,in}^l \leq m_{w,in} \leq m_{w,in}^u \quad (1)$$

$m_{w,in}^l$ and $m_{w,in}^u$ are the lower and upper limits of the inlet stream flow rate which are expressed at exit stream temperature of the cooling tower. Cooling tower water outlet temperature varies between the minimum value, considering wet bulb and minimum approach temperature, and the maximum value, considering environmental temperature discharge limit:

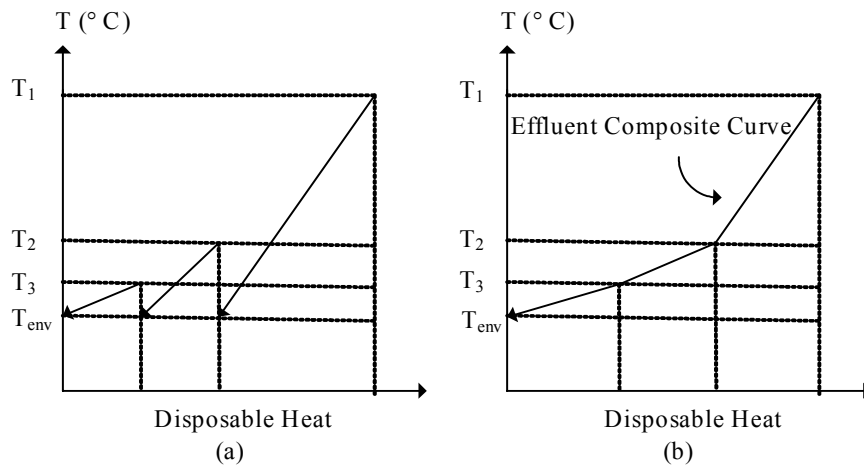


Fig. 3. Construction of the effluent profile composite curve

$$T_{out,min} \leq T_{out} \leq T_{env} \quad (2)$$

$$T_{out,min} = T_{WB} + T_{MA} \quad (3)$$

Accordingly, upper limit of the inlet stream flow rate expresses the full centralized conditions (Ataei, 2008):

$$m_{w,in}^u = \sum_{i=1}^n m_{wi} \quad (4)$$

Fig. 4. shows feasible boundaries for the distributed cooling system. As shown in (Fig. 4). the feasible area is the region limited by the full centralized conditions (maximum water flow rate), considering the environmental temperature discharge limit, and the minimum cooling flow rate, considering the minimum exit stream temperature of the cooling tower.

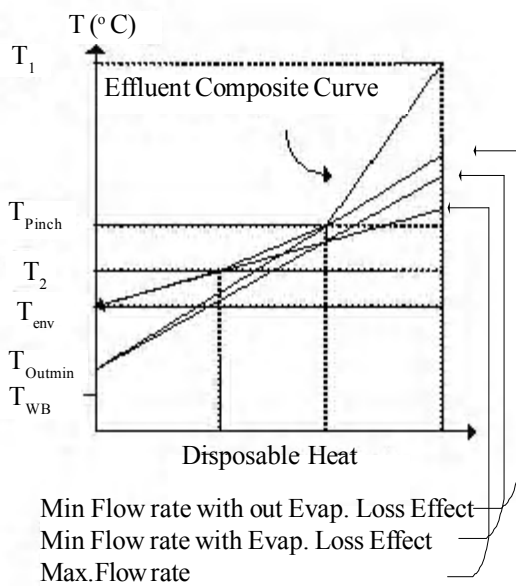


Fig. 4. Feasible boundaries for the distributed cooling system

In the third stage of the ODEC, the optimum inlet effluent flow rate to cooling tower should be targeted by exploring the feasible area. In distributed cooling systems, the segregation of the effluents maintains a high driving force for cooling and also maximizes the potential of recovering as much heat as possible from the effluent streams. To investigate the interactions within the system, a distributed thermal treatment model, including a cooling tower, has been introduced. To achieve this aim, other system components have been added to the cooling tower model. The model has been developed to illustrate the conditions of the exit water and the air from the system for the given design conditions. (Fig. 5). shows the scheme for a distributed system. To determine the properties of the air and water in the system, related balances are set up for the overall control volume, the cooling tower, and the packing area. The mass and energy balances for the overall system (Fig. 5). are expressed by Equations 5 and 6, respectively.

$$m_{w1} + m_{w2} + m_{w3} = m_{w,out} + m_{w,by\ pass} + m_{evap} \quad (5)$$

$$m_{w1}C_{p1}T_1 + m_{w2}C_{p2}T_2 + m_{w3}C_{p3}T_3 = (m_{w,out} + m_{w,by\ pass})C_{p,env}T_{env} + m_{evap}h_{a,evap} \quad (6)$$

The mechanism of heat and mass transfer between the ambient air and the water inside the cooling tower packing is illustrated in (Fig. 6).

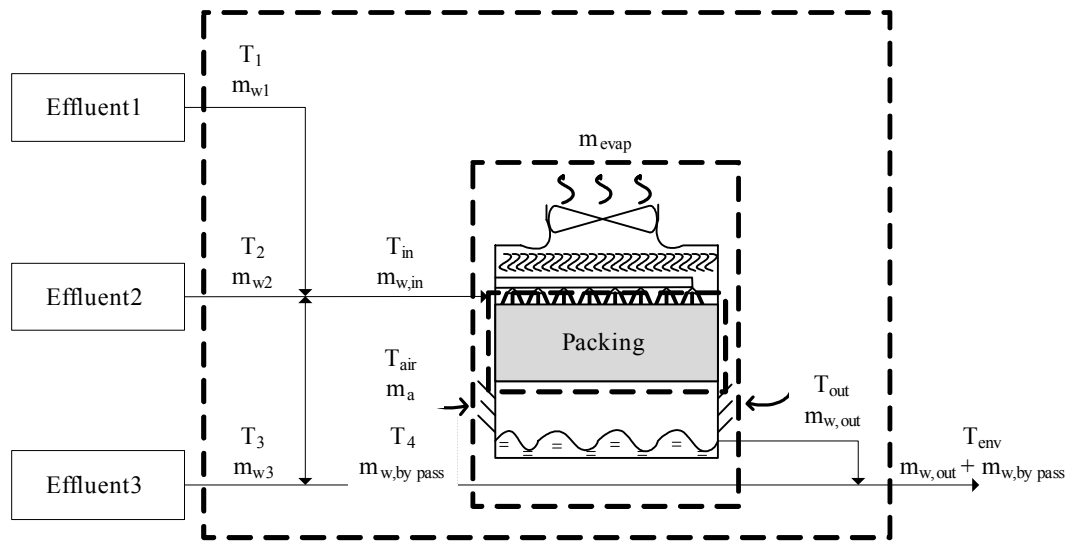


Fig. 5. Scheme of the distributed cooling system

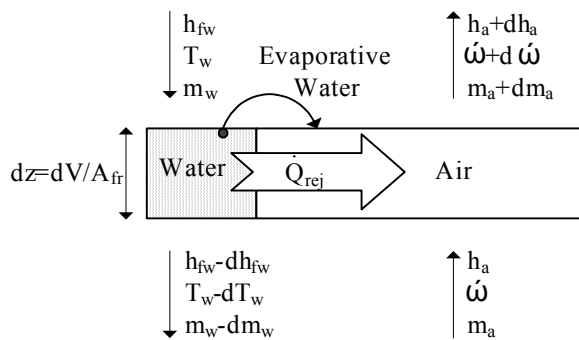


Fig. 6. Control volume of the tower packing

The energy balance for the cooling tower is expressed in Equation 7.

$$m_{w,in} C_{p,in} T_{in} - Q_{evap} = m_{w,out} C_{p,out} T_{out} \quad (7)$$

The rejection heat through the water is given in Equation 8 (Hollands, 2003).

$$dQ_{rej} = \left(m_w(z) C_p \frac{dT_w}{dz} + h_w \frac{dm_w}{dz} \right) dz \quad (8)$$

The water energy balance in terms of the heat and mass transfer coefficients is given by Equation 9.

$$m_w dh_{fw} = [h_d a A_{fr} (T_w - T) + h_a a A_{fr} (\omega_{sw} - \omega) h_{fg,w}] dz \quad (9)$$

By substituting the Lewis factor, expressed by Equation 10 (Kloppers and Kröger, 2005), in Equation 9, the water energy balance yields Equation 11.

$$Le_f = \frac{\alpha}{D} = \frac{h_a}{C_{pa} h_d} \quad (10)$$

$$m_w dh_{fw} = h_d a A_{fr} [Le_f C_{pa} (T_w - T) + (\omega_{sw} - \omega) h_{fg,w}] dz \quad (11)$$

Where h_a is the heat transfer coefficient of water (Deng and Tan, 2003). An amount of water dm_{evap} is evaporated in the control volume. The water flow is cooled by temperature decrement dT_w because of the latent heat of evaporation and because of convective heat transfer. Evaporation at the water surface can be written as Equation 12 (Kröger, 2004).

$$dm_{evap} = m_a d\omega \quad (12)$$

$$dQ_a = m_w dh_{fw} + h_{fw} m_a d\omega \quad (13)$$

The targeting method of ODEC incorporates the evaporation effect. The outlet water conditions of flow rate and temperature are affected by evaporation. In other words, the exit water flow rate of the cooling tower is reduced by evaporative loss. This affects the cooling performance. Thus, evaporative loss forces an increase in the cooling tower supply flow rate, but the environmental discharge limit is satisfied. Therefore, a new boundary for the minimum water flow rate is set, taking into consideration the evaporation loss

effect. The new minimum water flow rate of ODEC targeting was also shown in Fig. 4. The setting water supply is between the new minimum water flow rate and the maximum flow rate. The optimum amount of water is determined by exploring the feasible region, taking into consideration the minimum total cost. The constant value of the approach does not guarantee the minimum cooling cost. Conversely, the performances of the cooling tower and the distributed system is governed by the cooling tower design variables: range, approach, air flow rate, and water flow rate (Khan and Zubair, 2001). Therefore, to achieve the optimum target supply, the cooling tower design variables are considered as rigid values. The range and approach definitions are expressed by Equation 14 and Equation 15, respectively (Khan *et al.*, 2004).

$$R = T_{in} - T_{out} \quad (14)$$

$$A = T_{out} - T_{WB} \quad (15)$$

The water entering the cooling tower is given as Equation 16 (Ataei *et al.*, 2009).

$$m_{w,in} = \frac{Disposed\ Heat}{C_p \Delta T} \quad (16)$$

The amount of evaporation depends on the air flow rate, the humidity of the inlet air and the humidity of the cooling tower outlet air. The exit air humidity is related to the water temperature and the transfer area of the packing. Therefore, the evaporated water loss is not constant when flexible design variables are considered. The change in the air humidity ratio along the cooling tower is expressed by Equation 17 (Qureshi and Zubair, 2006).

$$\frac{d\omega}{dz} = \frac{KaA_{fr}}{m_a} (\omega_{sw} - \omega) \quad (17)$$

The saturated humidity ratio at water temperature is given by Equation 18 (Ataei *et al.*, 2009).

$$\omega_{sw} = 0.622 \frac{P^s}{(P - P^s)} \quad (18)$$

The cooling tower characteristic is given by Equation 19 (Kröger and Kloppers, 2005).

$$\frac{KaV}{L} = \int_{T_{out}}^{T_{in}} \frac{C_p dT_w}{(h_{asw} - h_{awv})} \quad (19)$$

The operating cost and the capital cost of the cooling tower have different effects on the overall cost of the distributed cooling system (Prasad, 2004). Therefore, the problem of targeting the distributed cooling system becomes an optimization problem, to find the optimal cooling line. The total cost of the cooling tower, as the objective function, is expressed in Equation 20 (Söylemez, 2001).

$$MinTC = C_i \left(\frac{A_i}{Ry} \right) + \left[\frac{C_{elec} E_f m_a^3 Ry^2 Z^2 S \left(6.5 + K_{el} + 2 \left(\frac{A_i}{RyZA_{fan}} \right)^2 \right)}{2\rho_a A_i^2 \eta_{fan} \eta_{motor}} \right] + A_{ic} \quad (20)$$

At end of third stage of ODEC, the targeting procedure of the ODEC will be completed. In other words, the optimum effluent temperatures and flow rates of inlet and outlet conditions can be targeted to achieve minimum total cost of cooling system. After complication of the targeting procedure, the design procedure of the ODEC which contains the fourth and fifth stages should be considered. In the fourth stage of the ODEC, the cooling network to achieve the target should be designed. To achieve this aim, the modified grouping rules which proposed by Kou and Smith (1997) can be applied. For applying the grouping rules in the fourth stage of ODEC, some modifications are needed to account the effects of evaporation loss. Because the optimum cooling tower supply line in ODEC, which was achieved in the third stage, does not correspond to the minimum flow rate (because of the evaporation loss effect), no pinch point is created with the limiting cooling water composite curve (Fig. 4). The grouping rules are based on the concept of pinch technology cannot be applied to problems without pinch. The new minimum cooling tower supply line represents a boundary between the feasible and non-feasible operations. In other words, any composite curve below the original one is feasible. Therefore, the effluent composite curve must be modified to create a new pinch point with the desired cooling tower supply line in the feasible region. To achieve this aim, pinch migration is applied on the basis of temperature

shifting, in which the effluent composite curve moves along the temperature axis (Kim and Smith, 2001). The migrated pinch temperature can be calculated with Equation 21. (Fig. 7). shows the creating of a migrated pinch point.

$$T_{Pinch}^* = \left[\frac{(T_{in} - T_{out})}{Q_{Total}} \times Q_{Pinch} \right] + T_{out} \quad (21)$$

The effluent streams with starting temperature located above the migrated pinch (Group I) pass through the thermal treatment process totally. The effluent streams located at the migrated pinch (Group II) are partially treated and partially bypassed. The effluent streams located below the migrated pinch (Group III) totally bypass the thermal treatment process.

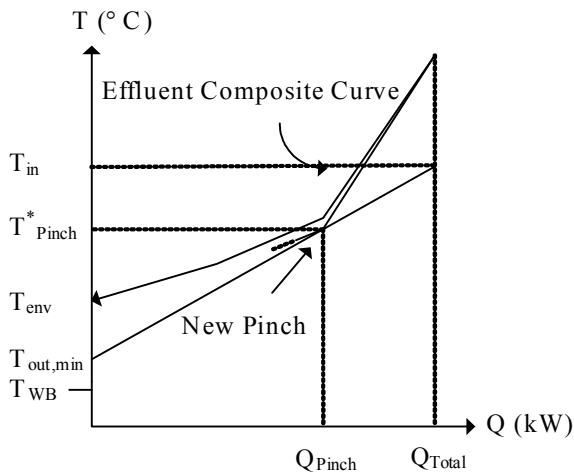


Fig. 7. Creating a migrated pinch point

After the target flow rates for the thermal treatment processes for given effluent streams are set, thermal treatment networks are designed to achieve those targets with the modified grouping strategy considering the migrated pinch point. Moreover, the operating characteristics of the cooling tower are incorporated into the ODEC and are combined with the distributed cooling system to identify the optimum design for effluent temperature reduction. In final stage of ODEC, design of the cooling tower is carried out through a mathematical iterational procedure, using known design variables, to achieve the total cost of cooling tower which was targeted in the third stage of ODEC. In a counter-flow wet 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. It has noted that the rate of energy transferred from the water is equal to the rate of energy gained by air (Equation 22).

$$Q_a = m_a (h_{a,out} - h_{a,in}) \quad (22)$$

The air flow rate of the tower can be achieved through Equation 23, with a known water flow rate which was calculated by Equation 16 (Ataei et al., 2009).

$$m_a = \frac{m_w C_{pw}}{C_{pa}} \quad (23)$$

The change in the air humidity ratio along the cooling tower and the saturated humidity ratio at water temperature were given in Equations 17-18. Also the air and water temperatures are given in Equations 24 and 25 (Kim and Smith, 2001).

$$\frac{dT_w}{dz} = \frac{h_d A_{fr}}{m_w C_{pw}} (T_w - T_i) \quad (24)$$

$$\frac{dT_a}{dz} = \frac{h_a A_{fr}}{m_a C_{pa}} (T_i - T_a) \quad (25)$$

For the air-water system, heat and mass transfer coefficients are represented as a function of air and water flow rates. The related coefficients are given in Equations 26 to 28 (Coulson and Richardson, 1996).

$$K_a A_{fr} = a_1 m_a^{b1} m_w^{c1} \quad (26)$$

$$h_d A_{fr} = a_2 m_a^{b2} m_w^{c2} \quad (27)$$

$$h_a A_{fr} = a_2 m_a^{b2} m_w^{c2} \quad (28)$$

The optimum heat and mass transfer area can be calculated by Equation 29 (Söylemez, 2001).

$$A_{i,opt} = \sqrt[3]{\frac{C_{elec} E_f m_a^3 R y^3 Z^2 S [6.5 + K_{el} + 2(A_{fr} / A_{fan})^2]}{\rho_a^2 \eta_{fan} \eta_{motor} C_i}} \quad (29)$$

The optimum cross sectional area is given by Equation 30 (Ataei et al., 2009).

$$A_{Cr,opt} = \frac{A_{i,opt}}{RyZ} \quad (30)$$

It is assumed that the cooling tower frontal area and cross-sectional area will be approximately equal. If the design is for a rectangular cooling tower, the frontal area is given by (Kröger, 2004):

$$A_{Cr} \approx A_{fr} = Z \times W \quad (31)$$

To achieve the optimum cooling tower design, an iterative calculation is required. The computation procedure is presented in (Fig. 8). The ODEC provides a way of targeting the optimum flow rate for a thermal treatment. It also provides design guidelines to achieve the targets in practice. The ODEC is applied to an illustrative example and the results are compared with the conventional design (centralized design) of the effluent cooling system.

RESULTS AND DISCUSSION

The effluent streams data in (Table 1) was examined as an illustrative example for optimum design of effluent cooling system, using the proposed design method (ODEC).

Table 1. Effluent stream data

Effluent	Flow rate (kg/s)	Temperature (°C)
1	83.33	60
2	83.33	45
3	111.11	32

The following parameters were used for the illustrative example:

The electricity cost is 0.1 \$/kWh. The eliminator characteristic is $2.8 \times 10^5 \text{ m}^{-1}$. The eliminator friction coefficient is 4.6. The operating period is 8600h/yr. The environmental temperature discharge limit is 30 °C. The wet bulb temperature is 20 °C and minimum approach temperature is 5 °C. Accordingly, the cooling tower exit temperature varies between 25 °C to 30 °C for optimization purposes. The ODEC segregates streams for thermal treatment and then combines or bypasses them if appropriate. In the ODEC targeting procedure, the effluent stream data and the environmental conditions are used to construct the

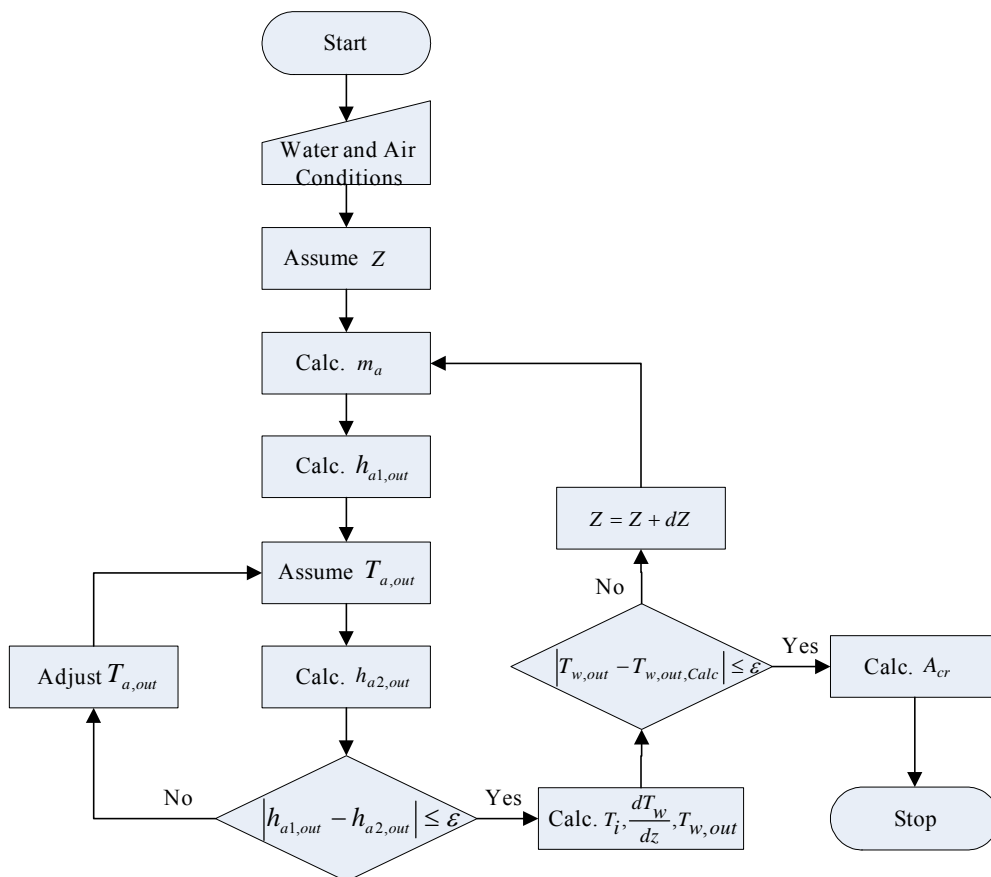


Fig. 8. Flowchart of optimum cooling tower design

effluent composite curve and to define the feasible region. (Fig. 9). shows the effluent composite curve and the feasible region. We note that as the cooling flow rate increases, the approach becomes large and the range becomes small. The optimum cooling tower supply line can be achieved by exploring the feasible region. The feasible boundary temperatures and flow rates are presented in Table 2.

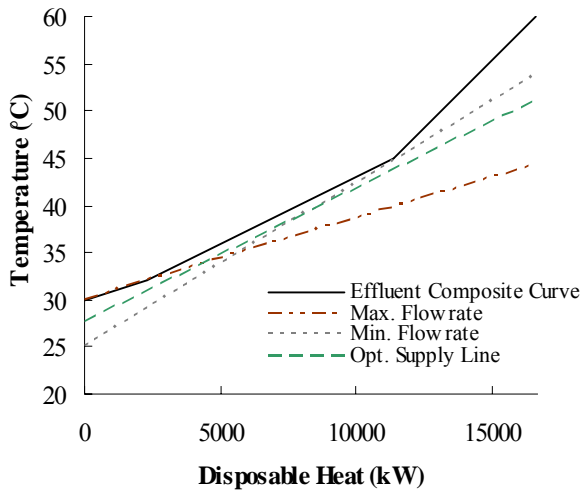


Fig. 9. The feasible region of the distributed cooling system

Table 2. The feasible boundary water supply conditions

Effluent condition	Flow rate (kg/s)	Inlet temperature (°C)	Outlet temperature (°C)
Min. flow rate	137.61	53.74	25
Max. flow rate	277.77	44.31	30

Fig. 10. illustrates the effect of the water flow rate on the capital and operation costs of the distributed cooling system. The results reveal that an increase in the water flow rate reduces the cooling tower capital cost, whereas the operating cost increases. Therefore, a trade-off between the capital cost and the energy cost has been introduced. The optimum water flow rate is achieved by considering this trade-off. The optimum cooling line, which is located between the maximum and minimum flow rates, achieves the minimum total cost. (Table 3) shows a comparison of the water supply conditions of ODEC and those of the conventional design (centralized cooling system).

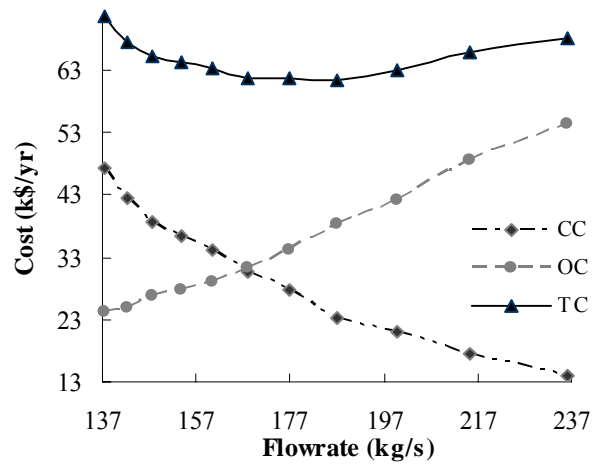


Fig. 10. Overall cost of the distributed cooling system

Table 3. Water supply conditions with conventional and ODEC design methods

Design method	Flow rate (kg/s)	Inlet temperature (°C)	Outlet temperature (°C)
Conventional	277.77	44.31	30
ODEC	169.00	51.07	27.55

In the design procedure, the optimum water supply has been applied to the effluent network, taking into consideration the modified grouping design rules. The results indicate that the migrated pinch point, created with the ODEC method, is at 32 °C. Accordingly, to achieve the targeted cooling tower supply flow rate, the effluent 1 and effluent 2 should be passed through the cooling tower totally and the effluent 3 located at the migrated pinch (Group II) should be partially cooled and partially bypassed. (Fig. 11). shows the optimum effluent network produced with the ODEC on the basis of the modified grouping design rules. These results indicate that, by distributing the cooling system, the effluent streams are partially treated thermally by the cooling tower. Therefore, the required cooling tower in the distributed system is smaller than that in the centralized system. Therefore, applying the ODEC has resulted in cost minimization relative to that of the conventional (centralized cooling system) design method. (Table 4). shows the cost comparison for the cooling towers designed with the conventional design method and ODEC.

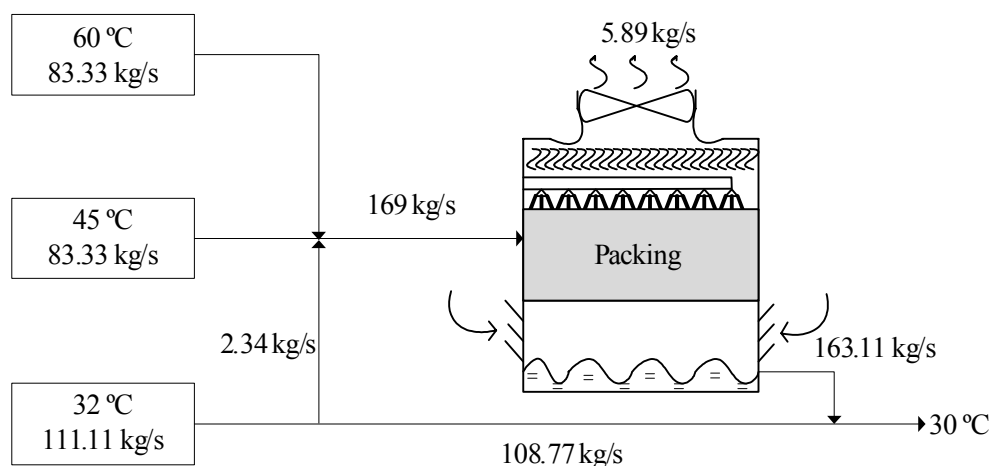


Fig. 11. Optimum effluent network of the ODEC

Table 4. Cost comparison of conventional design method and ODEC

Design method	Operating cost (k\$/yr)	Capital cost (k\$/yr)	Total cost (k\$/yr)
Conventional	45.52	41.79	87.31
ODEC	31.51	30.31	61.82

The ODEC allows the optimum cooling tower design to be achieved. The cooling tower design parameters for the proposed design method (ODEC) and the conventional design (centralized cooling system) method are given in (Table 5). It is usually possible to reuse effluent for some usages such as washing or gardening. With the ODEC, the evaporative loss is reduced by distributing the effluent system. Therefore, ODEC achieves greater water conservation opportunity compared with that of the conventional design. In other words, ODEC provides greater water reusing opportunities relative to the conventional design method. Table 6 shows the water conservation opportunity achieved with the ODEC.

Table 5. The cooling tower design parameters for the ODEC and the conventional design method

Design method	Q_{rej} (KW)	W (m)	Z (m)	A_{cr} (m ²)
Conventional	17150	10.82	5.61	60.7
ODEC	17150	9.7	4.65	45.11

Table 6. Water conservation opportunity with the ODEC

Design method	Evaporative loss (kg/s)	Water saving (%)
Conventional	7.79	-
ODEC	5.89	24%

CONCLUSION

Though quality of wastewater is site-specific, the assessment of effluents usually involves the volume, discharge rate and concentration of pollutants, the temperature, pH and the quality of the receiving water. The change of temperature in surface /ground water, by the addition of wastewater heat, affects the physiochemical and hydrological properties of the water and potentially impacts on overall ecosystem. Temperature restrictions on aqueous effluents dictate that streams with a temperature higher than the permitted level must pass through a cooling system to reduce the effluent temperature before discharge. It has been used to reduce the temperature of effluents that the effluents are diluted with regional water (river, lake, estuaries or coastal water) near industrial sites and discharged to the environment. But this practice is not a long-term solution and is also restricted by government authorities for ground/surface water protection. So the introduction of cooling systems is inevitable for solving effluent temperature reduction problems. Effluent temperature reduction can be accomplished by simply installing cooling equipment before discharge. However, this can be expensive and inefficient. As a centralized cooling policy cannot avoid the degradation caused by mixing effluents with low temperatures, a distributed cooling policy for cooling systems should be considered.

In this study, a new design method, the “Optimum Design method of distributed Effluent Cooling system (ODEC)”, has been introduced

to cope with problems of thermal pollution. In this method, the pinch technology for effluent temperature reduction has been improved, taking into consideration the system limitations. To achieve this objective, the effects of evaporative loss, flexible design variables, and physical properties on cooling performance and cost have been considered. With this method, a feasible region limited by the full centralized conditions and the minimum cooling flow rate has been explored to achieve the optimum cooling tower supply line. The thermal treatment network has then been designed with the modified grouping design rules to achieve the target. Moreover, in the proposed method, optimum design of wet cooling tower has been achieved through a mathematical model.

In the method introduced here, ODEC, the effluent streams are distributed for cooling purposes. This method allows the system

interactions to be investigated with a new model of effluent thermal treatment. In the proposed model, a mechanical draft counter-flow wet cooling tower is assumed. By distributing the cooling system, the effluent streams are partially treated thermally by the cooling tower. Therefore, the required cooling tower in the distributed system is smaller than that required for a centralized system, so applying the ODEC results in a minimized total cost relative to that of the conventional design (centralized design). After thermal treatment through the cooling tower, the cooled effluents are mixed with the bypassed streams to meet the discharge temperature limitation. If reuse of effluent for some usages are possible, applying ODEC can be resulted in more water conservational opportunities. Related coding in Visual Studio 2003, C++ was developed to achieve the optimization computations and mathematical calculations.

NOMENCLATURE

a	air-water interface area per unit volume of tower, m^2/m^3	$h_{fg,w}$	enthalpy change of saturated liquid and vapor evaluated at T_w , kJ/kg
$a_{1,2,3}$, $b_{1,2,3}$, $c_{1,2,3}$	constant value of mass transfer coefficient	K_a	Mass transfer coefficient of air, m/s
A	cooling tower approach, $^{\circ}C$	Ka	tower characteristic, $kg/m^3 s$
A_{cr}	cross section area, m^2	K_{el}	eliminator coefficient
A_{fan}	fan casing area, m^2	L	water flow rate, kg/s
A_{fr}	tower frontal area, m^2	Le_f	Lewis factor
A_i	heat and mass transfer area, m^2	m	flow rate, kg/s
A_{ic}	area-independent initial cost, \$	n	number of effluent streams
C_{elec}	electricity cost, \$/kWh	Q	heat transfer rate, kW
C_i	initial cost of tower per unit volume, $\$/m^3$	R	cooling tower range, $^{\circ}C$
C_{pa}	specific heat of dry air at constant pressure, $kJ/kg^{\circ}C$	Ry	eliminator characteristic, m^{-1}
C_p	Specific heat of water at constant pressure, $kJ/kg^{\circ}C$	S	annual total operation time, h
D	diffusion coefficient, m^2/s	T	temperature, $^{\circ}C$
E	effluent collection points	T^*	migrated pinch temperature, $^{\circ}C$
E_f	economic factor	T_i	temperature of interface, $^{\circ}C$
h	Enthalpy, kJ/kg	TC	total cost, $\$/yr$
h_a	heat transfer coefficient of air, $kW/m^2^{\circ}C$	T_{MA}	minimum approach, $^{\circ}C$
h_{asw}	enthalpy of saturated air at water temperature, kJ/kg	V	tower volume, m^3
h_{awv}	enthalpy of air-water vapor mixture, kJ/kg	W	cooling tower width, m
h_d	heat transfer coefficient of water, $kW/m^2^{\circ}C$	z	height of control volume, m
h_{fw}	enthalpy of saturated water, evaluated as water temperature, kJ/kg	Z	cooling tower height, m

Greek Letters

α	thermal diffusivity, m^2/s
η	Efficiency
ρ	density, kg/m^3

Subscripts

a	air
evap	evaporation
env	environment
i	number of streams
in	inlet
min	minimum

Superscripts

l	lower limit
u	upper limit

ω	humidity of moist air, kg_w/kg_a
ω_{sw}	saturated humidity ratio at water temperature, kg_w/kg_a

n	maximum number of streams
out	outlet
rej	rejection
opt	optimum
w	water
WB	wet bulb

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