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Optimum design of cooling water systems for energy and water conservation

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ABSTRACT

Re-circulating cooling water systems (RCWSs) are widely used to reject waste process heat to the environment, conserve fresh water and reduce thermal pollution relative to once-through systems. Research on RCWS has mostly focused on individual components, cooling tower and heat-exchanger network. Kim and Smith [Kim, J.K. and Smith, R., 2001, Cooling water system design, Chem Eng Sci, 56(12): 3641–3658] developed a grass-root design method of RCWS (KSD). In this paper, the KSD method is expanded and a comprehensive simulation model of RCWS is developed accounting for interaction between cooling tower and heat-exchanger network. Regarding this model, a modern grass-root design method of RCWS, we call it Advanced Pinch Design (APD), based on combined pinch technology and mathematical programming is developed for minimum cost achievement. Having considered cycle water quality through introducing ozone treatment technology, APD methodology is further improved. This technique that we call Enhanced Cooling Water System Design (ECWSD), as the APD supplementary methodology, is provided water and energy conservation, minimum cost and environmental impacts. Related coding in MATLAB version 7.1 is developed for the illustrative example to get optimal values in RCWS design method computations. Finally the results of the introduced grass-root design methodologies, APD and ECWSD, are compared with KSD.

Keywords: Re-circulating cooling water system; Cooling tower; Pinch technology; Mathematical programming; Ozone treatment; Water-energy conservation

1. Introduction

Re-circulating cooling water systems (RCWSs) are by far the most common industrial waste process heat rejection systems to the environment. RCWS provides conservational opportunity for water and energy and pollution reduction relative to once-through systems because of water re-use possibility.

Previous related works, have been paid attention to issues of cooling water systems individually (Castro et al., 2000; Heikkila and Milosavljevic, 2001), water re-use and waste water minimization (Mann and Liu, 1999), numerical analysis of heat and mass transfer inside a reversibly used water cooling tower (Deng and Tan, 2003) and other operational aspects of cooling tower. Little consideration has been placed to the interaction between cooling tower and heat-exchanger network. To RCWS design, the effect of any possible changes of the system components on the cooling performance should be predicted properly. Therefore, the directly interacted cycle components should be considered simultaneously. Pinch technology as the most common design tools is helped. This technology is based on targeting before design and exploits conceptual understanding.

Kim and Smith (2001) represented a grass-root design methodology of RCWS. Kim and Smith Design (KSD) method allowed the existing interactions within the cooling water system to be considered. In the KSD method, the maximum water re-use profile (minimum water flow rate) is participated in the design of the network configuration. Moreover, fix approach

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Nomenclature

a_1, b, c	constant value of mass transfer coefficient
A	approach (°C)
A_0, B_0, C_0	constant value of vapor pressure
APD	advanced pinch design
B	blow-down (t/h)
C_P	water heat capacity (MJ/t °C)
C_{pa}	air heat capacity (MJ/t °C)
CC	capital cost (k$/yr)
dA	differential of cooling tower area (m^2)
D	drift loss (t/h)
E	evaporation loss (t/h)
ECWSD	enhanced cooling water system design
F_{air}	air flow rate (t/h)
F_{in}	cooling system inlet water flow rate (t/h)
F_{in}^{l}	cooling tower inlet water flow rate lower limit (t/h)
F_{in}^{u}	cooling tower inlet water flow rate upper limit (t/h)
F_1	outlet water flow rate of cooling tower (t/h)
F_2	inlet water flow rate to cooling tower (t/h)
h	pumping head (m)
h_a	air enthalpy (kJ/t)
h_d	convective heat transfer coefficient (kW/m^2 °C)
h_w	water enthalpy (kJ/t)
K_G	mass transfer coefficient of air (m/s)
KSD	Kim & Smith design
m_a	air flow rate at control volume
m_w	water flow rate at control volume
M	make-up (t/h)
M_i	initial make-up (t/h)
OC	operation cost (k$/yr)
P	total pressure (bar)
PP	pumping power (hp)
P^s	vapor pressure (bar)
Q	overall enthalpy (MJ/t)
Q_{ACT}	actual heat removal (MJ)
Q_c	enthalpy associated with convective transfer (MJ/t)
Q_{HEN}	overall network heat duty (MJ)
Q_m	enthalpy associated with mass transfer (MJ/t)
Q_{max}	maximum heat removal (MJ)
Q_i^{Pinch}	heat load at pinch point (MJ)
R	range (°C)
TC	total cost (k$/yr)
T_a	air temperature (°C)
T_{amb}	ambient temperature (°C)
$T_{HEN_{min}}$	minimum network temperature (°C)
T_{in}	cooling tower inlet water temperature (°C)
ΔT_{min}	minimum temperature approach of network (°C)
T_{MA}	minimum approach (°C)
T_{MN}	minimum temperature with respect to ΔT_{min} of the network (°C)
T_{MR}	temperature of max. water re-use at network (°C)
T_{NR}	temperature at which no re-use at network (°C)
T_{out}	cooling tower outlet water temperature (°C)
T_{TL}	temperature limitation (°C)
T_w	water temperature (°C)
T_{WB}	wet bulb temperature (°C)
T_i^{Pinch}	temperature at pinch point (°C)
V_i	water volume (m^3)
w_{air}	air humidity ratio (kgw/kga)
$w_{ga(WBT)}$	air humidity at wet bulb temperature (kgw/kga)
w_{in}	inlet air humidity (kgw/kga)
w_{out}	interface humidity ratio (kgw/kga)
$w_{sat(WBT)}$	saturated humidity at wet bulb temperature (kgw/kga)
X_B	concentration in blow-down
X_m	concentration in make-up
Z	cooling tower height (m)

Greek letters

η_P	pump efficiency
π_C	cycle of concentration
π_{C_i}	initial cycle of concentration
$\pi_{C_{ii}}$	new cycle of concentration
ρ_{water}	water density (kg/m^3)

value is considered in design procedure. However the minimum cooling water flow rate through the fix approach value does not necessarily ensure optimum value and the minimum cost of the cooling system.

In the present paper, the grass-root design methodology introduced by Kim and Smith (2001) (KSD) is expanded. The pinch technology in water system design is improved through principle concepts to make opportunities for energy saving. A new systematic approach for the optimum design of cooling water systems, Advanced Pinch Design (APD) method, is developed. The presented grass-root design method allowed interaction between the cooling tower performance and heat-exchanger network configuration to be considered simultaneously. Also, the influence of any probable changes of RCWS components on the whole cooling cycle is taken into consideration. To achieve the above objectives, the cooling tower and the cooling water network are studied separately. Furthermore, a model of cooling water systems is developed to examine the cooling performance and efficiency to re-circulation flow rate and return temperature. Finally, the design of the overall cooling water system is developed by investigating the interactions and process constraints. The APD methodology allowed optimal heat-exchanger network, accessible water and energy conservation to be achieved. Having considered cycle water quality by introducing ozone treatment technology, APD is further improved. This grass-root design technique, we call it Enhanced Cooling Water System Design (ECWSD), as the supplementary methodology of APD, is accomplished maximum water and energy conservation, minimum cost and environmental impacts.

2. Cooling tower and heat-exchanger network interaction

Conventional cooling water network design utilizes parallel configuration (Fig. 1) (Kim and Smith, 2001). In parallel configuration, fresh cooling water is supplied to individual heat-exchanger directly. The hot cooling water returns the cooling tower afterward.

Mixing water from individual heat-exchanger decreases inlet water temperature and increases inlet water flow rate of