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Synthesis cooling water system with air coolers

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ABSTRACT

Adding air coolers to cooling water system is an effective way to reduce heat load and the cost of cooling water system. It is also an effective method to prevent fouling and save water in the region where water is scarce. There is a trade-off between air cooler system and cooling water system. When heat load of air cooler is high, cooling tower consumes less fresh water, but the cost of air cooler can be high. Conventionally, the two systems are optimized separately. This paper presents an optimization model for synthesizing cooling water system with air coolers. The water coolers, air coolers, pumping scheme and cooling tower are simultaneously optimized. Each hot stream can be cooled down by air cooler to certain degree and then cooled down by water cooler to target temperature. Or it can be cooled down by the air cooler or water cooler exclusively. The model is formulated as mixed-integer nonlinear programming (MINLP) problem. The objective is to formulate the cooling water system with the minimizing total annual cost. The case is optimized under two cities with different prices of water and electricity. Results show that optimization model yields 29.4% and 13.1% TAC reduction. Results also indicate that it is particularly necessary to add air coolers to cooling water system in region where water is scarce and electricity price is low.

1. Introduction

Water cooling and air cooling are among the two most common methods that are employed to reject industrial waste heat to environment. Because water has suitable thermal properties and non-harmful chemical composition, cooling water system by far, has been widely used and thoroughly studied. The pioneer work conducted by Kim and Smith (2001) introduced mathematic model that emphasizes interaction between cooling tower and cooler network. Cooling water is reused in mixed parallel/series cooler arrangement, and cooling tower has better performance owning to low cooling water flow rate and high water return temperature. To reduce complexity and improve flexibility of cooler network, Feng et al. (2005) proposed a cooling water network with an intermediate main that is easy to control and operate. Introducing intermediate mains allows water to be reused which in turn leads to increase of tower efficiency. Research conducted by Castro et al. (2000) also focuses on reducing the operational cost of cooling water system by minimizing water flowrate. Because water cooling consumes fresh water and produces waste water, the system has certain impact on local environment. Panjeshahi et al. (2009) optimized cooling water system that involved environmental considerations as well as energy conservation. However, all the models previously mentioned mainly focus on minimizing water flowrate. In order to achieve the heat exchanging service, more contact areas are required. Later, Ponce-Ortega et al. (2007) proposed an MINLP model that considered the capital cost of coolers and cooling water cost simultaneously. In their work, stage-wise cooler network was proposed. The objective was minimizing the total cost and this model was more economical than other model previously mentioned. Few years later, they studied the detailed design of cooling tower, the optimization of cooling tower was based on MINLP model (Serna-González et al., 2010) and rigorous poppe model (Rubio-Castro et al., 2011). For optimizing cooling tower, Singh and Das (2017) optimized performance parameters and energy consumption of cooling tower simultaneously. Xie et al. (2017a,b) conducted experimental investigation as well as numerical analysis on

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Nomenclature

a,b,c,c_a	Constants of cooler capital cost
Af	Annualized factor
$Ar_a(i)$	Exchanger area of air cooler i
$Ar_w(i)$	Exchanger area of water cooler i
cp	Specific heat capacity of cooling water
Cf_{pump}	Fixed charge for pump
C_{pump}	Pressure cost coefficient for pumps
d_i	Internal tube diameter
$dt_{in}(i)$	Temperature approach between hot stream outlet temperature and cold stream inlet temperature in water cooler
$dt_{out}(i)$	Temperature approach between hot stream inlet temperature and cold stream outlet temperature in water cooler
$dt_{ain}(i)$	Temperature approach between hot stream outlet temperature and air inlet temperature in air cooler
$dt_{aout}(i)$	Temperature approach between hot stream inlet temperature and air outlet temperature in air cooler
e	Unit cost of electricity
f	Factor of friction
f_a	Air capacity flowrate rate
$fw(i)$	Mass flowrate of fresh cooling water in cooler E–i
$fin(i)$	Mass flowrate of cooling water in cooler E–i
G	Air mass velocity
G_{max}	Maximum air mass velocity
g_c	Gravitational constant
h	Annual operational time
$h(i)$	Film transfer coefficient of hot stream i
hw	Film transfer coefficient of cooling water
ha	Film transfer coefficient of air
k_t	Conductivity of cooling water
$Kt(i)$	Parameter used in relating physical properties to pressure drop
N_b	Number of bundles
$OC_{fan\text{-}tower}$	Operational cost of cooling tower fan
OC_{pump}	Pump operational cost
CC_{pump}	Pump capital cost
$p_{fan\text{-}cooler}$	Fan power consumption
$p_t(i)$	Cooler E–i tube pressure drop
Δp_{air}	Pressure drop of air cooler's fan
Δp_{total}	Total pressure drop of cooler network
$q_a(i)$	Heat load of air cooler i
$q_w(i)$	Heat load of water cooler i
$T_{ambient}$	Air inlet temperature of air cooler i
T_{aout}	Air outlet temperature of air cooler i
$Th_{aout}(i)$	Hot stream outlet temperature of air cooler i
$Th_{in}(i)$	Hot stream inlet temperature of air cooler i
$Th_{out}(i)$	Hot stream outlet temperature of water cooler i
ΔT_{min}	Minimum temperature difference
T_{fw}	Temperature of fresh cooling water
V_F	Face velocity of air cooler
V_{NF}	Actual face velocity of air cooler
w	Fresh water price
$Z_{i,j}$	Whether cooler E–i send the outlet cooling water to cooler E–j

Greek letter

Φ_t	Viscosity correction factor
μ_t	Cooling water viscosity
η_{pump}	Pump efficiency
$\eta_{fan\text{-}cooler}$	Cooler's fan efficiency
ρ	Density of cooling water
γ	Exponent for the pump cost function

heat transfer of wet cooling tower. Both of cooling tower and cooler network should be optimized simultaneously because of intrinsic interaction between them. Later, the simultaneously optimized model was proposed by Ponce-Ortega et al. (2010). In this work, they optimized pump, cooler network, and cooling tower all together, the most optimal configuration was presented. Although they proposed effective model to optimize cooling water system, the stage-wise cooler network they employed involved too many mixers and splitters, which leads to high complexity of system. In comparison with stage-wise network, series-parallel cooler network is more practical and flexible. Series-parallel network was employed in many research works (Ma et al., 2017; Sun et al., 2015). And it turns out the series-parallel network is an effective configuration to increase the water reuse and decrease the total annual cost of system.

All the literatures cited above are grassroots design problem. Retrofitting the existed cooling water system also has the great significance in industry, and many scholars studied the retrofitting problem. As mentioned before, when coolers are arranged in series configuration, cooling water is reused, which leads to the increase of tower performance. But coolers cannot be arranged arbitrarily. The problem that which pair of coolers should be arranged in series has to be addressed. Wang et al. (2014) have proposed the two-step method to convert parallel configuration into series-parallel structure without adding more contact area. Retrofitting parallel cooler network into series-parallel network will reduce water flowrate. However, because coolers are in series connection, the pressure drop will increase, which requires more pumping energy to transport cooling water. To cope with pressure drop effects, many optimization model of cooling water network considering pressure drop were proposed (Kim and Smith, 2003; Gololo and Majozi, 2013). Except converting cooler network into series arrangement, other researchers proposed optimization model that considering piping cost (Reddy et al., 2013), or adds new cooler to system (Picón-Núñez et al., 2012).

Cooling water system has been studied for a long period of time. Another common cooling method, the air cooling, has also been studied by many scholars. Doodman et al. (2009) proposed optimized model for designing air cooler. Detailed design of air cooler is quite complex, so they employed global sensitivity analysis and harmony search algorithm to optimized the air cooler. Manassaldi et al. (2014) proposed disjunctive mathematical model for the optimal design of air cooler, which minimize the heat transfer area as well as the fan power consumption. Kashani et al. (2013) addressed conflict between temperature approach and the total annual cost by employing non-dominated sorting genetic-algorithm. Their work presented proper procedure for selecting and designing air cooler. Other researchers studied the environmental effects on air cooler, like the freezing of air cooler (Chen et al., 2016; Wang et al., 2017), or the impact of ambient air temperature (Fahmy and Nabih, 2016) or the fouling effects (Kuruneru et al., 2016).

Air cooling and water cooling have been studied over a long period of time due to their extraordinary cooling capacity. However, no researchers have ever combined both cooling mechanisms in a single system to obtain the optimal matches between air cooling and water cooling. Air heat capacity (1.004 kJ/(kg K)) is only a quarter of water heat capacity (4.183 kJ/(kg K)). Cooling down a same hot stream, the air mass flowrate of air cooler is four more times than the water mass flowrate of the water cooler. The film transfer coefficient heat capacity of air are lower than the coefficients of water, air cooler always has

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