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Optimization of Cooling Water System with Precooling Air Cooler

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Each year, large quantity of fresh water is consumed by cooling water system. Installing air coolers in cooling water system leads to a reduction on work load of cooling tower and saves on fresh water. This paper gives an optimization model for formulating cooling water system with air coolers. The air coolers are used to cool down the process hot streams as well as the returned cooling water. One precooling air cooler is used to cool down the returned cooling water before the water entering the tower. Besides, branch air coolers are considered for cooling down the returned cooling water on the branches of cooler network. The cooler network, air coolers, and cooling tower are optimized simultaneously. The objective of this work is to obtain framework with minimum cost. Case study taken from existing literature is employed to show the effectiveness of proposed model. Final results indicate that introducing precooling air cooler in grassroots design problem can reduce both fresh water consumption and total cost.

1. Introduction

Cooling water system is widely used in industry, especially in energy sector. Many methods have been proposed for designing an energy saving and environmentally friendly cooling water system.

Cooling water can be properly reused by designing an optimal cooler network. When the cooling water is reused, the flowrate of cooling water reduced and returned temperature increased. Therefore, the efficiency of cooling tower increased and the energy consumption of cooling tower decreased. Kim and Smith (2001) first introduced a mixed parallel/series cooler arrangement, cooling water is reused between different coolers. Later, Ponce-Ortega et al. (2007) proposed an MINLP model where capital cost of coolers and cooling water cost were considered simultaneously. Not only the water was reused, but also the overall cost of system was minimized. Zhu et al. (2017) investigated the operation of cooler network. Based on their superstructure approach, the operation cost of system was largely reduced. Liu et al. (2017) considered fouling problem in cooling water system design.

In order to transport cooling water from tower to coolers, pumps consumed a huge quantity of electricity. Designing the energy saving pump network can help reduce the energy consumption of system. Sun et al. (2014) first proposed main-auxiliary pump network. With the installation of auxiliary pumps, the pressure head of main pump is largely reduced and the overall electricity consumption is reduced. Gao et al. (2017) formulated machinery network of cooling water system, the pumps and hydro turbines are included. They explored the power target of cooling water system. The formulated machinery network recovered a large amount of pressure energy of cooling water system. Souza et al. (2017) studied the hydraulic performance of cooling water system. They gave a detailed guide on the installation of pump and pipe for reducing the energy consumption of system.

Apart from the large energy demand, cooling water system also consumes a huge amount of fresh water. It has been reported that 60-70% of industrial fresh water is consumed by cooling water system each year. Rahmani (2017) reduced the fresh water consumption by changing cycles of concentration, the scaling inhibitor is used to prevent scaling of coolers and reduce the discharged waste water of cooling tower. Altman et al. (2012) employed pressure driven membrane to purify the side stream of recirculating cooling water, it has been reported that near a half of discharged water was saved. Walker et al. (2013) utilized the treated

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municipal wastewater as a source of tower makeup water, and reduced the fresh water consumption of system. Although the water treatment techniques can largely reduce fresh water consumption of cooling water system, the corresponding cost and energy demand are significant. Instead of purifying the water, reducing the heat load of cooling tower is a promising method for saving fresh water. Ma et al. (2017) proposed a two stage cooling method where air coolers are introduced to cooling water system. In their work, 50% of the heat load on cooling tower was reduced.

Based on the study of Ma et al. (2017), this paper presents a model that introducing precooling air coolers to cooling water system. Different from their work, precooling air coolers are coolers that used for cooling down hot cooling water. It cools down the returned cooling water before the water entering the tower so that the heat duty of cooling tower can be reduced. The proposed model redistributed the heat load between air cooler, precooling air cooler and cooling tower. Air cooling cost and cooling tower, as well as other cost were optimized simultaneously. A case study is used to show the effectiveness of the method. The trade-off between air cooling cost, fresh water cost and water treatment cost is studied.

2. Model formulation

2.1 Formulation of heat exchanger network

The detailed design of air cooler and cooling tower can be seen in the work of Ma et al. (2017). This section describes the superstructure of heat exchanger network, both of air and water cooler are included. As shown in Figure 1, the hot stream is transported into the air cooler. At second stage, the cooling water cools down the hot stream to target temperature. The cooling water is either fresh water or used water. The used water of each cooler is transported to other coolers or cooling tower.

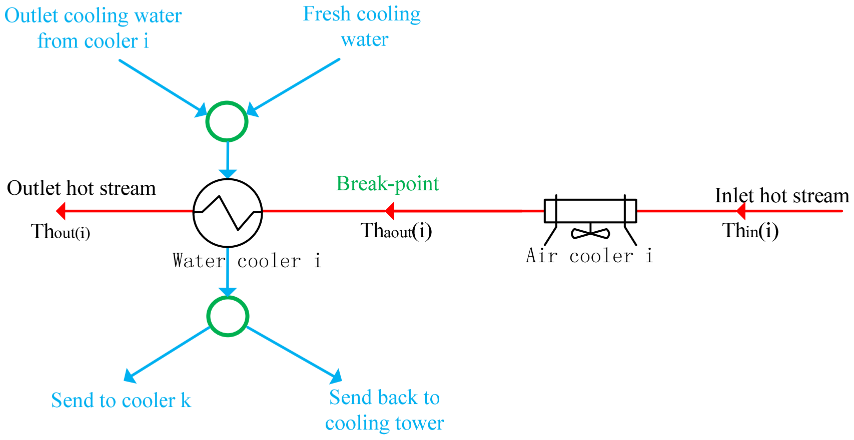

Figure 1: Superstructure of heat exchanger network (from Ma et al. (2017))

In Eq.(1), $q_a(i)$ is the amount of heat transferred at air cooler i, $Th_{in}(i)$ and $Th_{aout}(i)$ are inlet and outlet temperature of hot stream i, fh(i) is heat capacity flowrate of hot stream. $T_{ambient}$ and $T_{aout}(i)$ are the air temperature on both side of cooler, fa(i) is air heat capacity flowrate.

$$q_a(i) = (Th_{in}(i) - Th_{aout}(i)) \cdot fh(i) = (T_{aout}(i) - T_{ambient}) \cdot fa(i) \tag{1}$$

In Eq.(2) and Eq.(3), dt_{ain} and dt_{aout} are temperature difference on both sides of air cooler. Temperature difference should not be smaller than the minimum temperature difference of air cooler. In Eq.(4), Ar_a is air cooler contact area, h(i) and h_a represent the film transfer coefficients.

$$Th_{in}(i) - T_{aout}(i) = dt_{ain} \ge \Delta T_{min} \tag{2}$$

$$Th_{aout}(i) - T_{ambient} = dt_{aout} \ge \Delta T_{min} \tag{3}$$

$$Ar_a(i) = \frac{q_a(i)}{\left[dt_{ain}(i) \cdot dt_{aout}(i) \cdot \frac{dt_{ain}(i) + dt_{aout}(i)}{2} \right]^{1/3}} \cdot \left(\frac{1}{h(i)} + \frac{1}{h_a}\right) \tag{4}$$

In this work, cooling water is reused between different coolers. Binary variable Z(i,j) denotes the connection pattern between different coolers. When the value of Z(i,j) equals to 1, cooler E-i and cooler E-j are connected. As shown in Eq.(5), outlet cooling water of each cooler is transported to no more than one cooler.

$$\sum_{j=1}^{n} Z_{i,j} \le 1 \tag{5}$$

As shown in Eq.(6), each cooler cannot accept the outlet water from more than one cooler.

$$\sum_{i=1}^{n} Z_{i,j} \le 1 \tag{6}$$

Eq.(7) is employed for defining inlet temperature of each cooler. Tin(i) and Tout(i) are the temperature on both sides of cooler E-i. T_{fw} is the temperature of water from cooling tower. When cooler E-i use the water from cooling tower water, the inlet temperature of cooler E-i equals to temperature of water from cooling tower. Meanwhile, when cooler E-i accepts water from cooler E-j, the inlet temperature of cooler E-i equals to outlet temperature of cooler E-j.

$$T_{in}(i) = T_{fw} \cdot \left[1 - \sum_{j=1}^{n} Z_{j,i} \right] + \sum_{j=1}^{n} (Z_{j,i} \cdot T_{out}(j)) \tag{7}$$

Eq.(8) defines the flowrate of each cooler. fw(i) is the quantity of water transported from cooling tower to cooler E-i. fin(i) is the total water flowrate of cooler E-i.

$$fin(i) = fw(i) \cdot \left[1 - \sum_{j=1}^{n} Z_{j,i} \right] + \sum_{j=1}^{n} (Z_{j,i} \cdot fw(j)) \tag{8}$$

In Eq.(9), ft represents total flowrate of cooling water. The amount of total water flowrate equals to the sum of fresh water flowrate of each cooler.

$$ft = \sum_{i=1}^{n} fw(i) \tag{9}$$

Eq.(10) defines the heat load of each cooler.

$$q_w(i) = (Th_{aout}(i) - Th_{out}(i)) \cdot fh(i) = (T_{wout}(i) - T_{win}(i)) \cdot cp \cdot fin(i) \tag{10}$$

In Eq.(11) $dt_{in}(i)$ and $dt_{out}(i)$ are temperature difference on both sides of cooler. h(i) and h_w are the heat transfer coefficients of hot stream and cooling water. Ar_w is the exchanger area

$$Ar_w(i) = \frac{q_w(i)}{\left[dt_{in}(i) \cdot dt_{out}(i) \cdot \dfrac{dt_{in}(i) + dt_{out}(i)}{2} \right]^{1/3}} \cdot \left(\frac{1}{h(i)} + \frac{1}{h_w} \right) \tag{11}$$

Temperature difference should not be smaller than the minimum temperature difference. $Th_{aout}(i)$ and $Th_{out}(i)$ are inlet temperature of hot stream in water cooler and outlet temperature of hot stream.

$$dt_{in}(i) = Th_{out}(i) - T_{in}(i) \ge \Delta T_{\min} \tag{12}$$

$$dt_{out}(i) = Th_{aout}(i) - T_{out}(i) \ge \Delta T_{\min} \tag{13}$$

Pumps are installed for transporting cooling water from tower to cooler. To transport cooling water, pumps have to overcome the pressure drop among the tube side of cooler. In this paper, only the tube side pressure drop is considered. In Eq(14), p_t represents the pressure drop along the tube side. Kt denotes the coefficient of pressure drop, which depends on the parameters of streams.

$$p_t(i) = Kt(i) \cdot Ar(i) \cdot ht^{3.5} \tag{14}$$

2.2 Formulation of precooling air cooler and branch air coolers

As shown in Figure.1, the returned cooling water is cooled down by precooling air cooler at first stage. The heat load of precooling air cooler is given by Eq.(15).

$$q_{precooling} = (T_{tin} - T_{precooling}) \cdot Cp \cdot ft \tag{15}$$

Meanwhile, the inlet temperature of cooling tower is lower than the inlet temperature of precooling air cooler.

$$T_{tin} \le T_{precooling} \tag{16}$$

The objective is to minimize total annual cost. TAC of system includes capital and operation cost of pumps, air coolers, water coolers and cooling tower.

$$TAC = Af \cdot \left[Cf_{pump} + C_{pump} \left(\frac{ft \cdot \Delta p}{\rho} \right) \right] + \frac{ft \cdot \Delta p}{\rho \cdot \eta_{pump}} \cdot e \cdot h + Af \sum_{i=1}^{n} \left[a + b \cdot Ar_w^c(i) \right] + Af \sum_{i=1}^{n} \left[C_a + b \cdot Ar_a^c(i) \right] \tag{17}$$
$$+ Af \left[c_{precooling} + Ar_{precooling}^c \right] + e \cdot h \cdot P_{fan} + CC_{tower} + OC_{tower}$$

In this study, the model is formulated as MINLP problem. GAMs software is used to solve the problem.

3. Case study

To verify the cost saving and water saving potentials of proposed model, one case taken from Ma et al. (2017) is employed. In Ma’s work, air cooler is only used to cool down the hot streams. The water consumption is largely reduced, owning to the installation of air coolers. Figure 2 is the optimized configuration of this work. Apart from the air coolers that are used for cooling the hot streams, one precooling air cooler is employed for cooling down the returned cooling water. As shown in Figure 2, seven air cooler are used to cool down the hot streams, the returned temperature of cooling water is 54.6 °C. The precooling air cooler cooled down the returned cooling water from 54.6 °C to 40 °C. The heat load on the precooling air cooler is 13,405 kW. In comparison with the base case, the heat load on the cooling tower has reduced from 29,496 kW to 16,356 kW. Meanwhile, the water consumption of cooling water reduced from 14.4 kg/s to 8.82 kg/s, because of the reduction on the heat load of cooling tower. Therefore, 160,000 ton of fresh water can be saved each year.

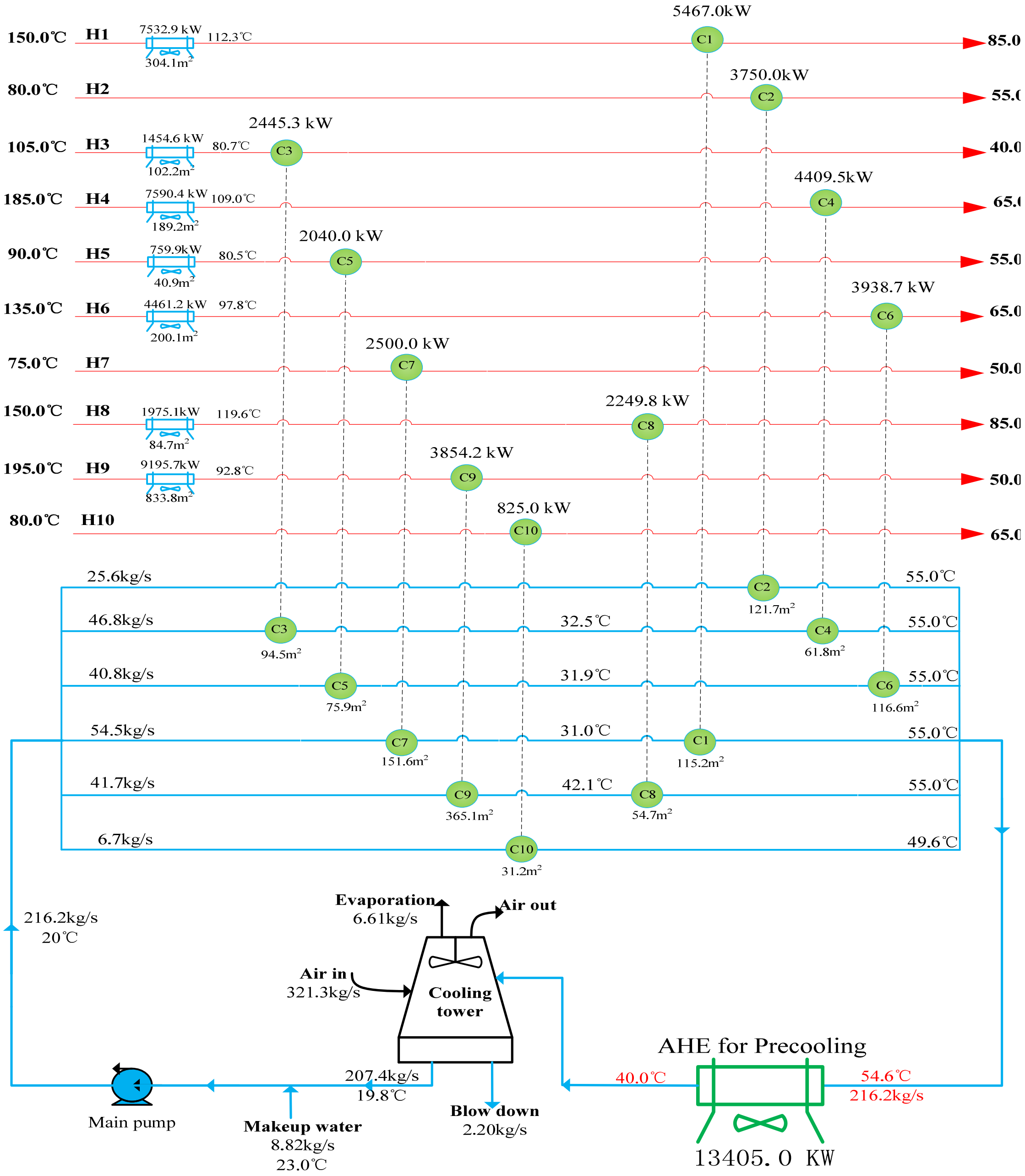

Figure 2: Cooling water system with AHE precooling

Introducing the air cooler for precooling the returned cooling water can reduce both water consumption, and the cost of system. A sensitivity analysis on the partition temperature of precooling air cooler and cooling tower is conducted. Figure 3 is employed to display the effect of partition temperature on the cost of cooling tower and precooling air cooler. As shown in Figure 3, when the partition temperature is 40 °C, the combined cost of precooling air cooler and cooling tower is the smallest.

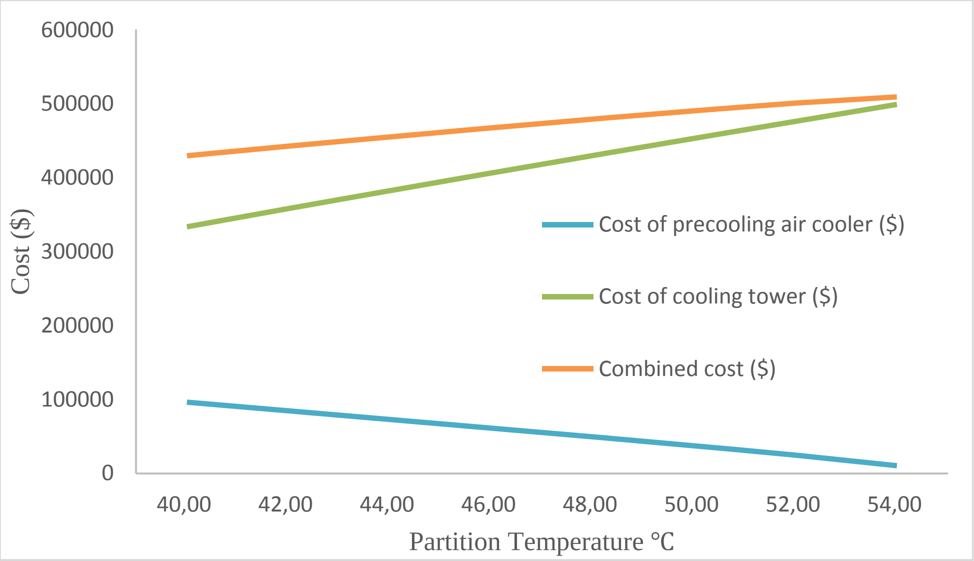

Figure 3: Cost of CT and AHE with different partition temperature

Figure 4 is used to compare the cost of optimized structure and base case study. The capital cost of water cooler and air cooler for hot streams are almost the same. However, with the installation of precooling air cooler, the cost of cooling tower has reduced significantly. This is because the heat load on cooling tower has reduced by 44.5%. The fan cost as well as fresh water cost of cooling tower are reduced. As shown in the pie chart, for the base case study, the cost of cooling tower occupied more than 50% of TAC. Meanwhile, for the optimized configuration, the cost of cooling tower only occupied 39% of TAC but precooling air cooler needs a large amount of investment. Finally, the total annual cost of optimized configuration of this study is $ 832,058, which is 7.6% lower than the total annual cost of structure of base case ($ 900,272).

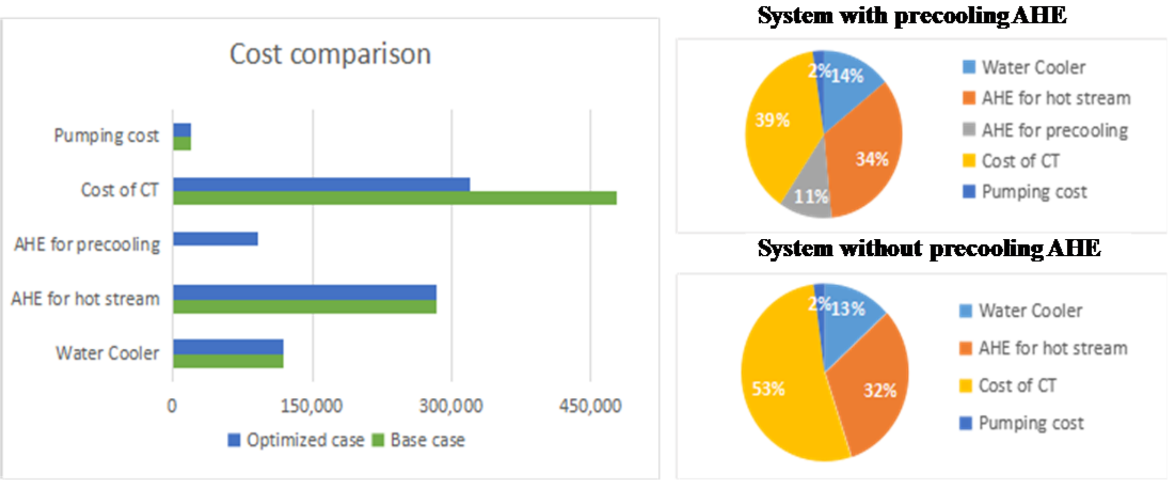

Figure 4: Comparison of Cost

Figure 5 is the heat load distribution of air coolers and water coolers. After introducing precooling air cooler, the proportion of heat load of water cooling reduced from 46% to 28%.

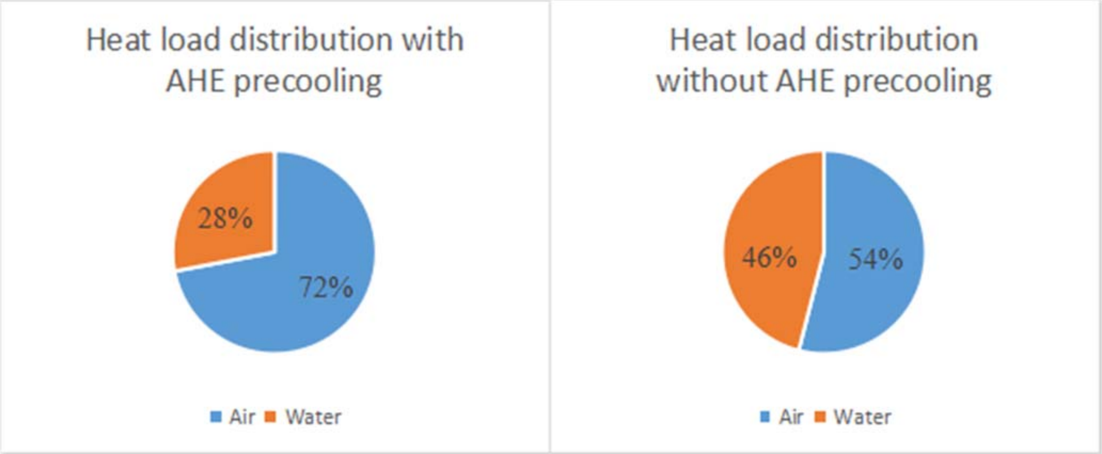

Figure 5: Comparison of heat load distribution

4. Conclusions

In this paper, a new model that considered the precooling air cooler in cooling water system is presented. Different from convention air cooler, precooling air cooler is used to cooling down cooling water rather than hot process streams. In case study, after introducing precooling air coolers to the system, 7.6% reduction on the total annual cost and 44.5% reduction on the fresh water consumption are yielded, owning to the reduction on the heat load of cooling tower. The optimal partition temperature between precooling air cooler and cooling tower is obtained. The obtained results indicate that cooling down the returned cooling water by air cooler can largely reduce water consumption of cooling water system. The proposed model can be utilized as an effective method for reducing the water consumption of cooling water system.

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