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Simultaneous Optimisation of Cooler and Pump Networks for Industrial Cooling-Water Systems

Jin Sun[a], Xiao Feng*[,b], Yufei Wang[b]

[a]College of Chemistry and Chemical Engineering, Southwest Petroleum University, Chengdu, China, 610500
[b]State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing, China, 102249
xfeng@cup.edu.cn

For a cooling water system (CWS), the cooling water (CW) from a cooling tower is supplied to the cooler network that usually has a parallel configuration. Re-use of CW between different coolers has been proved to be an effective way to reduce CW flow-rate and increase the capacity of cooling tower for a new design and retrofit. However, coolers with series configurations require a higher pressure head of the corresponding branch pipe. In order to minimise the power consumption, a novel methodology is proposed to simultaneously consider CW reuse exploration in the cooler network and pump arrangement in the pump network. The total annualised cost of cooling water systems (CWSs) is taken as its objective function, including CW cost, pumping cost and capital cost of coolers and pumps. A superstructure of CWSs is developed to consider the interactions between the design of cooler network and the performance of pumps. The proposed model is tested by a case study based on the simplified CWS of a refinery.

1. Introduction

CW is widely used as cold utility in industries. The main components of CWSs include a cooler network and a pump network. Because of the interactions between the pipeline characteristic curve and pump characteristic curve, the cooler network and pump network of CWSs should be designed or optimised simultaneously. Conventional design of a cooler network has parallel configuration, in which fresh CW is supplied to each individual cooler directly, leading to high water flowrate and a poor performance of cooling tower. However, not all hot process streams require the CW inlet temperatures equal the supply one from cooling tower. It is possible to reutilise the outlet CW of some coolers for some others. Cooler network optimisation received much attention in recent decades. Klemeš (2012) provided a brief overview of the recent techniques and methodologies in industrial water reuse/recycle. Kim and Smith (2001) minimised the total flow-rate of cooler networks based on pinch analysis. Feng et al. (2005) considered the reuse of CW between coolers and proposed the cooler network models which is solved by LINGO. Chen et al. (2007) did the similar research but solve the mathematic model with GAMS.

However, the total pressure drop might increase accordingly as a result of modifying the parallel configuration of cooler network to series or series-parallel configurations. Hence, the pressure head of the main pump on the header pipe would be increased to match the pipeline characteristic curve of series or series-parallel configurations. Adding auxiliary pumps properly before coolers has been verified to be an effective way to avoid the energy penalty associated with the increased pressure head, thereby reducing the operation cost of pumps (Sun et al., 2014a). The method proposed by Sun et al. (2014a) of installing auxiliary pumps on some branch pipes is adopted in this paper. The pump heads of main pumps and auxiliary pumps are the decision variables to be optimised. Sun et al. (2014b) proposed a novel sequential method to optimise the CWS but did not consider the interaction between the cooler network and the pump network. In this paper, a superstructure based model to simultaneously optimise CWSs is constructed to consider the interaction of configurations between cooler network and pump network.

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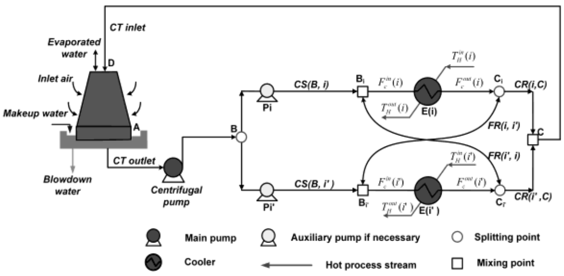
2. Mathematical Model

2.1 Superstructure

Figure 1 illustrates a superstructure of CWS with a cooling tower, a main pump, auxiliary pumps and coolers. All of the piping options for connecting between the splitting node B and inlet mixing node of cooler E(i'), and among outlet splitting node of cooler E(i), inlet mixing node of cooler E(i'), and node C are incorporated in the superstructure. The main pump is installed between the start node A and node B. The possible location of an auxiliary pump is between node B and the inlet mixing node B_i of cooler E(i).

Figure 2 demonstrates the pressure distribution of each node, pressure drop of each pipe section and possible locations of auxiliary pumps. $\Delta P_{\text{main}}^{\text{pump}}$ and $\Delta P_{auxi,B\rightarrow i}^{pump}$ indicate the pressure elevation of main pumps and auxiliary pumps, respectively. The dotted lines indicate possible existence of connecting pipes. The binary variable $y_{auxi}^{pump}(\mathrm{B,i})$ indicates the existence of auxiliary pumps.



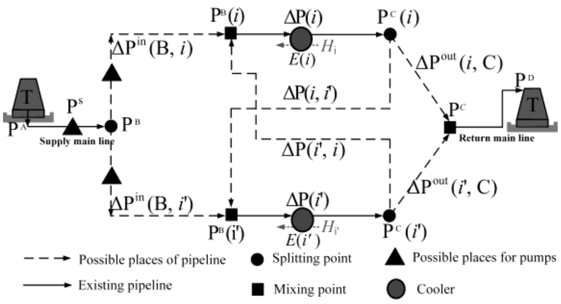


Figure 1: A Superstructure of CWSs *Figure 2: Pressure Drop Description of CWSs*

2.2 Constraints of cooler network

The balances of heat capacity flow-rates of the cooling tower and coolers are shown as follows.

$$F_{RW} = \sum_{i \in I} CS(B,i), \qquad \forall i \in I \tag{1}$$

$$F_{RW} = \sum_{i \in I} CR(i,C), \qquad \forall i \in I \tag{2}$$

$$F_c^{in}(i) = CS(B,i) + \sum_{i' \in I} FR(i',i), \qquad \forall i \in I, i' \neq i \tag{3}$$

$$F_c^{out}(i) = CR(i,C) + \sum_{i' \in I} FR(i,i'), \qquad \forall i \in I, i \neq i' \tag{4}$$

$$F_c^{in}(i) = F_c^{out}(i), \qquad \forall i \in I \tag{5}$$

The upper and lower bound of CW flow-rates through cooler *E*(i) can be calculated from Eq(6)-(7).

$$F_c^{\,in,U}(i) = \frac{Q(i)}{c_p[T_c^{out,U}(i) - T_c^{in,U}(i)]}, \qquad \forall i \in I \tag{6}$$

$$F_c^{\,in,L}(i) = \frac{Q(i)}{c_p[T_c^{out,U}(i) - T_c^{in,L}(i)]}, \qquad \forall i \in I \tag{7}$$

CW temperature bounds through each cooler *E*(i) are shown in Eq(8), Eq(9) and Eq(10).

$$T_c^{out,U}(i) = \min\left\{T_H^{in}(i) - \Delta T_{\min}, T_c^{ret,U}(T)\right\}, \qquad \forall i \in I \tag{8}$$

$$T_c^{in,U}(i) = \min\left\{T_H^{out}(i) - \Delta T_{\min}, T_c^{ret,U}(T) - t_{\min}\right\}, \qquad \forall i \in I \tag{9}$$

$$T_c^{in,L}(i) = T(S), \qquad \forall i \in I \tag{10}$$

$F_c^{\,in,U}(i)$ and $F_c^{\,in,L}(i)$ are defined as upper and lower bounds of CW stream for each cooler *E*(i).

$$F_c^{\,in,L}(i) \leq F_c^{in}(i) \leq F_c^{\,in,U}(i), \qquad \forall i \in I \tag{11}$$

Energy balance for cooler *E*(i) is shown in Eq(12).

$$Q(i) = F_c^{in}(i) \cdot [T_c^{out}(i) - T_c^{in}(i)], \qquad \forall i \in I \tag{12}$$

The inlet temperature of cooler *E*(i) can be defined as:

$$T_c^{in}(i) = \frac{CS(B,i) \times T(S) + \sum FR(i',i) \times T_c^{out}(i')}{F_c^{in}(i)}, \qquad \forall i, i' \in I, i' \neq i \tag{13}$$

Substituting the term $T_c^{in}(i)$ into Eq(12), the energy balance for cooler *E*(i) can be written as Eq(14).

$$CS(B,i) \times T(S) + \sum FR(i',i) \times T_c^{out}(i') + Q(i) = F_c^{in}(i) \times T_c^{out}(i), \qquad \forall i, i' \in I, i' \neq i \tag{14}$$

The bilinear terms in Eq(14) lead to concave characteristic of constraints and are difficult to solve in GAMS. Majozi and Moodley's (2008) method of replacing $T_c^{out}(i)$ with $T_c^{out,U}(i)$ is referred in this paper to avoid the bilinear terms because a CWS in which every cooler has maximum outlet temperature will require minimum CW flowrate from the cooling tower. This becomes a necessary condition for optimality in CWSs. Imposing this condition in constraints (14) allows the energy balance equation to be linearised without any loss of optimality and guarantees a globally optimal solution. Hence, Eq(14) can be represented as Eq(15).

$$CS(B,i) \times T(S) + \sum FR(i',i) \times T_c^{out,U}(i') + Q(i) = F_c^{in}(i) \times T_c^{out,U}(i), \qquad \forall i, i' \in I, i' \neq i \tag{15}$$

$ys(B,i)$, $yr(i,C)$ and $y(i,i')$ are the binary variables indicating the existence of pipe connection from the splitting node *B* to inlet mixing node of cooler *E*(i), the outlet splitting node of cooler *E*(i) to the mixing node *C* and between the outlet splitting node of cooler *E*(i) and inlet mixing node of cooler *E*(i'), respectively.
In order to restrict the complexity of cooler network and keep it easy to operate, the upper bound of cooler's inlet streams should be limited to no more than the specified upper bound, $NS^U(i)$.

$$y(T,i) + \sum_{i' \in I} y(i',i) \leq NS^U(i), \qquad \forall i, i' \in I, i \neq i' \tag{16}$$

2.3 Constraints of Pump Network

The pressure difference between nodes consists of piping frictional pressure drop and static pressure difference due to elevation of nodes. The node B_i and C_i represent the inlet mixing and outlet splitting nodes of cooler *E*(i). The starting node *A* and ending node *D* represent the CW outlet and inlet location of the cooling tower. The splitting node *B* and mixing node *C* represent the header line positions where fresh CW is distributed to coolers and hot water from coolers return directly to the cooling tower. P^A , $P^B(i)$, $P^C(i)$ and P^D indicate the pressure of node *A*, B_i , C_i and *D*. The pressure constraints of CWS are given as follows:

$$P^A + \Delta P_{main}^{pump} + \Delta P_{auxi,B \to i}^{pump} - P^B(i) + LV \times [1 - ys(B,i)] \geq \Delta P^{in}(A,B) + \Delta P^{in}(B,i), \qquad \forall i \in I \tag{17}$$

$$P^C(i') - P^B(i) + LV \times [1 - y(i',i)] \geq \Delta P(i',i), \qquad \forall i, i' \in I, i \neq i' \tag{18}$$

$$P^B(i) - P^C(i) = \Delta P(i), \qquad \forall i \in I \tag{19}$$

$$P^C(i) - P^D + LV \times [1 - yr(i,C)] \geq \Delta P^{out}(i,C) + \Delta P^{out}(C,D), \qquad \forall i \in I \tag{20}$$

where, $\Delta P^{in}(B,i)$ represents the pressure difference between the splitting node B and inlet mixing node of cooler *E*(i). $\Delta P(i',i)$ indicates the pressure difference between the outlet splitting node of cooler *E*(i') and inlet mixing node of cooler *E*(i). $\Delta P^{out}(i,C)$ denotes the pressure difference between the outlet splitting node of cooler *E*(i) and mixing node *C*. $\Delta P(i)$ represents the pressure drop of cooler *E*(i), which is calculated based on the linear correlation proposed by Reddy et al. (2013).

$$\Delta P(i) = \alpha_i \cdot F_c^{in}(i) + \beta_i \tag{21}$$

According to the "critical path algorithm" (Kim et al., 2003), the overall pressure drop of CWSs cannot be calculated until its configuration is known. To address the problem without knowing the configuration of CWSs in advance, Eq(17), Eq(18), and Eq(20) for the connections between each mixing and splitting node are formulated with the aid of binary variables which are introduced with a sufficiently large value to consider whether this constraint is activated or not. The pressure difference between nodes can be calculated by the linear equation proposed by Reddy et al. (2013).
For example, the pressure difference between the node B and node B_i can be expressed as Eq(22).

$$\Delta P^{in}(B,\ i) = [-0.0096 \times CS(B,i) + 9.0925 \times ys(B,i)] \times \frac{L_p(B,i)}{100} + h(i) \times ys(B,i) \times g \qquad (22)$$

$ys(B,i)$ is the binary variable for the absence (= 0) or the presence (= 1) of flow and pipe from the node *B* and node B_i. Note that this binary variable is multiplied by only the constant term in the linear piping pressure drop expression, which leads to the MILP model. The elevations of the node *A*, *B* and *C* are assumed to be zero because they are located on the main pipe laid just underneath the ground. $h(i)$ is the height of cooler *E*(i) compared to the ground. The elevations of the node B_i and C_i are the height of coolers, $h(i)$. The elevation of node *D* is the height of cooling tower, h_T.

2.4 Objective Function

The total annualised cost of a CWS, consisting of CW cost, pumping cost and capital cost of coolers and pumps, is taken as the objective function.

$$\text{obj} = \text{cost}_s^{cw} + \text{cost}_{main}^{pump,op} + \sum_{i \in I} \text{cost}_{auxi,B \to i}^{pump,op} + \delta_{pump} \frac{I_{CE}}{I_{CEbase}^{pump}} (\text{cost}_{main}^{pump,cap} + \sum_{i \in I} \text{cost}_{auxi,B \to i}^{pump,cap}) + \delta_{cooler} \frac{I_{CE}}{I_{CEbase}^{cooler}} (\sum_{i \in I} \text{cost}_i^{cooler}) \qquad (23)$$

CW cost is related to annual operating hour of equipment and unit cost of CW.

$$\text{cost}_s^{cw} = 3,600 \frac{C^{cu} F_{RW} H_Y}{c_p} \qquad (24)$$

The pumping cost is related to annual operating hour and unit cost of electricity. The investment cost of pumps can be correlated with shaft power and their relationship linearised by Reddy et al. (2013) is used in this paper. The way to calculate the operating cost and capital cost of auxiliary pumps are demonstrated in Eqs(25)-(27). The costs associated with main pumps are calculated in a similar manner.

$$\text{cost}_{auxi,B \to i}^{pump,op} = c^e \cdot P_{auxi,B \to i}^{pump} \cdot H_Y \qquad (25)$$

$$\text{cost}_{auxi,B \to i}^{pump,cap} = \gamma \cdot P_{auxi,B \to i}^{pump} + \kappa \cdot y_{auxi}^{pump}(B,i) \qquad (26)$$

$$P_{auxi,B \to i}^{pump} = \frac{CS(B,i) \cdot \Delta P_{auxi,B \to i}^{pump}}{\rho \cdot c_p \cdot \eta_{auxi}^{pump} \cdot \eta_{auxi}^{motor}} \qquad (27)$$

Hence, the cost terms in the objective function can be substituted by the above equations. The only nonlinear term in the calculation of shaft power make the optimisation problem as a NLP model.

Because the outlet temperature of CW is fixed to equal the upper bound of CW outlet temperature for each cooler, the variables of coolers lies in the inlet temperature and flowrate of CW. It can be deduced that the inlet temperature of CW only relates to its inlet flowrate. So the investment cost of coolers can be linearised as Eq(32) from Eq(28) to Eq(31), which has linear relationship with CW inlet flow-rates of coolers.

$$Q(i) = F_c^{in}(i) \cdot [T_c^{out,U}(i) - T_c^{in}(i)], \qquad \forall i \in I \qquad (28)$$

$$\text{cost}_i^{cooler} = a + b(A_i^{cooler})^{\beta}, \qquad \forall i \in I \qquad (29)$$

$$A_i^{cooler} = (1/h_i + 1/h_{cu}) \cdot Q(i) / \Delta t_m(i), \qquad \forall i \in I \qquad (30)$$

$$\Delta t_m(i) = 0.5 \cdot [(T_H^{in}(i) - T_c^{out,U}(i)) + (T_H^{out}(i) - T_c^{in}(i))], \qquad \forall i \in I \qquad (31)$$

$$\text{cost}_i^{cooler} = a' \cdot [F_c^{in}(i)] + b', \qquad \forall i \in I \qquad (32)$$

3. Case study

The example, taken from Ponce-Ortega et al. (2007), is used as the case study. The CW temperature rise of each cooler for the original parallel configuration is assumed to be 10 °C. Figure 3 demonstrates the original parallel configuration of the cooler network. The head loads, and temperatures of hot streams, CW flow-rates and heights of coolers and minimum pressure heads of parallel branch lines are shows in Table 1. The inlet temperature for the CW is 20 °C and the maximum allowable return temperature of the CW is 55 °C. The annual operating time is assumed to be 8,000 h/y and the annualised factor (A_{f1}) for capital cost of coolers and pumps to be 0.2983 and 0.398. The C_{pc} for the cold utility is taken as 4.18 kJ/(kg °C), the film heat transfer coefficient for the side of the cold utility as 2.5 kW/(m^2 °C), and the unit cost of CW and electricity as 5.0×10^{-6} $/kg and 0.53 $/kWh.

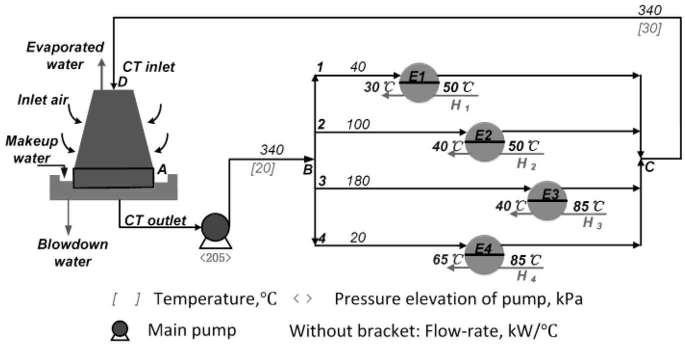


Figure 3: Original Parallel Configuration of Cooler Network for the Base Case.

Table1: Data of hot process streams and coolers for the original parallel configuration

Stream	$T_H^{in}(i)$ (°C)	$T_H^{out}(i)$ (°C)	h kW/(m^2°C)	Q_i (kW)	Cooler	$F_c^{in}(i)$ (kW/°C)	$h(i)$ (m)	H_{min} (kPa)
H_1	50	30	0.854	400	E_1	40	15	98.4
H_2	50	40	0.743	1,000	E_2	100	5	128.7
H_3	85	40	0.72	1,800	E_3	180	8	205.2
H_4	85	65	1.352	200	E_4	20	10	93.0
-	-	-	-	-	*Tower*	340	5.5	-

Table 2 presents the distance matrix for the Case Study.

Table 2: Distance between nodes for the case (unit: m)

Node	E_1	E_2	E_3	E_4	A	D
B	50	60	50	80	80	-
E_1	0	60	120	170	-	-
E_2	60	0	40	90	-	-
E_3	120	40	0	50	-	-
E_4	170	90	50	0	-	-
C	120	55	25	100	-	120

Table 3: Pressure drop and investment cost vs heat capacity flowrate linear relationship of coolers

Cooler	Tube-side pressure drop correlation (kPa)	Investment correlation ($/y)
E_1	$\Delta P('1') = 0.56\ F_c^{in}('1') - 4.3$	$\text{cost}_1^{cooler} = 2{,}199.3 \times F_c^{in}('1') + 1{,}000$
E_2	$\Delta P('2') = 0.98\ F_c^{in}('2') - 18.2$	$\text{cost}_2^{cooler} = 824.6 \times F_c^{in}('2') + 42{,}846$
E_3	$\Delta P('3') = 1.05\ F_c^{in}('3') - 54.9$	$\text{cost}_3^{cooler} = 1{,}426.6 \times F_c^{in}('3') + 45{,}200$
E_4	$\Delta P('4') = 0.86\ F_c^{in}('4') - 5.8$	$\text{cost}_4^{cooler} = 143.9 \times F_c^{in}('4') + 4{,}707.3$

The pressure drops and capital cost of coolers are given in Table 3. The assigned values of outlet temperatures ($T_c^{out}(i) = T_c^{out,U}(i)$) in the model reduce its computational effort and meet the requirement in the optimal network. Table 4 compares the total cost of the Base Case with the optimal results of CWSs optimised by sequential and simultaneous method. The operating cost reduces greatly because of the reduction of overall flowrate and the consideration of interaction between networks avoids energy penalty. Due to the reduction of temperature difference of coolers after optimisation, the capital cost of coolers should be increased. The profit of optimising networks simultaneously is much higher when comparing to the result from the sequential method, saving 47.9s % of total cost after optimisation. Figure 4 shows the configuration of optimal CWS.

Table 4: Cost comparison for the case

	Cost ×10^4 ($/y)					Saving
	Operating cost		Annualised capital cost		Overall cost	(%)
	CW	Pumping	Pumps	Coolers		
Base Case	1.17	10.47	0.86	4.9	17.4	-
Sequential optimisation	0.99	7.06	0.85	5.0	13.8	20.7
Simultaneous optimisation	0.41	1.63	0.52	6.5	9.1	47.9

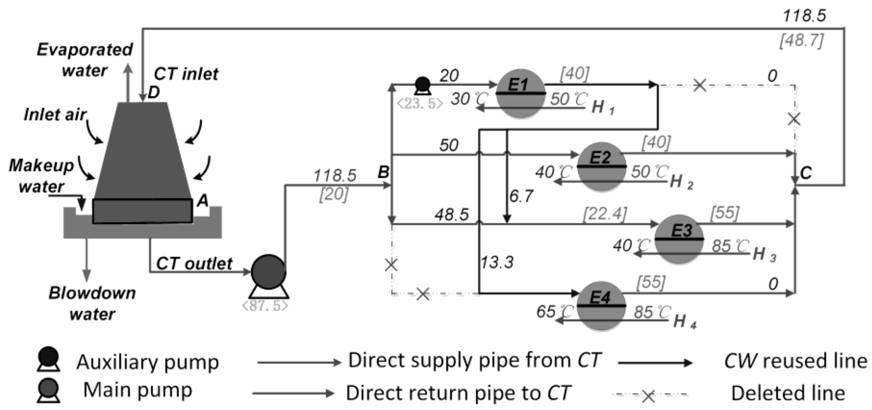


Figure 4: Optimal CWS after simultaneously optimising cooler and pump networks.

4. Conclusion

A simultaneous optimisation method for design of CWSs is proposed in this paper. The economic tradeoffs between CW cost, pumping cost and capital costs of coolers and pumps are carried out simultaneously. The complexity of CWS is controlled through the manipulation of binary variables in the model. The outlet temperatures of CW from coolers are assigned to avoid bilinear terms and nonlinear equations are linearised to keep all the constraints in the model linear, except in the objective function. The profit of optimising networks simultaneously is much higher when comparing with the result from the sequential method (Sun et al., 2014b), saving 47.9 % of total cost after optimisation. It identifies that this simultaneous method is better than the sequential methodology proposed by Sun et al (2014b).

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