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Optimisation of Cooling-Water Systems Considering Temperature-Rise and Pressure-Drop

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Cooling-water systems (CWS) are widely used in process industries as a cold utility. In re-circulating CWS, cooling water from the cooling tower (CT) is transported only by pumps on the main supply pipeline and supplied to a coolers network that usually has a parallel configuration. However, series-parallel configuration of coolers can obviously reduce the cooling water flow-rate and increase its return temperature as well as the effectiveness of the CT, but the pressure drop along pipelines will increase accordingly. To save energy and cost, a mathematical model is established to optimise the cooling water system. A two-step solution strategy is proposed to obtain the optimal cooling-water network (CWN) with minimal total cost. Firstly the optimal heat exchanger network (HEN) is obtained, and then the optimal pump network with auxiliary pumps is synthesized. The proposed optimisation model can identify the optimal distribution of cooling water within the network and the optimal installation location and capacity of pumps required for CWS. An example has been provided to demonstrate the effectiveness of the method.

1. Introduction

CWS is one of the most popular methods to discharge waste heat of processes to the environment. Typical re-circulating CWS are composed of three major components: a heat exchanger network (HEN), a cooling tower and a pump network. The most influential factor to the temperature and flow-rate of cooling water is the HEN. The most popular design of a HEN in CWS is in parallel configuration where cooling water transported to each cooler with the same temperature. However, the optimal structure may not require the same supply temperature of the cooling water because not all hot streams have the same inlet and target temperatures. For hot streams with higher target temperature, there exists possibility to reuse cold utility between coolers. Compared with parallel configuration, this serial configuration can not only save cooling water, but also improve the efficiency of the cooling tower and achieve better effect of energy saving.

Over the last decade, a large number of studies about CWS have been reported in the literature, ranging from insight-based Pinch analysis to mathematical-based optimisation methods. Kim and Smith (2001) proposed a cooling water design approach based on Pinch analysis to target minimum cooling water consumption of CWN. Due to low heat transfer temperature difference, the heat transfer area of CWN is large which incurs excessive investment cost. Based on mathematical optimisation technique, Feng et al. (2005) proposed the internal water main structure with simple configuration which can be designed and controlled easily. Picón-Núñez et al. (2007) studied the effect of the configuration of CWN on the total heat exchanger area. Ponce-Ortega et al. (2007) proposed a new superstructure and a mathematical programming model for the optimal synthesis of CWN and minimized the utility and capital costs simultaneously. Serna-González and Ponce-Ortega (2011) presented a total cost targeting method for heat exchanger network synthesis. Nemet et al. (2013) presented an optimisation methodology for a Heat Exchanger Network design over its entire lifespan. Besides, Sun et al (2014) proposed the auxiliary pump network to minimize the total cost of the cooling water pump network. In this paper, a thermodynamic model and a hydraulic model are established respectively to optimise the total cost of CWN, and a two-step sequential approach is proposed for the optimisation of CWS.

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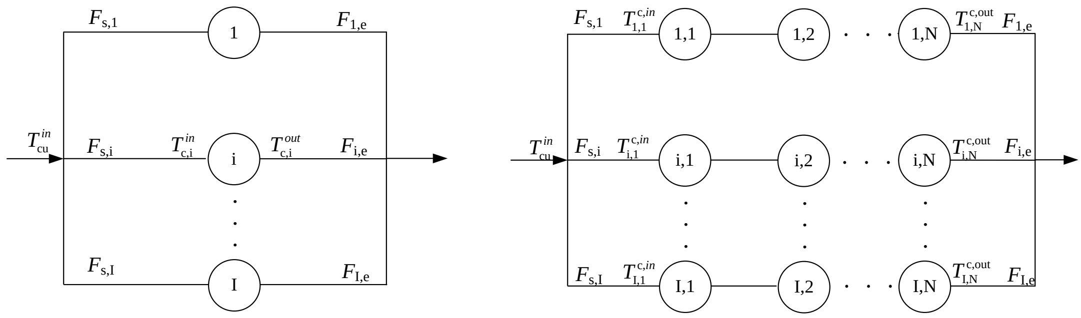
2. Superstructure and Model of the HEN in CWS

2.1 The Superstructure of CWS

Figure 1(a) depicts the traditional parallel configuration of the HEN in CWS. In the configuration, hot process stream *i* exchange heat with cooling water on parallel branch pipe *i*. Hot process stream *i* corresponds to cooler E-*i*. The inlet and target temperatures of hot process stream *i* are $T_{\rm i}^{\rm H,in}$ and $T_{\rm i}^{\rm H,out}$, respectively.



(a) Parallel configuration

(b) Series-parallel configuration

Figure 1: Two different configurations of HEN for CWS

Figure 1(b) shows the superstructure for the series-parallel configuration of the HEN in CWS. For the purpose of simplicity and operability, the serial number of coolers in each parallel branch pipe is no more than *N* and each hot stream corresponds to only one cooler. There are *I* parallel branch lines and *N* coolers installed serially on the branch pipe *i*. The models of the series-parallel configuration of the HEN in this article are the same as that of Ponce-Ortega et al. (2007). Eqs. (1) - (2) show the Energy balances for each parallel pipe in this configuration.

$$F^H CP_{\rm i}^H (T_{\rm i}^{\rm H,in} - T_{\rm i}^{\rm H,out}) = q_{\rm i} \qquad \forall\ {\rm i} \in I \tag{1}$$

$$F_{\rm s,i} Cp_{\rm Cu} (T_{\rm i,N}^{\rm c,out} - T_{\rm i,1}^{\rm c,in}) = \sum_{n=1}^{N} q_{i,n} y_{i,n} \qquad \forall\ {\rm i} \in I \tag{2}$$

where F^H and $F_{\rm s,i}$ are flow-rates of hot stream and cold utility on parallel branch *i*; $CP_{\rm i}^H$ and $Cp_{\rm Cu}$ the specific heat capacity of hot stream and cold utility; $T_{\rm i}^{\rm H,in}$ and $T_{\rm i}^{\rm H,out}$ the inlet and target temperature of hot stream and cold utility; $q_{\rm i}$ the heat load of hot stream ; $q_{i,n}$ the heat exchanged on the *n* th cooler of parallel line i, and $y_{i,n}$ is a binary variable.

The binary variable $y_{i,n}$ is introduced to indicate the existence of the *n*-th cooler on parallel branch pipe *i*. The capital letter *I* represents the number of hot process streams and its set. The constraint condition of the binary variable $y_{i,n}$ is shown as follows:

$$\sum_{n=1}^{N} y_{i,n} \le N \qquad \forall\ {\rm i} \in I \tag{3}$$

$$\sum_{i=1}^{I} \sum_{n=1}^{N} y_{i,n} = I \tag{4}$$

where *N* and *I* are the total number of parallel branch lines and hot process streams.

The cooling water inlet temperature of the first cooler in each parallel branch equals the outlet temperature of the cooling tower. The constraint conditions of the temperatures are as follows:

$$T_{\rm i,1}^{\rm c,in} = T_{\rm Cu}^{\rm in} \qquad \forall\ {\rm i} \in I \tag{5}$$

$$T_{i,n}^{c,out} = T_{i,n+1}^{c,in} \qquad \forall\ {\rm i} \in I, {\rm n} \in 1,2,...{\rm N}\text{-}1; \tag{6}$$

$$T_{\rm i,N}^{\rm c,out} \le T_{\rm C}^{\rm max} \qquad \forall\ {\rm i} \in I \tag{7}$$

$$F_{\mathrm{s,i}} Cp_{\mathrm{Cu}} T_{\mathrm{Cu}}^{\mathrm{in}} + \sum_{n=1}^{N} q_{i,n} y_{i,n} \le F_{\mathrm{s,i}} Cp_{\mathrm{Cu}} T_{\mathrm{C}}^{\mathrm{max}} \qquad \forall\ \mathrm{i} \in I \tag{8}$$

where $T_{\mathrm{i,1}}^{\mathrm{c,in}}$ is inlet temperature of the first cooler in parallel line *i*, $T_{\mathrm{C}}^{\mathrm{max}}$ is the maximum temperature of cold utility and $T_{i,n}^{c,out}$ is the outlet temperature of cold utility for the *n* th cooler in parallel line *i*.

The minimum mass flow-rate of cooling water can be deduced from Eq.(8) and is expressed as the following Equation:

$$F_{\mathrm{s,i}}^{\mathrm{min}} = \frac{\sum_{n=1}^{N} q_{i,n} y_{i,n}}{Cp_{\mathrm{Cu}} (T_{C}^{\mathrm{max}} - T_{Cu}^{in})} \qquad \forall\ \mathrm{i} \in I \tag{9}$$

where $F_{\mathrm{s,i}}^{\mathrm{min}}$ is the minimum mass flow-rate of cooling water in parallel pipe *i*.

2.2 The objective function

The objective function is the total annual cost, namely the annualized capital cost for the heat exchangers and the utility cost, as shown in Eqs. (10)-(11). Eq. (12) is the investment cost of a heat exchanger.

$$\min\ F_1 = \sum_{i=1}^{I} f_i \tag{10}$$

$$\min\ f_i = \sum_{\mathrm{n}=1}^{N} [A_{f1} \times C_{i,n}^{Ex} \times y_{i,n}] + C^{\mathrm{cu}} H_Y F_{\mathrm{s,i}} \qquad \forall\ \ \mathrm{i} \in I \tag{11}$$

$$C^{Ex} = a + bA^{\beta} \tag{12}$$

where A_{f1} is heat exchanger area; C^{cu} the unit cost for the cold utility; H_Y the equipment operating time per year; $F_{\mathrm{s,i}}$ the cold utility of flow-rate and a , b , β are heat exchanger cost parameters.

3. Pump network model

3.1 The minimum pressure head of parallel branch pipes

The method proposed by Sun et al (2014) to calculate the minimum pressure head of a cooler can be referred to calculate the minimum pressure head of each parallel pipe. The minimum pressure head of parallel pipe *n* can be calculated by Eq. (13).

$$H_{\mathrm{n}}{}^{\mathrm{min}} = \frac{\Delta P_{A-D}}{\rho g} + z_D - z_A \tag{13}$$

where ΔP_{A-D} is the pressure drop between node A and node D, respectively; z_A and z_D the height of section A and D, respectively; ρ the water density and g is the gravity factor.

The total pressure drop from node *A* (the inlet section) to node *D* (the outlet section) consists the pressure drops of the header feed pipe and of parallel branch pipes, which can be formulated as Eq. (14). In this article, the detail pressure drop of CWN follows Sun et al (2014) method.

$$\Delta P_{A-D} = \Delta P_{A-B} + \Delta P_{B-C} + \Delta P_{C-D} \tag{14}$$

3.2 The optimisation of cooling water auxiliary pump network

The Sun et al’s method (2014) to optimise the auxiliary pump network is adopted in this paper. The objective function is the total cost of the main and auxiliary pump networks which includes the operation cost and the capital cost of pumps and motors, and can be formulated as Eq. (15).

$$\min F_2 = OC_{main} + OC_{auxi} + A_{f2} \times (CC_{P_i} + CC_{P_j} + CC_{M_i} + CC_{M_j}) \tag{15}$$

where OC_{main} and OC_{auxi} are the operation cost of main pump network and auxiliary pump network, respectively; A_{f2} is the annualized factor of pumps and motors; CC_{P_i} , CC_{P_j} are the capital cost of main pumps and auxiliary pumps; CC_{M_i} and CC_{M_j} are the capital cost of main motors and auxiliary motors, respectively.

4. Case study

The example, taken from Ponce-Ortega et al. (2007), is used as the case study. The hot stream data is shown in Table 1. The specified data are follows: $\Delta T_{\min}$ is taken as 10 ºC, the inlet temperature for the cold utility is 20 ºC and the maximum allowable temperature of cooling water is 55 ºC. The cost function for the capital cost of the heat exchangers is based on $1,000+700 A (area in m^2). The annual operating time of equipment is assumed to be 2.88×10^7 s/y and the annualisation factor (A_{f1}) for capital cost of heat exchangers to be 0.2983. The C_{pc} for the cold utility is taken as 4.18 kJ/(kg ºC), the film heat transfer coefficient for the side of the cold utility as 2.5 kW/(m^2 ºC), and the unit cost of cooling water as $ 5×10^{-6}/kg. All these data are from Ponce-Ortega et al. (2007).

Table 1: Hot process stream data

Stream	$T_{\mathrm{H,i}}^{\mathrm{in}}$ (ºC)	$T_{\mathrm{H,i}}^{\mathrm{out}}$ (ºC)	$FCP_{\mathrm{i}}^{\mathrm{H}}$ (kW/ºC)	h(W/m^2 ºC)
1	50	30	20	854
2	50	40	100	743
3	85	40	40	520
4	85	65	10	1,352

Based on the above model, the optimal HEN is shown in Figure 2, which is the same as that in Ponce-Ortega et al. (2007). In this series-parallel configuration, coolers E1, E2 and E3 are installed in series, with a parallel branch pipe containing cooler E4. Figure 2 shows the flow-rate distribution and heat exchange area in detail. The total cost of the optimal series-parallel structure of HEN and the parallel configuration of HEN are 64,978 $/y and 80,639 $/y. The annual saving of the total cost can achieved at 19.4%.

After determining the optimal heat exchanger network, the minimum pressure head of all parallel branches can be calculated. Table 2 shows the main parameters of coolers and pipes with fittings, which are used to calculate the minimum pressure head of parallel lines. Four main pumps are installed in parallel in the main pump network, three of which are on duty and one on standby. All the factors are referred to Sun et al (2014).

The Minimum pressure head of parallel branches are given in Table 3. Tables 3 and 4 compare the total cost of pump network before and after pump network optimisation, which are 1.22 ×10^5 $/y and1.14×10^4 $/y. The annual saving of the total cost can achieved at 6.1%.

The optimal cooling water network after pump network optimisation is shown in Figure 3. The main pump pressure head is 11 m and an auxiliary pump with pressure head of 10 m is installed on parallel branch pipe B-1-C.

Table 2: Data for the piping layout of pipeline network

Pipe segment	Pipe length (m)	Inside diameter (m)	Mass flowrate (kg/s)	Coolers *Ei*	Maximum installation height of coolers (m)	Pipe fittings
A-B	80	0.24	70.26	—	—	Gate valve (2*) Globe valve(1) Check valve (1) Orifice valve (1) Bend (3)
B-1-C	300	0.18	39.5	E1 E2 E4	15	Sudden contraction (1) Sudden expansion (1) Bend (2) Gate valve (2)
B-2-C	75	0.16	30.76	E3	8	Sudden contraction (1) Sudden expansion (1) Bend (2) Gate valve (2)
C-D	120	0.24	0.949	—	—	Bend (2) Gate valve (2)

* Number in brackets indicates the number of pipe fittings.

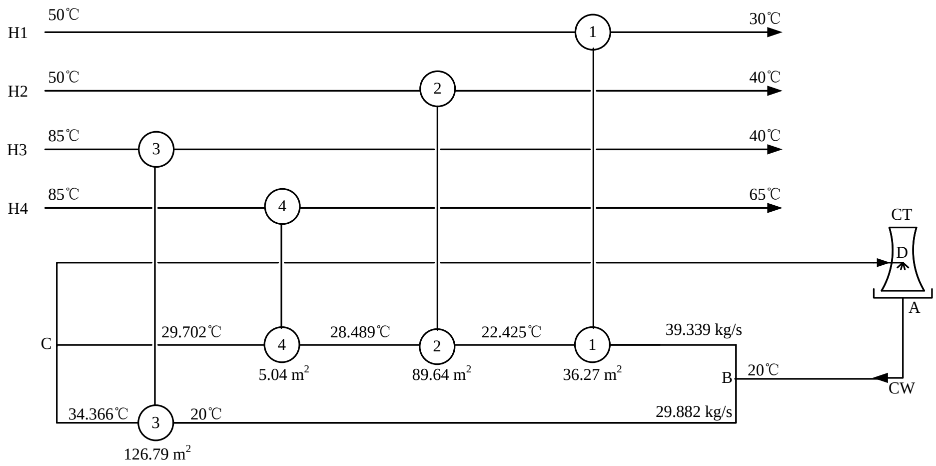


Figure 2: Optimal heat exchanger network of CWS without auxiliary pump installation

Table 3: Pump pressure heads and costs before optimisation

Pipe section	Pump	H_i(m)	H_n^{min} (m)	OC×10^4($/y)	CC×10^4($/y)	TC×10^4($/y)
A-B	P_i	21	-	8.2	4.03	12.23
B-1-C	-	-	21	0	0	0
B-2-C	-	-	11	0	0	0

Table 4: Pump pressure heads and costs after optimisation

Pipe section	Pump	H_i(m)	OC×10^4($/y)	CC×10^4($/y)	TC×10^4($/y)
A-B	P_i	11	4.6	2.43	7.03
B-1-C	P_1	10	2.5	1.95	4.45
B-2-C	-	-	0	0	0

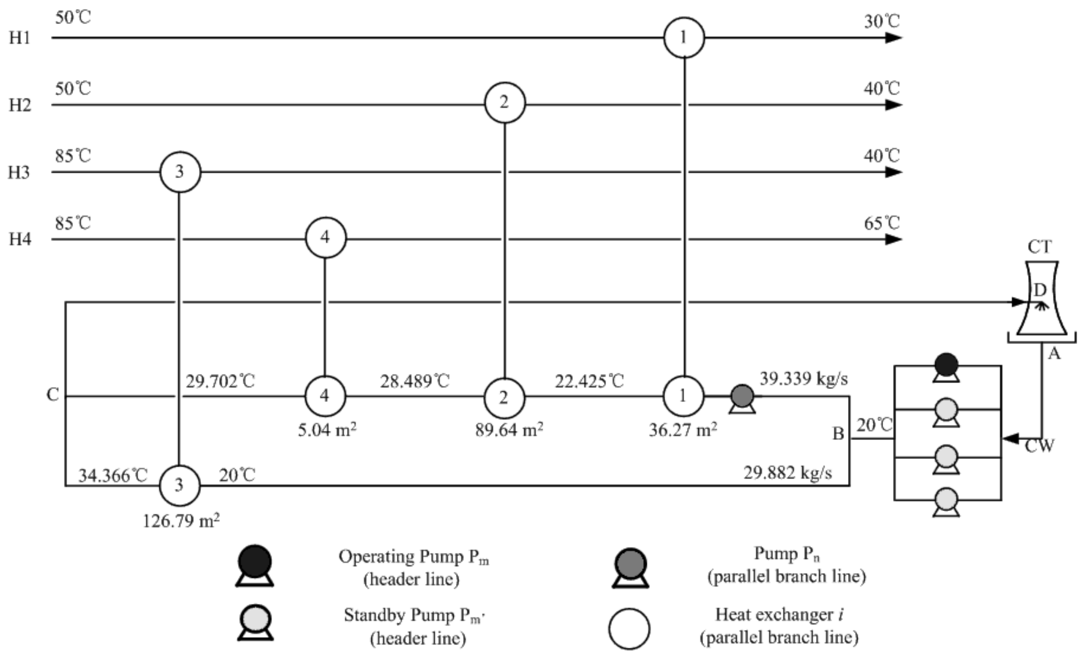


Figure 3: Optimal cooling water network with auxiliary pump installation (after pump network optimisation)

5. Conclusions

The thermodynamic model is developed to obtain the HEN with minimum heat exchanger cost and utility cost and the hydraulic model is proposed to optimise the pump network. For the simplification of solving process, the two-step sequential approach adopted for the two models separately to obtain the optimal CWN, for the minimum pressure head of the network can be targeted when the configuration of the HEN in the CWN is determined. The result of the case study shows that this method is effective and can be useful for CWN design and retrofit. Simultaneously optimising the HEN and the pump network to obtain the optimal cooling water system will be our further work, for there are interactions between the HEN and the pump network.

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