Energy xxx (2014) 1–7

Contents lists available at ScienceDirect

Energy

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Pump network optimization for a cooling water system

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ARTICLE INFO

Article history:
Received 14 September 2013
Received in revised form
10 December 2013
Accepted 8 January 2014
Available online xxx

Keywords:
Pump network
Cooling water system
Superstructure
Optimization

ABSTRACT

Centrifugal pumps are widely used in cooling water systems to transport cooling water to its users. They are installed in the header line of the feed pipe, constituting a main pump network. The pressure head of the main pumps must be large enough to satisfy the pressure heads of all coolers. The pressure drop of parallel branch pipes must be balanced by reducing the opening of valves for some coolers, incurring an energy penalty on some pumps. To attain energy savings, this paper proposes an auxiliary pump network whereby auxiliary pumps are installed in parallel branch pipes. A superstructure-based mathematical model is developed to optimize the total cost of the main and auxiliary pump networks. The optimal number of auxiliary pumps and their installation locations are determined by solving the model with a simulated annealing algorithm. The effectiveness of the model is tested by a case study based on the cooling water network of a refinery.

1. Introduction

With increasingly acute energy shortage and stringent environmental regulations, novel ideas for energy saving and energy efficiency improvements in the process industries are attracting a lot of attention. For example, efficient use of pump power in cooling water systems is an area of research and practical interest. As shown in Fig. 1, cooling water is recycled only by the main pumps in the header line of the feed pipe which are arranged in a parallel configuration. The pressure head of the main pumps must be large enough to transport cooling water to all coolers. Due to large heat load and pressure drop of the cooling water network, the flow rate and pressure head of the main pumps must be correspondingly large enough, resulting in a tremendous consumption of energy. Owing to its parallel configuration, the pressure drop of each branch pipe must be equal. In order to obtain the required flow rate distribution of a cooling water network, some coolers' local resistance must be increased by partially closing their outlet valves when their minimum pressure heads are comparatively small. Such adjustment results in an energy penalty of pump power. To avoid this type of energy penalty, this paper proposes an auxiliary pump network. The auxiliary pumps are installed before coolers that are placed in parallel branch lines. Through this method, the pressure head of the main pump does not need to be larger than the minimum pressure heads of all coolers.

Typical re-circulating cooling water systems are composed of three major components: a heat exchanger network, a cooling tower and a pump network. Earlier works on these systems have concentrated on the optimization of heat exchanger networks [1–5] and cooling towers [6–9] in order to save energy. However, studies on pump networks are rather rare. In the area of wastewater treatment, Zhang et al. [10] studied six different types of sewage pumps in parallel configuration under different operating conditions. They proposed a pump network scheduling model, which integrates the models of energy consumption and wastewater flow rate. It can target the optimal pump network configuration under different working conditions which greatly reduces energy consumption of the pump network. This pump network scheduling model may be adapted to the main pump network discussed in this study. Westerlund et al. [11,12] introduced a superstructure-based model to optimize pump configurations. In their model, the pumps on the same installation height are centrifugal pumps of the same size and the same rotational speed. Besides, for each installation height, this model requires that the number of pumps on each parallel line must be the same. Because the number, size and rotational speed of pumps on each parallel branch pipe for the cooling water auxiliary pump network proposed here can be different, the model of Westerlund et al. [11,12] is not suitable for optimizing the auxiliary pump network.

This paper proposes a superstructure of a cooling water pump network containing both a main pump network and an auxiliary pump network. Adding auxiliary pumps properly can avoid the energy penalty associated with the turning down of some valves, thereby reducing the operation cost of the pump network. It,

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http://dx.doi.org/10.1016/j.energy.2014.01.028

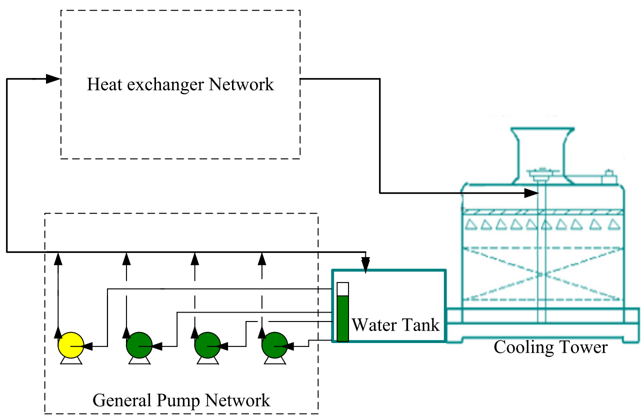

Fig. 1. The general pump network of cooling water system.

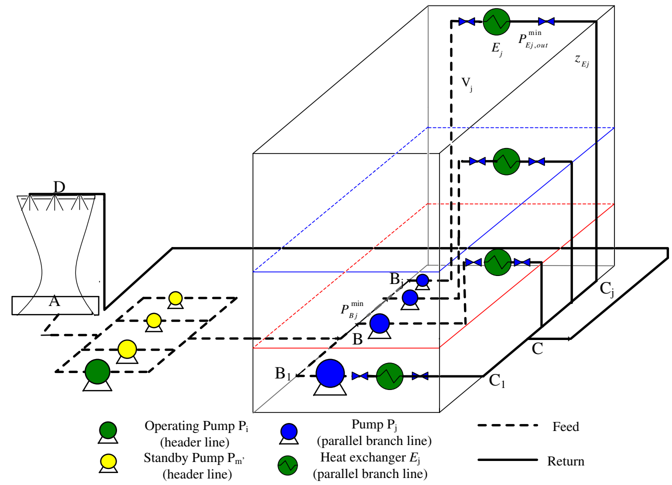

Fig. 2. Pump network superstructure of cooling water system.

however, will increase the capital cost due to the need to purchase auxiliary pumps and motors. The purpose of this paper is to minimize the total cost of a pump network, which includes both the operation cost and the annualized capital cost. By adding auxiliary pumps with suitable pressure head on parallel branch lines, an auxiliary pump network superstructure is developed. A mathematical model is built to minimize the total cost of a pump network by optimizing the main pump pressure head. The optimal auxiliary pump network can then be obtained. The model, based on a generalized cooling water pump network, is treated as a mixed integer non-linear programming problem (MINLP). The effectiveness and practicability of this model is verified by applying it to a simplified cooling water network of a refinery.

The pump network of a cooling water system is a complex structure which includes intricate interactions between its components (the main pump pressure head, the auxiliary pumps pressure heads and the number and location of auxiliary pumps, etc). A single change of one component in the network may affect the performance of several others. Due to the complexity of a cooling water pump network, the simulated annealing method is used to solve the model as it can avoid local optima.

2. Problem statement

The general pump network considered here consists of several centrifugal pumps installed on the header feed pipe just after the water tank. Fig. 1 illustrates the general pump network of a cooling water system. The number of pumps under operation is adjustable according to the total flow rate required. When hot streams transfer their heat to cooling water, the outlet temperature of cooling water from the heat exchanger network will be increased. It returns directly to the top of the cooling tower for cooling. Electric fan is installed at the top of the cooling tower to enhance the extent of evaporation and cooling. Then, cooling water flows back to the water tank for reuse.

In a cooling water system, coolers in various units have different specified installation heights and their distances from pumps are also different, leading to different minimum pressure heads. The entire pump network of the cooling water system analyzed in this paper consists of a main pump network and an auxiliary pump network, as shown in Fig. 2. The main pump network on the left side has m number of pumps. The pressure heads of each main pump are the same, but the flow rates may be different. According to the flow rate requirement, m' pumps are running at the same time. The auxiliary pump network on the right side consists of n parallel branch pipes. Cooler E_j is installed on line j. If the pressure head of the main pump is less than the minimum required pressure head of cooler E_j, an auxiliary pump P_j must be installed to satisfy the pressure requirement. Otherwise, auxiliary pump P_j is not necessary. N_P is the number of auxiliary pumps, H_i is the main pump pressure head, $H_{E_j}^{min}$ and Z_{E_j} are respectively the minimum pressure head of cooler E_j and its installation height and the flow rates of the feed pipe and parallel branch pipe j are V_{tot} and V_j, respectively. By optimizing the main pump pressure head, an optimal auxiliary pump network is obtained.

3. Mathematical model

3.1. Objective function

The total cost of the two pump networks is taken as the objective function. The total cost includes the operation cost and the capital cost of pumps and motors and can be formulated as Eq. (1).

$$\text{Obj} = \text{MIN}[\text{TC}] = \text{MIN}[\text{OC} + \text{CC}] \quad (1)$$

where TC represents the total cost of the pump networks and OC and CC denote the operation cost and capital cost of the pump networks, respectively.

Operation cost mainly refers to the energy cost incurred by electric motors. The shaft power of a pump is proportional to its pressure head and flow rate, but is inversely proportional to the pump efficiency (η_P) and the motor efficiency (η_M). The operation cost of the pump networks is given by Eq. (2).

$$\begin{aligned} \text{OC} &= \text{OC}_{main} + \text{OC}_{auxi} \\ &= \left[\sum_{i=1}^{m'} \frac{H_i V_i \rho g}{1000 \eta_{P_i} \eta_{M_i}} + \sum_{j=1}^{n} \frac{H_j V_j \rho g}{1000 \eta_{P_j} \eta_{M_j}} y_j\right] \cdot h \cdot e \end{aligned} \quad (2)$$

In Eq. (2), the main pump pressure head H_i is an optimization variable while the volumetric flow rate V is a specified parameter, h denotes pump annual operation time, e is the unit cost of electricity, and OC_{main} and OC_{auxi} are operation costs of main and auxiliary pumps, respectively. Binary variables are used to activate (if the unit exists, $y_j = 1$) or deactivate (if the unit does not exist, $y_j = 0$) the constraints for auxiliary pumps.

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Capital cost includes the costs of purchasing running and standby pumps (CC_{pump}) and motors (CC_{Motor}) which are functions of the flow rate, pressure head and structural material. The capital cost of pumps can be computed from Eqs. (3)–(5) [13].

$$CC_{pump} = CC_{P_i} + CC_{P_j} = \frac{I_{CE}}{I_{CEbase}}\left(\sum_{i=1}^{m'} F_{T_1,P_i}F_{M_i}C_{B_1,P_i} + \sum_{j=1}^{n} F_{T_1,P_j}F_{M_j}C_{B_1,P_j}y_j\right) \quad (3)$$

$$C_{B_1} = \exp\left\{b_1 - b_2[\ln(S)] + b_3[\ln(S)]^2\right\} \quad (4)$$

$$S = V(H)^{0.5} \quad (5)$$

where I_{CE} and I_{CEbase} denote current chemical equipment index and base chemical equipment index, respectively, $F_{T1,P}$ and F_M denote pump type factor and material factor, respectively, C_{B1} is the base cost of pump, S is size factor of pump, and b_1–b_3 are constants in the pump base cost equation.

The capital cost of electric motors, which varies with shaft power (P_P) and the rotation speed of pump, can be determined as follows [13]:

$$CC_{Motor} = CC_{M_i} + CC_{M_j} = \frac{I_{CE}}{I_{CEbase}}\left(\sum_{i=1}^{m'} F_{T_2,M_i}C_{B_2,M_i} + \sum_{j=1}^{n} F_{T_2,M_j}C_{B_2,M_j}y_j\right) \quad (6)$$

$$C_{B2} = \exp\left\{a_1 + a_2[\ln(P_P)] + a_3[\ln(P_P)]^2 + a_4[\ln(P_P)]^3 - a_5[\ln(P_P)]^4\right\} \quad (7)$$

$$P_P = \frac{P_T}{\eta_P\eta_M} = \frac{VH\rho}{1000\eta_P\eta_M} \quad (8)$$

where $F_{T2,M}$ is motor type factor, C_{B2} is the base cost of motor in CNY, a_1–a_5 are constants in the motor base cost equation, and P_p and P_T are motor shaft power consumption and theoretical power of pumps in kW, respectively.

Long-term running of pumps may lead to pump degradation which results from abrasive wear of impeller or sealing parts of pumps. The lifespan of impeller and other components depends on the material of construction. In general, pumps are regularly checked and maintained to ensure optimal performance. If a pump's performance deteriorates due to pump degradation, a standby pump will be turned on and the running pump is taken out for servicing. This will incur extra investment cost for the pump networks. We handle the problem of pump aging by multiplying the capital cost with a correction factor. Capital cost is annualized with an annualization factor that is defined by a chosen interest rate and a number of expected running years and can be expressed as Eq. (9).

$$CC = \delta\cdot\gamma_c\cdot(CC_{Pump} + CC_{motor}) \quad (9)$$

where δ is the annualization factor for capital cost and γ_c is a correction factor for mechanical maintenance costs.

3.2. Variables

The main pump pressure head (H_i) and the binary variable (y_j) are the variables to be optimized. The former determines the number of auxiliary pumps while the latter indicates whether an auxiliary pump needs to be installed. For a certain cooler, whether an auxiliary pump is installed depends on the relative magnitudes of the main pump pressure head and the cooler's minimum pressure head. In other words, if the main pump pressure head is smaller than the minimum pressure head requirement of a cooler, an auxiliary pump should be installed on its line and vice versa.

3.3. Constraint conditions

There are three constraint conditions in the optimization process. The first one ensures that the sum of the main pump pressure head (H_i) and the auxiliary pump pressure head (H_j) must be larger than the minimum pressure head of cooler E_j.

$$H_i + H_j - H_{E_j}^{min} - \varepsilon = 0 \quad (10)$$

$$0 \le \varepsilon \le 1e^{-6} \quad (11)$$

$$H_j = \begin{cases} H_{E_j}^{min} - H_i & \left(H_i < H_{E_j}^{min}\right) \\ 0 & \left(H_i \ge H_{E_j}^{min}\right) \end{cases} \quad (12)$$

where $H_{E_j}^{min}$ represents the minimum pressure head of cooler E_j and ε is a slack variable.

The second constraint condition is that the sum of the flow rates for each parallel branch pipe must equal the flow rate of the header feed pipe.

$$\sum_{j=1}^{n} V_j = V_{tot} \quad (13)$$

The third one ensures that the number of auxiliary pumps must be no more than the total number of parallel branch lines. The binary variable y_j determines whether an auxiliary pump (P_j) is installed or not. The sum of binary variable y_j should not exceed the total number of parallel branch lines.

$$y_j = \begin{cases} 1 & \left(H_{E_j}^{min} > H_i\right) \\ 0 & \left(H_{E_j}^{min} \le H_i\right) \end{cases} \quad (14)$$

$$\sum y_j \le n \quad (15)$$

$$N_p = \sum_{j=1}^{n} y_j \quad (16)$$

3.4. Coolers' minimum pressure head ($H_{E_j}^{min}$)

In order to calculate the minimum pressure head of cooler E_j, two assumptions are made as described below.

(1) Exit valves of all coolers are fully opened. The partial closure of exit valves would definitely increase the pressure drop of the pipe fittings and that of the total pipe network. To avoid this complication, the exit valves of all coolers are assumed to be fully opened which will allow a convenient way to calculate the minimum pressure heads of all coolers and to solve the model.
(2) The gauge pressures of both section A and section D (shown in Fig. 2) are zero. This assumption reflects the real situation. Because section A and section D are exposed to the atmosphere, their gauge pressure is zero.

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Dynamic pressure head is relatively small and can be ignored when calculating the pressure drop. The pressure drop between section A and section D is defined by Eqs. (17)–(21).

$$P_A + \rho g z_A + \rho g H_{E_j}^{\min} = P_{B_j}^{\min} + \Delta P_{A-B_j} \tag{17}$$

$$P_{B_j}^{\min} = P_{E_{j,\mathrm{out}}}^{\min} + \Delta P_{B_j - E_{j,\mathrm{out}}} + \rho g z_{E_j} \tag{18}$$

$$\rho g z_{E_j} + P_{E_{j,\mathrm{out}}}^{\min} = \rho g z_D + \Delta P_{E_{j,\mathrm{out}} - C_j} + \Delta P_{C_j - D} + P_D \tag{19}$$

$$P_A = 0 \tag{20}$$

$$P_D = 0 \tag{21}$$

where z represents the installation height, P and ΔP denote the gauge pressure of a node and pressure drop of a specified pipe section, respectively.

In order to calculate the minimum pressure head of all coolers, the if-then-else statements are given by Eqs. (22)–(23). If the gravitational pressure head of cooler E_j is large enough to send cooling water to node D of the cooling tower, the minimum pressure head of the cooler outlet node ($E_{j,\mathrm{out}}$) can be zero.

$$\begin{aligned} &\rho g z_{E_j} > \rho g z_D + \Delta P_{E_{j,\mathrm{out}} - C_j} + \Delta P_{C_j - D} \\ &P_{E_{j,\mathrm{out}}}^{\min} = 0 \end{aligned} \tag{22}$$

If the gravitational head of cooler E_j is not large enough to send cooling water to node D of the cooling tower, the minimum pressure head of the cooler outlet node ($E_{j,\mathrm{out}}$) can be computed from Eq. (23).

$$P_{E_{j,\mathrm{out}}}^{\min} = \Delta P_{E_{j,\mathrm{out}} - C_j} + \Delta P_{C_j - D} + \rho g \left(z_D - z_{E_j} \right) \tag{23}$$

The minimum pressure head of cooler E_j can be calculated from the following equation which is based on Eqs. (18)–(23).

$$H_{E_j}^{\min} = \frac{\Delta P_{A-D}}{\rho g} + z_D - z_A \tag{24}$$

3.5. Pipeline pressure drop

The pressure drop of each parallel branch line is equal. The total pressure drop from node A (the inlet section) to node D (the outlet section) in Fig. 2 consists of the pressure drops of the header feed pipe and those of parallel branch pipes, which can be formulated as Eq. (25).

$$\Delta P_{A-D} = \Delta P_{A-B_j} + \Delta P_{B_j - C_j} + \Delta P_{C_j - D} \tag{25}$$

The diameter and length of the parallel header lines from node B_1 to node B_n and from node C_1 to node C_n are respectively much larger and shorter than those of the parallel branch lines from node B_i to node C_i. For mathematical simplicity, the pressure drops of these parallel header lines are ignored. The pressure drops of each section can be formulated as Eqs. (26)–(30) [14].

$$\begin{aligned} \Delta P_{A-B_j} &= \Delta P_{\mathrm{pipe},A-B_j} + \Delta P_{\mathrm{Fit},A-B_j} \\ &= V_{\mathrm{tot}}^2 \sum \left(K_{\mathrm{pipe},A-B_j} + K_{\mathrm{Fit},A-B_j} \right) \end{aligned} \tag{26}$$

$$\begin{aligned} \Delta P_{B_j - C_j} &= \Delta P_{\mathrm{pipe},B_j - C_j} + \Delta P_{\mathrm{Fit},B_j - C_j} + \Delta P_{E_j} \\ &= V_j^2 \sum \left(K_{\mathrm{pipe},B_j - C_j} + K_{\mathrm{Fit},B_j - C_j} + K_{E_j} \right) \end{aligned} \tag{27}$$

$$\begin{aligned} \Delta P_{C_j - D} &= \Delta P_{\mathrm{pipe},C_j - D} + \Delta P_{\mathrm{Fit},C_j - D} \\ &= V_{\mathrm{tot}}^2 \sum \left(K_{\mathrm{pipe},C_j - D} + K_{\mathrm{Fit},C_j - D} \right) \end{aligned} \tag{28}$$

$$\Delta P_{B_j - E_{j,\mathrm{out}}} = V_j^2 \left(K_{\mathrm{pipe},B_j - E_j} + K_{\mathrm{Fit},B_j - E_j} \right) + \Delta P_{E_j} \tag{29}$$

$$\Delta P_{E_{j,\mathrm{out}} - C_j} = V_j^2 \left(K_{\mathrm{pipe},E_{j,\mathrm{out}} - C_j} + K_{\mathrm{Fit},E_{j,\mathrm{out}} - C_j} \right) \tag{30}$$

The cooling tower is operated at atmospheric pressure. The pressure drop of the system is related to the operation pressure of pumps. The pressure drop of a pipe and its fittings can be calculated from the following equations [14]:

$$\Delta P_{\mathrm{pipe}} = K_{\mathrm{pipe}} V^2 \tag{31}$$

$$K_{\mathrm{pipe}} = \frac{8 \rho l f}{\pi^2 d^5} \tag{32}$$

$$\Delta P_{\mathrm{Fit}} = K_{\mathrm{Fit}} V^2 \tag{33}$$

$$K_{\mathrm{Fit}} = \frac{8 \rho \sum c_{\mathrm{L}}}{\pi^2 d^4} \tag{34}$$

Normally, the pressure drop of a cooler is less than its design pressure drop ΔP_{Ex}. The velocity of water in the pipe is in the range of 1.5–3 m/s and the corresponding Reynolds number falls within the range of 1×10^5–3×10^6. Thus, the frictional factor of the pipe can be expressed as follows.

$$f = 0.0032 + \frac{0.221}{Re^{0.237}} \tag{35}$$

$$Re = \frac{\rho d c}{\nu} \tag{36}$$

3.6. Solution method

Simulated annealing (SA) [15] is a widely used optimization algorithm. It derives from the Metropolis algorithm and can avoid local optima in non-convex problems. The algorithm utilizes a control parameter called annealing temperature to conduct the optimization. At the beginning of the optimization, the annealing temperature is set to a high value, which is the initial annealing temperature. The annealing temperature decreases as the optimization progresses. The annealing temperature reduction is conducted by a cooling schedule. The process of SA optimization starts with an initial trial solution which usually roots in approximate calculations or heuristic methodology. SA algorithm is a universal optimization algorithm. It has global optimization performance and has been widely applied in engineering.

Cooling water pump networks are complex networks that involve several variables including main pump pressure head, auxiliary pump pressure head, and the number of auxiliary pumps with complex interactions between them. A change in a single variable will affect the values of other variables and the objective function. The proposed model is an MINLP model and highly nonlinear. Due to the complexity of the pump networks, the SA optimization method is used in this paper.

4. Industrial case study

4.1. Existing pump network

Fig. 3 shows the pump network of a refinery's cooling water system. Table 1 shows the main parameters of coolers and pipes with fittings. Four main pumps are installed in parallel in the main pump network: three are on duty and one on standby. The shaft rotational speed is 18,000 rpm and the flow rate is in the range of 0.0157–0.315 m^3/s. The pump pressure head is in the range of 15.24–152.4 m and the maximum motor power is 183.87 kW. The main pump type factor is 2.0. The main pump material factor is 1.35. The main motor type factor is 0.9. The annualization factor and the correction factor for capital cost are assumed as 0.4 and 1.5, respectively. A pump efficiency of 0.75 and an electric motor efficiency factor of 0.9 are used. The fluid density is 995 kg m^{-3} and pump yearly running time is 8600 h. The pumping cost is calculated with an electricity price of 0.5 CNY/kWh. Chemical engineering plant cost indices I_{CEbase} (in mid-2000) and I_{CE} (in 2012) are 394 and 584.6, respectively [16].

Table 2 shows the total cost of the pump network before optimization which amounts to 3.24×10^6 CNY/yr. The operation cost and the annualized capital cost are 2.52×10^6 CNY/yr and 7.24×10^5 CNY/yr, respectively.

4.2. Optimal scheme of pump networks

Eqs. (1)–(9) are used to calculate the costs of a pump network and Eqs. (25)–(36) to calculate pressure drops of all pipe segments based on the data in Table 1. Constraints 12, 14, 22 and 23 consist of if-then-else statements, so Microsoft Excel 2007 is used to pretreated these logic statements as well as Eqs. (1)–(9) and (25)–(36). These equations are regarded as black-box models when the SA algorithm is used to solve them. The upper and lower bounds of H_{main} are specified before applying the SA algorithm. For the case study, the upper and lower bounds of H_{main} are assumed to be 49 and 12 m, respectively. The mathematical model involves 53 variables, including 4 binary variables. CPU time is determined by the number of computations. For the case study, we set a maximum of 1000 iterative computations for the SA algorithm. When the optimality tolerance is set as 1.0×10^{-8}, the solution converges after 467 iterations. The global optimal solution is obtained within 27 s using a 3.2 GHz Pentium Dual-Core E5800 processor with 2.0 GB RAM.

The results obtained by the SA algorithm are presented in Fig. 4. The case study contains four coolers (E_1, E_2, E_3 and E_4). There are zone

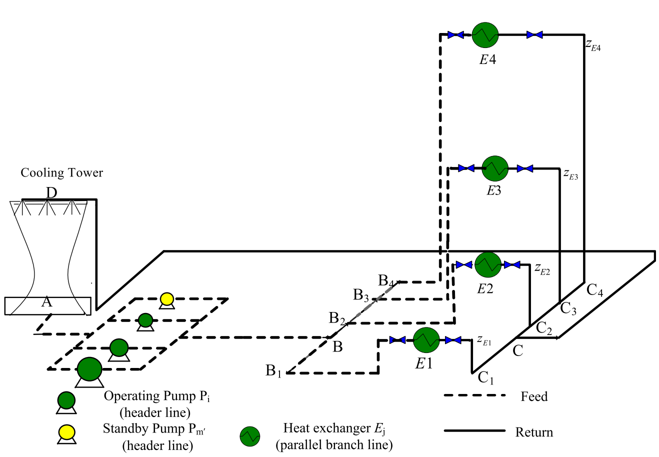

Fig. 3. Existing cooling water network of a refinery.

Table 1
Data for the piping layout of pipeline network.

Pipe segment	Pipe length (m)	Inside diameter (m)	Volumetric flowrate (m^3/s)	Cooler E_j	Installation height of cooler Z_{E_j} (m)	Pipe fittings
$A–B$	80	0.9	0.949	–	–	Gate valve (2[a]) Globe valve (1) Check valve (1) Orifice valve (1) Bend (3)
$B_1–E_{1,out}$	75	0.3	0.104	E_1	3	Sudden contraction (1) Bend (1) Gate valve (1)
$E_{1,out}–C_1$	75	0.3	0.104	–	–	Sudden expansion (1) Bend (1) Gate valve (1)
$B_2–E_{2,out}$	100	0.35	0.143	E_2	8	Sudden contraction (1) Bend (1) Gate valve (1)
$E_{2,out}–C_2$	100	0.35	0.143	–	–	Sudden expansion (1) Bend (1) Gate valve (1)
$B_3–E_{3,out}$	125	0.45	0.237	E_3	15	Sudden contraction (1) Bend (1) Gate valve (1)
$E_{3,out}–C_3$	125	0.45	0.237	–	–	Sudden expansion (1) Bend (1) Gate valve (1)
$B_4–E_{4,out}$	150	0.6	0.464	E_4	30	Sudden contraction (1) Bend (1) Gate valve (1)
$E_{4,out}–C_4$	150	0.6	0.464	–	–	Sudden expansion (1) Bend (1) Gate valve (1)
$C–D$	120	0.9	0.949	–	–	Bend (2) Gate valve (2)

[a] Number in brackets indicates the number of pipe fittings.

I, zone II, zone IIII, zone IV and zone V, corresponding to adding four, three, two, one and zero auxiliary pumps. The coolers' minimum pressure head relationship is $H_{E_1}^{min} < H_{E_2}^{min} < H_{E_3}^{min} < H_{E_4}^{min}$.

When $H_{E_4}^{min} \le H_i \le 49$ m, there is no need to add any auxiliary pump. The relationship between the total cost and the main pump pressure head is indicated by the section from point E to point E′ in Fig. 4. The total cost decreases as the main pump pressure head decreases. When the main pump pressure head equals $H_{E_4}^{min}$, the total cost can be found at the first local optimum (point E).

Table 2
Pump pressure heads and costs before optimization.

Pipe segment	Pump	H_i (m)	E_j	$H_{E_j}^{min}$ (m)	OC $\times 10^6$ (CNY/yr)	CC $\times 10^5$ (CNY/yr)	TC $\times 10^6$ (CNY/yr)
$A–B$	P_i	42.68	–	–	2.52	7.24	3.24
$B_1–E_{1,out}$	–	–	E_1	18.29	0	0	0
$B_2–E_{2,out}$	–	–	E_2	20.40	0	0	0
$B_3–E_{3,out}$	–	–	E_3	27.37	0	0	0
$B_4–E_{4,out}$	–	–	E_4	42.39	0	0	0

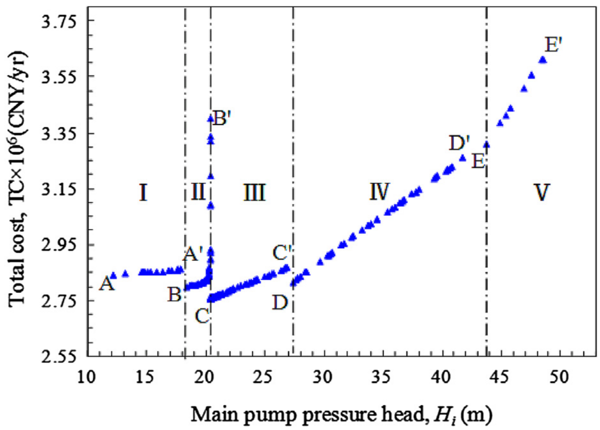

Fig. 4. Relationship between the main pump pressure head and the total cost of pumps.

When $H_{E_3}^{\min} \le H_i < H_{E_4}^{\min}$, only one auxiliary pump needs to be installed in the parallel branch before cooler E_4. The relationship between the total cost and the main pump pressure head is defined by the section from point D to point D′ in Fig. 4. The total cost decreases with decreasing main pump pressure head. When the main pump pressure head equals $H_{E_3}^{\min}$, the total cost can be found at the second local optimum (point D).

When $H_{E_2}^{\min} \le H_i < H_{E_3}^{\min}$, two auxiliary pumps need to be installed in the parallel branch lines before coolers E_3 and E_4. The relationship between the total cost and the main pump pressure head is given by the section from point C to point C′ in Fig. 4. When the main pump pressure head equals $H_{E_2}^{\min}$, the total cost is located at the third local optimum (point C).

When $H_{E_1}^{\min} \le H_i < H_{E_2}^{\min}$, three auxiliary pumps need to be installed in the parallel branch lines before coolers E_2, E_3 and E_4. The relationship between the total cost and the main pump pressure head is characterized by the section from point B to point B′ in Fig. 4. When the main pump pressure head equals $H_{E_1}^{\min}$, the total cost is situated at the fourth local optimum (point B).

When 12 m $\le H_i < H_{E_1}^{\min}$, four auxiliary pumps need to be installed in the parallel branches before coolers E_1, E_2, E_3 and E_4. The relationship between the total cost and the main pump pressure head is described by the section from point A to point A′ in Fig. 4. When the main pump pressure head equals 17 m, the total cost is located at the fifth local optimum (point A).

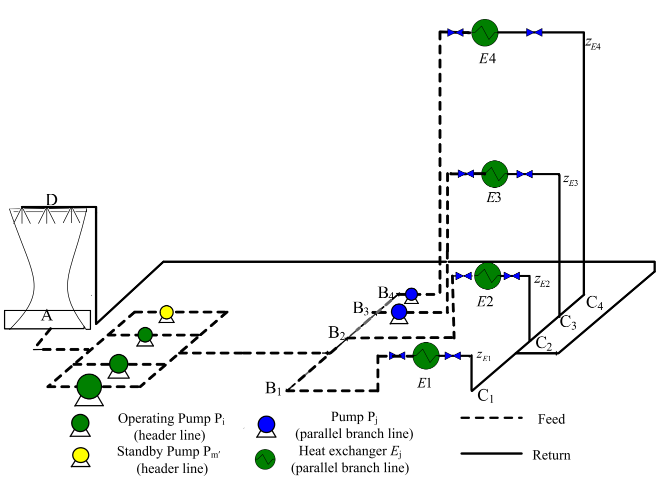

Fig. 5. Optimal pump network.

Table 3
Pump pressure heads and costs after optimization.

Pipe section	Pump	H_i/H_j (m)	OC × 10^6 (CNY/yr)	CC × 10^5 (CNY/yr)	TC × 10^5 (CNY/yr)
A–B	P_i	20.40	1.21	5.38	17.4
B_1–$E_{1,out}$	P_1	–	0	0	0
B_2–$E_{2,out}$	P_2	–	0	0	0
B_3–$E_{3,out}$	P_3	7	0.10	0.80	1.82
B_4–$E_{4,out}$	P_4	22	0.63	1.97	8.31

The results show that when the main pump pressure head is equal to each cooler's minimum pressure head the total cost can be found at a local optimum. Specifically, when the main pump pressure head equals $H_{E_2}^{\min}$, the total cost is the global optimum. The pump networks with the global optimum are shown in Fig. 5. Two auxiliary pumps need to be installed in the parallel branch lines before coolers E_3 and E_4, each requiring a pressure head of 7 m and 22 m, respectively. Table 3 shows that the total cost of the pump networks after optimization is 2.76 × 10^6 CNY/yr. The operation cost and annualized capital cost are 1.94 × 10^6 CNY/yr and 8.15 × 10^5 CNY/yr, respectively. Compared with the costs before optimization, the optimization achieves a saving of 5.8 × 10^5 CNY/yr or 23% in the operation cost and a saving of 4.8 × 10^5 CNY/yr or 14.8% in the total cost.

5. Conclusion

This paper proposes a novel pump network structure for a cooling water system by adding auxiliary pumps to parallel branch lines, and establishes a pump network superstructure that contains both a main pump network and an auxiliary pump network. Compared to the general pump network structure containing only the main pump network, the proposed network structure can provide significant energy savings. To optimize the main and auxiliary pump networks, the total cost is taken as the objective function. The mathematical model is an MINLP model and contains two optimization variables, the main pump pressure head and the binary variable y_j. Simulated annealing algorithm is used to solve this model.

The model is tested on a case study based on the pump network of a refinery's cooling water system. The optimal number and locations of auxiliary pumps vary with the magnitude of the main pump pressure head. The simulation results show that when the main pump pressure head equals the minimum pressure head of each cooler, the total cost reaches a local optimum. For the case study, two auxiliary pumps need to be installed. The operation cost and the total cost can respectively be reduced by 28% and 14.8% as a result of energy savings.

Conflict of interest statement

The authors declare no competing financial interest.

Acknowledgments

Financial support from the National Basic Research Program of China (973 Program: 2012CB720500) and the National Natural Science Foundation of China under Grant No. 21306228 is gratefully acknowledged.

Nomenclature

c	velocity of fluid, m/s
C_{B1}	base cost of pump, CNY
C_{B_1,P_i}	base cost of main pump, CNY

C_{B_1,P_j} base cost of auxiliary pump, CNY
C_{B_2} base cost of motor, CNY
C_{B_2,M_i} base cost of main motor, CNY
C_{B_2,M_j} base cost of auxiliary motor, CNY
CC_{M_i} capital cost of main motors, CNY
CC_{M_j} capital cost of auxiliary motors, CNY
CC_{Motor} capital cost of motors, CNY
CC_{P_i} capital cost of main pump network, CNY
CC_{P_j} capital cost of auxiliary pump network, CNY
CC_{Pump} capital cost of pump networks, CNY
c_L frictional factor of pipe fitting
d diameter of pipe, m
e electricity price, CNY/kWh
f frictional factor of pipe
F_{M_i} main pump material factor
F_{M_j} auxiliary pump material factor
F_{T_1,P_i} main pump type factor
F_{T_1,P_j} auxiliary pump type factor
F_{T_2,M_i} main motor type factor
F_{T_2,M_j} auxiliary motor type factor
g gravity factor, m/s^2
h pump annual operation time, h
H pressure head of pump, m
$H_{E_j}^{\min}$ minimum pressure head of cooler E_j, m
H_i main pump pressure head, m
H_j auxiliary pump pressure head, m
I_{CE} current chemical equipment index
I_{CEbase} base chemical equipment index
K_{E_j} resistance coefficient of cooler E_j
K_{Fit} resistance coefficient of pipe fitting
K_{pipe} resistance coefficient of pipe
l length of pipe, m
m' number of main pumps in operation
n number of parallel branch lines
m total number of main pumps
N_p number of auxiliary pumps
OC_{auxi} operation cost of auxiliary pump network, CNY
OC_{main} operation cost of main pump network, CNY
P_A gauge pressure of section A, Pa
$P_{B_j}^{\min}$ minimum gauge pressure of node B_j, Pa
P_D gauge pressure of section D, Pa
$P_{E_{j,\text{out}}}^{\min}$ minimum gauge pressure of node $E_{j,\text{out}}$, Pa
P_P motor shaft power consumption, kW
P_T theoretical power of pump, kW
Re Reynolds number
S size factor of pump
TC total cost of pump networks
ν fluid viscosity, N s m^{-2}
V volumetric flow rate, m^3/s
V_i flow rate of main pump, m^3/s
V_j flow rate of parallel branch pipe, m^3/s
V_{tot} flow rate of header feed pipe, m^3/s
y_j binary decision variable
z_A height of section A, m
z_D height of section D, m
z_{E_j} height of cooler E_j, m

Greek letters
$\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, b_1, b_2, b_3$ cost parameters
ε slack variable
η_{M_i} main motor efficiency
η_{M_j} auxiliary motor efficiency
η_{P_i} main pump efficiency
η_{P_j} auxiliary pump efficiency
ρ water density (kg/m^3)
δ annualization factor for capital cost
γ_c correction factor
ΔP_{A-B_j} pressure drop between node A and node B_j, Pa
$\Delta P_{B_j-E_{j,\text{out}}}$ pressure drop between node B_j and node $E_{j,\text{out}}$, Pa
$\Delta P_{E_{j,\text{out}}-C_j}$ pressure drop between node $E_{j,\text{out}}$ and node C_j, Pa
ΔP_{E_j} pressure drop of cooler E_j, Pa
ΔP_{Fit} pressure drop of pipe fitting, Pa
ΔP_{pipe} pressure drop of pipe, Pa

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Please cite this article in press as: Sun J, et al., Pump network optimization for a cooling water system, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.01.028