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Pump network optimization for a cooling water system

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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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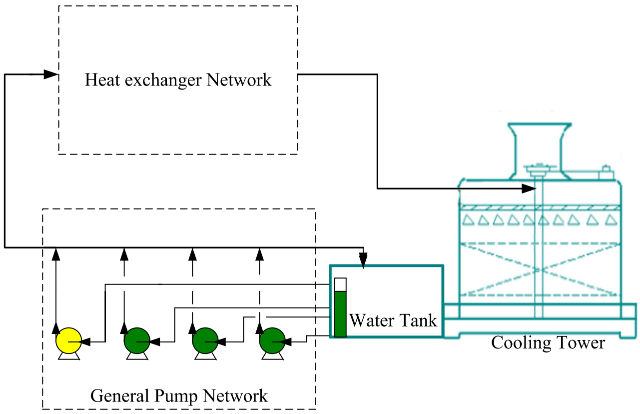

Fig. 1. The general pump network of cooling water system.

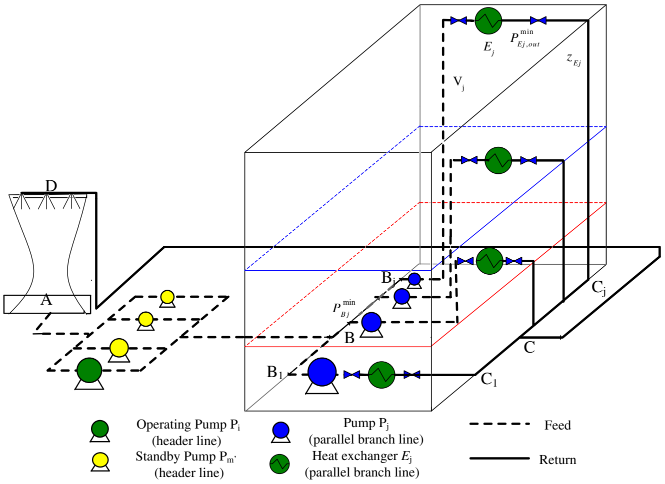

Fig. 2. Pump network superstructure of cooling water system.

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, $H^{min}_{E_j}$ 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).

$$\mathrm{Obj} = \mathrm{MIN}[\mathrm{TC}] = \mathrm{MIN}[\mathrm{OC} + \mathrm{CC}] \tag{1}$$

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).

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

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.