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Research paper

Cooling-water system optimisation with a novel two-step sequential method

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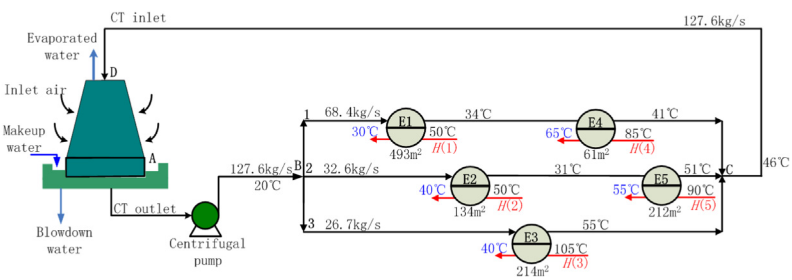
GRAPHICAL ABSTRACT



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ABSTRACT

In cooling water systems, conventional cooler networks usually operate in a parallel configuration and traditional pump networks consist of pumps which are installed only on the main supply pipeline. However, a series-parallel configuration of coolers can substantially increase the cooling-water return temperature and reduce its flow-rate as well as the efficiency of the cooling tower, but the pressure drop along pipes would increase correspondingly. This paper presents a novel two-step sequential methodology for the optimisation of cooling-water system (CWS). The first step is to use a thermodynamic model to obtain the optimal cooler network. In the second step, the hydraulic model is established to obtain the optimal pump network with auxiliary pumps installed in parallel branch pipes. The proposed model can identify the optimal distribution of cooling water within the network and the optimal installation locations and pressure head of pumps required for CWS. A case study is presented to demonstrate the effectiveness of the proposed methodology. It can save up to 23.3% of the cooler network cost and additional 11% of the pump network cost after optimisation.

1. Introduction

A cooler network is one of major components of a CWS in process plants; the other major component is a pump network. Most of the industrial cooler networks are designed with parallel configurations. In practical terms, the implication of this arrangement is that cooling water enters each cooler at the same temperature supplied by the cooling tower. Although this arrangement is very flexible in operation, it results in inefficient use of cooling tower capacity and incurs undue operation and capital cost. The traditional cooler network [1] can be retrofitted by changing coolers from parallel configuration to series or series-parallel arrangement. Previous research on a CWS is mainly focused on methods to reduce cooling-water consumption [2], coolers investment [1] and the operation and capital cost of pumps [3].

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In series or seies-parallel configuration of cooler network, cooling water can be recycled or reused between coolers. Klemes [4] provided a brief overview of the recent techniques and methodologies in industrial water recycle/reuse. Lee et al. [5] proposed a mathematical model for the synthesis and design of chilled water networks and explored opportunities of reusing or recycling chilled water. One of the earliest methods to design a cooler network was introduced by Kim and Smith [2]. Their design methodology concentrated mainly on minimising cooling water flow-rate. Although their goals can be achieved, the area requirement of the corresponding cooler network can be too large and therefore coolers would need more heat transfer area to meet the required heat load. Kim and Smith [6] also developed an automated design procedure for the cooler network where the network complexity, pressure-drop constraints, and the efficient use of cooling towers are considered. Castro et al. [7] presented a mathematic model for the minimisation of operating cost and de-bottlenecking by analysing the hydraulic and the thermal interrelationship among the cooler network, pumping network and cooling tower. Picón-Núñez et al. [8] researched the influence of cooler network configuration upon the total heat exchange area. Following works from this group [9] developed a simplified model and considered the scenario of introducing new coolers into existing networks [10]. Feng et al. [11] proposed the internal water main structure with simple configuration which can be designed and controlled easily. Wang et al. [12] used the flow rate difference curve and sensitivity graphs to identify optimal cooler network. Shenoy et al. [13] used a Unified Targeting Algorithm and Nearest-Neighbors Algorithm to target and design of cooling water networks. Rubio-Castro et al. [7] presented a systematic approach to synthesise cooling water systems with multiple cooling towers. Reddy et al. [14] proposed a holistic approach for retrofit design of closed-loop cooling water systems involving multiple cooling towers and heat exchangers. To analyse the performance of a cooling water system systemically, Cortinovis et al. [15] presented an approach by combining experimental investigation with an integrated mathematical model.

Although the series-parallel configuration of coolers can obviously reduce the cooling water flow-rates and enhance the heat disposal efficiency of the cooling tower, this arrangement of coolers may result in an increase of pressure drop due to the cooling water reuse between coolers. This kind of configuration requires a higher pressure head of pumps in the main supply pipe. However, for some coolers and parallel branch pipes with their minimum pressure head comparatively small, their outlet valves has to be partially closed to balance cooling water distribution. Such adjustment results in an energy penalty of pump power. For retrofit scenarios, the original pressure head of main pumps may limit system modifications because of pressure drop constraints.

Sun et al. [3] proposed a hydraulic model for the optimisation of pump networks and considered the pressure-drop constraints. To attain energy savings of pump networks, they proposed an auxiliary pump network whereby auxiliary pumps are installed in parallel branch pipes. By this method, the pressure head of the main pump does not need to be larger than the minimum pressure heads of all coolers. 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. The Sun et al. method [3] of optimising the auxiliary pump network is adopted in this paper.

The objective of this study is to optimise a cooling-water system by using a two-step sequential optimisation approach. The first step is to use a thermodynamic model to obtain the optimal cooler network. After the optimal cooler network is obtained, the pump network is optimised by using Sun et al. method [16]. The problem of pump network optimisation is formulated as a mixed-integer nonlinear programming (MINLP) model. The pump network of a CWS is a complex system which includes an intricate interrelationship between its components (the pressure drops of main pump and auxiliary pumps, and the number and installation site of auxiliary pumps, etc). An alteration of one component may influence the effect of several others. Because of the complexity of pump network, the simulated annealing method is used to solve the hydraulic model constructed in this paper as it can avoid local optima.

2. Problem statement

Conventional cooler networks can be optimised by retrofitting traditional parallel configuration to series-parallel arrangement. Although the optimal cooler network can greatly reduce the cooling water consumption and enhance the heat disposal efficiency of the cooling tower, the pressure drop of this configuration may be increased due to cooling-water reuse between coolers. In order to optimise a CWS, a superstructure shown in Fig. 1 is established that embeds all possible configurations of coolers and installation locations of auxiliary pumps. In a cooler network optimisation problem, the given parameters are the temperature rise of each cooler, the inlet temperature for cold utility ($T_{\mathrm{Cu}}^{\mathrm{in}}$) and the maximum allowable returned temperature (T_{Tower}^{U}), a set of hot process streams with known flow-rates (F_{H_i}), inlet temperatures ($T_{\mathrm{i}}^{\mathrm{H,in}}$) and target temperatures ($T_{\mathrm{i}}^{\mathrm{H,out}}$). Prior to the optimisation of pump network, the pressure head of main pumps (H_m), pipeline layout parameters, and the installation levels of coolers ($z_{E_{\mathrm{i}}}$), are given.

The mathematical model developed in this paper employs several assumptions:

1. The specific heat capacities of both hot and cold streams are constant throughout the temperature range.
2. Overall heat transfer coefficients are constant for coolers.
3. Cooler operation can be represented as a counter-current heat exchange operation.
4. Each hot stream corresponds to only one cooler.
5. The original cooler network structure is bases on a parallel configuration.

3. Model formulation

3.1. Cooler network model for CWS

In the model formulation, the following nomenclature is used: H denotes both the number and the set of hot process streams, I represents both the number and the set of parallel branch pipes in the initial parallel configuration. N represents the maximum number of coolers in each parallel branch pipe of a cooler network. CW stands for cooling water. Cooler $E(i)$ is the cooler installed on branch pipe i of the initial cooler network. For cooler $E(i, j)$, i represents that the cooler is installed on branch pipe i of the series-parallel configuration, while j denotes that the serial number location of pipe i where the cooler is installed. Similarly, $H(i)$ represents the hot process stream i. It should be noted that each hot stream i corresponds to only one cooler in the series-parallel configuration for the assumption above.

The initial network structure is based on a parallel configuration and each hot stream corresponds to only one cooler. The cooler network superstructure with the series-parallel configuration is shown in Fig. 1. There are I parallel branch pipes and at most N coolers installed in series on the parallel branch pipe i. The energy balances of each parallel branch pipe in this configuration are shown in Eqs. (1)–(3). Binary $y(i, j)$ and $y(i)$ are introduced to illustrate the existence of cooler $E(i, j)$ and branch pipe i.