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Research article

A novel step-by-step optimization method for interplant water networks

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ABSTRACT

This paper evaluated the characteristics of interplant water networks along with superstructure models of such networks coordinated with intermediate pools, with the latter being assessed via nonlinear programming tools. To overcome the inherent difficulties associated with nonlinear programming models, a superstructure model was ultimately simplified according to a unidirectional characteristic. A novel step-by-step optimization method was then set forth for this simplified model. And the novel method was then applied to two examples, a single contaminant example from the literature and a multiple contaminants example located in southern China, which could demonstrate the applicability and effectiveness of the proposed method.

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1. Introduction

Water shortages and water pollution have increasingly become key factors in restricting the optimal development of society and economics in the country of China, with the rapid expansion of process industries being one of the primary reasons for such shortages and pollution. Process industries not only consume an abundance of freshwater they also discharge large volumes of wastewater. It is therefore important to carry out research on water conservation and emission reduction techniques in processing industry.

The integration of water systems utilizing water-pinch technologies and mathematical programming methods has been demonstrated efficient for water conservation and emission reductions within the processing industry. Wang and Smith (1994) were the first to apply water-pinch technologies to water system integration and optimization. Since then, many researchers have applied water-pinch technologies in the petrochemical industry (Mohammadnejad et al., 2011), the food industry (Thevendiraraj et al., 2003), and numerous other industries, which has delivered benefits. However, these researches mainly focused on the single contaminant problem. Kuo and Smith, 1998 applied the water-pinch technologies to multiple contaminants water networks through migration strategies. But this method could only deal with simple water utilization network with multiple contaminants.

In contrast, mathematical programming techniques can easily handle scenarios involving multiple contaminants, and have therefore been widely used in water utilization network integration and optimization processes. Takama et al. (1981) established a superstructure model of a water utilization network with a single contaminant by employing a mathematical programming method used for oil refinery industrial applications, resulting in a novel structural design for such a subject network. Bagajewicz and Savelski (2001) set up an easily-solved Linear Programming (LP) model or Mixed Integer Linear Programming (MILP) model for the scenario of water utilization network optimization with a single contaminant. Bagajewicz (2000) constructed a mathematical model with the aim of minimizing economic cost. The model considered water price, pipeline construction costs and water pump operation costs. This model was applied to oil refinery operations. Because mathematical programming methods can be applied to the design of water utilization networks with multiple contaminants, it has consequently been used in specific industries to integrate and optimize water utilization networks. Examples include the petrochemical industry (Alva-Argaez et al., 2007), the brewing industry (Tokos and Pintaric, 2009) and catalyst manufacturing (Feng et al., 2006).

Current studies on methods to integrate and optimize water utilization networks have focused mainly on single-plant water networks. Historically for some large enterprises, however, there have been a considerable number of available water utilization

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processes which are typically distributed throughout various plants with long distances. In these cases, spatial distribution factors should have been considered during the process of optimizing water utilization networks.

Olesen and Polley (1996) first applied water-pinch technology to optimize interplant water networks based on a single contaminant. Liao et al. (2007) subsequently established the MILP model for interplant water network optimization, but this method was still limited to just single contaminant scenarios. Chew et al. (2008) proposed two different interplant water integration schemes, "direct" and "indirect" integration. A MILP model was formulated for the direct integration scheme and a Mixed Integer Nonlinear Programming (MINLP) model was formulated for the indirect integration scheme. Chen et al. (2010) placed central and decentralized water mains to interconnect the water utilization processes of the individual plants, and set up a MINLP model for the optimization of interplant water networks to minimize the freshwater consumption and total annualized cost. Castro et al. (2012) proposed a MINLP model for the optimal retrofit of water networks from different plants in the same industrial zone. Chew and Foo (2009) proposed their "cascade analysis method" using water-pinch technology to deal with the problem of interplant water network optimization. Shukla et al. (2013) also dealt with the challenge of interplant water network optimization through the cascade analysis method and ultimately applied this method to the integration and optimization of pulping and papermaking plants. Lee et al. (2014) proposed a two-stage method for optimizing continuous water utilization processes and intermittent water utilization processes, and then applied this method to the interplant water network optimization process. Alnouri et al. (2016) proposed a method to handle interplant water network problems with freshwater, wastewater, and treated water, which formulated a Nonlinear Programming (NLP) model to minimize of total annualized cost. Ibrić et al. (2017) studied the heat-integrated water network superstructure and proposed a MINLP model for the synthesis of single and interplant non-isothermal water networks.

Several researchers have attempted to employ water-pinch technologies or mathematical programming methods to optimize interplant water networks. The water-pinch technology was typically only found useful for single-contaminant water networks. The mathematical programming mainly including MILP, MINLP and NLP, and the MILP model can only handle simple problem, for example single contaminant scenarios or direct integration. MINLP and NLP models proved very difficult to fully implement and solution is not necessarily globally optimal.

In response to these challenges, this paper proposes a new mathematical programming method for optimizing interplant water networks. Firstly, a superstructure model for interplant water networking with intermediate pools was developed, which could greatly reduce the number of required connections. However, the superstructure model also need formulate MINLP model which proved difficult to solve. The unidirectional characteristic of the superstructure model was then ascertained, followed by its simplification based on the subject unidirectional principle. Ultimately, a novel step-by-step optimization method was implemented using the simplified model.

In a real-world application this newly developed optimization method was applied to a yeast processing enterprise in southern China. Corresponding optimization schemes for the associated interplant water network were proposed, with the resulting beneficial water-conservation and emission-reduction effects presented below.

2. Problem statement

Given a water utilization network has a set of water utilization processes located in different plants. The objective is to integrate the overall water utilization network to minimize the total freshwater consumption.

The following assumptions were adopted within the synthesis problem:

—The water utilization processes in these plants are all continuous processes.
—The water utilization network has just a single freshwater source without contaminants.
—Distance between different plants is ignored.
—Wastewater regeneration is not considered.
—Temperature was also considered in some literature about water system integration, which dealt with the problems of non-isothermal water networks. This paper only deal with the problems of isothermal water networks and fixed temperature of water streams is assumed.

3. Optimization method for interplant water networks

3.1. Superstructure model for interplant water networks

3.1.1. The superstructure model for interplant water networks with intermediate pools

Because distances between individual plants can be considerably farther than the distance between water utilization processes in a single-plant, more water pumps and pipelines need to be constructed when integrating and optimizing interplant water networks. Chew et al. (2008) proposed a centralized utility hub between the plants as a buffer, which can greatly reduce the number of connections between water utilization processes in different plants. But it will cause some problems to set only one centralized utility hub between different plants. The wastewater discharged from different plants will be mixed in the centralized utility hub, which will cause mixture of wastewater with different qualities for many times, and decrease the possibility to reuse the better quality wastewater. This paper consequently developed a superstructure model for interplant water networks with multiple intermediate pools, as shown in Fig. 1. This can avoid the secondary mixture of wastewater from different plants.

3.1.2. A simplified superstructure model for interplant water networks with intermediate pools

Similar to the superstructure model for indirect integration that Chew et al. (2008) proposed, which need formulate MINLP model, the superstructure model in Fig. 1 also need formulate MINLP model. And the MINLP model is difficult to solve. So the superstructure model in Fig. 1 needs to be simplified.

3.1.2.1. Unidirectional characteristic. According to the principle of conservation of matter, all plants will generate wastewater and all intermediate pools can collect residual wastewater from the corresponding plants. The residual wastewater is discharge from the plant because the residual wastewater cannot meet the requirements of all the water utilization processes in the corresponding plant. So one plant can only reuse the wastewater that quality is better than the quality of wastewater in the corresponding intermediate pool of the plant, which we called

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