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Research article

Synthesis of single and interplant non-isothermal water networks

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ABSTRACT

This paper addresses the synthesis problem of non-isothermal water networks using a mathematical programming approach. A heat-integrated water network superstructure and its corresponding mixed integer nonlinear programming (MINLP) model is proposed for the synthesis of individual as well as interplant water networks. A new feature of the proposed model includes piping installation cost within the objective function minimising the total annual cost of the network. This introduces additional trade-offs between operating and investment costs that can impact a final network design. Three examples were solved in order to demonstrate the applicability and effectiveness of the proposed model and solution approach. The results show that additional saving in total annual cost can be achieved by enabling direct water integration between plants. Improved solutions were obtained compared to those reported in the literature considering freshwater and utilities consumption as well as total annual cost.

1. Introduction

The efficient usage of natural resources is an important goal for achieving profitability as well as sustainability of industrial processes. The role of industrial water is especially important where it can be used for different purposes such as process water, cooling water, water for energy production etc.

Consumption of water and energy is related to each other e.g. water is required for energy production and energy is required for many water related industrial processes such as water transportation, wastewater treatment, heating and cooling etc. Savings in water consumption in industrial processes can be achieved by using holistic approaches based on Energy and Water Quality Management System (EWQMS) (Cherchi et al., 2015) on the operational level. In addition, on the retrofit or design level Process Integration techniques can be used, such as Pinch Analysis (PA) (Savulescu et al., 2005) and Mathematical Programming (MP) (Bagajewicz et al., 2002) that can be applied for batch (Majozi et al., 2006) and continuous processes (Bogataj and Bagajewicz, 2008). However, a combination of approaches can be used consisting of water audit, PA and process application in order to systematically identify water conservation opportunities (Agana et al., 2013).

Research related to efficient utilisation of natural resources and development and application of systematic tools have been popular research areas for more than forty years (Klemeš and Kravanja, 2013). During that time the scope of resource conservation networks (i.e. heat exchanger networks or water networks) has changed from integration of local sites (single-plant), towards integration of interplant networks and total site integration (Klemeš et al., 2013). This expands the integration potential for resource conservation, enabling additional savings in resource consumption. Chemical production sites can have a large number of water-using units (Olesen and Polley, 1996) that are usually grouped in different locations within the industrial complex.

A consideration of geographical location of process water-using units when synthesising water networks has been addressed in past (Olesen and Polley, 1996). By applying the water targeting procedure (Wang and Smith, 1994) to the overall site and to the geographically decomposed group of units, the water reuse opportunities between units at different locations can be identified. Using Water Cascade Analysis (WCA) (Manan et al., 2004) water reuse opportunities were first analysed within individual plants and afterwards a cross-plant water integration possibilities were

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investigated (Foo, 2008) enabling significant reduction of freshwater consumption. The targeting procedure based on PA for a single water network has been expanded into a linear programming (LP) optimisation based technique for interplant water integration (Chew and Foo, 2009). Thus, the minimum freshwater and cost targets (cost of interplant piping) for the interplant water network can be set prior to the network design. A novel integration scheme including centralised (between different plants) and decentralised (within individual plants) water mains was proposed (Chen et al., 2010). A corresponding model was formulated as a mixed integer nonlinear programming (MINLP) and solved for two scenarios including minimising freshwater consumption and minimising total annual cost (TAC).

These papers addressed only water integration options within and between plants assuming fixed temperature of water streams. However, in most cases, different process water-using units operate at different temperatures, and wastewater discharged into the environment has to satisfy regulations regarding not only contaminant concentration but also the effluent temperature. Therefore, some water streams will require heating or cooling demands. Accordingly, it is possible to integrate hot and cold water streams in order to minimise utilities consumption. For this reason, the objective is to minimise not just freshwater consumption but rather perform simultaneous optimisation of freshwater and energy consumption. This synthesis problem is known in the literature as the synthesis of non-isothermal water network, a heat integrated water network or a water allocation and heat exchange network.

Recent review paper (Ahmetović et al., 2015) presented a systematic and comprehensive literature review of studies within this field over the last two decades as well as possible future research directions. To the best of our knowledge, only a few papers address the issue of simultaneously synthesising heat-integrated interplant water networks. Authors firstly addressed the synthesis problem for fixed flow rate processes (Zhou et al., 2012a) and later expanding their research to fixed contaminant-load processes (Zhou et al., 2012b). The proposed approach is based on the multiscale state-space superstructure and corresponding MINLP model. The direct and indirect integration schemes were analysed along with their impact on network design and TAC that included a cross plant piping installation cost. In an industrial pulp and paper case study (Kermani et al., 2016), the total site is divided into four locations due to geographical constraints. Heat integration between these locations is favoured through the water network only (water streams act as heat transfer medium between locations). However, they did not consider piping cost of the water network. The established superstructure for simultaneous optimisation of water and energy has been later extended to address inter-plant operations (Kermani et al., 2017).

In order to synthesise a non-isothermal water network tradeoffs between water and energy costs and investment costs should be simultaneously explored. The piping cost has been rarely addressed within the studies in the literature (Leewongtanawit and Kim, 2008). However it is important to highlight that besides investment cost of heat exchangers and wastewater treatment units, piping cost can have influence on the final network design. As a result, less complex and more practical design can sometimes be obtained. The reader is referred to recent studies for more information about water and energy interactions (Varbanov, 2014) and industrial water use (Klemeš, 2012), as well as the comprehensive literature review of non-isothermal water network synthesis (Ahmetović et al., 2015).

The aim of this paper is to present the MP approach for the synthesis of single and interplant non-isothermal water networks. A recently proposed MINLP model (Ibrić et al., 2016) was modified by introducing binary parameters for identifying process units, wastewater treatment units and hot/cold streams within different plants and removing restricted connections between the units within different plants. This modified model enables the synthesis of interplant water networks simultaneously exploring different water and heat integration opportunities. In addition, a piping cost is included within the objective function minimising the TAC of the network. In the proposed approach, the piping cost is accounted for using economic pipe diameter for which the pumping cost is minimum. Thus, the trade-off between investment in pipe and its operating cost for water transportation is also explored.

2. Problem statement

Given sets of freshwater sources $s \in SFW$, process water-using units $p \in PU$, wastewater treatment units $t \in TU$. The objective is to find an optimal design of the non-isothermal water network minimising operating cost (freshwater, utilities and wastewater treatment) and investment cost (heat exchangers, wastewater treatment units and pipes) of the network.

The following common assumptions were adopted within the synthesis problem:

- The same water source at given temperature and contaminant concentration level is available for all the plants within the industrial complex,
- The existence of connections in interplant problems are defined ahead of the synthesis and are therefore not optimised,
- The process water-using units operate assuming fixed temperature and fixed mass load of contaminants transferred to the water stream entering the unit,
- Treatment units operate at fixed temperature and fixed removal ratio of the contaminants,
- Water heat capacity is constant (4.2 kJ/(kg K)) and independent of the streams temperature,
- Individual heat transfer coefficients of water streams and utilities are constant,
- Single hot and cold utilities are available,
- Water streams are at fixed temperature (no heat losses) with variable heat capacity flow rate,
- Fixed effluent temperature.

The goal of the synthesis problem is to determine the optimum design of a non-isothermal water network minimising the total annual cost (TAC), satisfying given constraints and exploring mass and heat exchange opportunities within and between different plants.

3. Superstructure representation

Fig. 1 shows a conceptual superstructure of an interplant heat-integrated water network involving two plants. A recently proposed compact superstructure (Ibrić et al., 2016) for individual plants has been modified in order to account for location of heating and cooling stages required for piping cost calculation as well as to represent connections between units within different plants.

Each individual water network consists of two networks, namely, water and wastewater treatment network (WN–WTN) and a heat exchange network (HEN). The first network (WN–WTN) enables water integration opportunities (water reuse, regeneration reuse and regeneration recycling) between water-using units ($p \in PU$) and wastewater treatment units ($t \in TU$). The second