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Sequential synthesis of heat integrated water networks: A new approach and its application to small and medium sized examples

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ABSTRACT

This paper presents a new step-wise sequential solution strategy for the synthesis of heat integrated water networks (HIWNs) comprising of two mathematical models. The first model minimizes water and energy costs. The optimal freshwater and water flow rates within the HIWN are determined from this model. Using these optimal flow rates, different configurations of HIWN are evaluated for the purpose of heat integration. The second model is the stage-wise heat exchanger network (Yee and Grossmann, 1990), which is solved for each of the evaluated network configuration in a sequential manner. Using this proposed strategy, a set of locally optimal HIWNs are produced and the best one is chosen based on the minimum total annual cost (TAC). The proposed sequential strategy is applied to small and medium sized examples in the literature. The results show that the proposed new sequential solution strategy can be successfully applied to small and medium sized HIWN problems.

1. Introduction

Water is essential in many process industries such as chemical, petrochemical, petroleum and biofuel based refinery, food, paper and pulp etc. Some of its primary functions include washing (water used as a cleansing medium to clean equipment, rinse and wash raw materials, products etc.), separation (water used as a mass separating agent in absorption, scrubbing and liquid–liquid extraction processes), product manufacture (water used as a prominent ingredient in the manufacture of chemicals, polymers etc.), energy generation (water used in boilers to produce steam and power) and cooling (water used as cooling water to cool process streams). The water used for the above purposes tends to get contaminated and this wastewater has to be treated before it is discharged into the environment. Scarcities of freshwater sources, ever increasing cost of freshwater and stringent environmental regulations on the quality of wastewater discharged into the environment have forced the process industries to adopt water management strategies to efficiently manage and utilize their water resources. The overall aim of these strategies is to efficiently utilize water, improve the quality of wastewater discharged into the environment and minimize the freshwater consumption. One of the key water management strategy is to optimally synthesize or design a water network. In this, the water needs (in the form of demand and availability) of all the water using, consuming, producing, treating and disposing units in a process industry are carefully analyzed; and a network topology is developed depicting the water distribution among all the units in the industry satisfying its water needs in an optimal manner. In other words, the water network synthesis or design refers to the optimal distribution, routing and allocation of water among the different units of an industry with water needs. Comprehensive review of water network design and details on the different process integration approaches (pinch analysis and mathematical programming) used to solve the same can be found in some literature works' (Bagajewicz, 2000; Foo, 2009; Jeżowski, 2010; Khor et al., 2014; Mann and Liu, 1999). Over the last decade, studies on energy minimization in water networks have gained tremendous significance and several literature works' were carried out in this direction. The reason for this is that, the units having water needs (water using, consuming, treating and disposing units) in a process industry have different temperature requirements for their water streams. This induces non-isothermal nature in the water network design, where water streams are subjected to units having different temperatures. This entails heating and cooling of water streams for which large amount of energy is required. In view of this energy consumption being large, heat (energy) integration among the water streams needs to be carried out. This can be now referred to as HIWN problem. The heat integration is performed by syn-

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thesizing a heat exchanger network (HEN). The development of a HEN for minimizing the cost of heat exchangers and overall energy consumption for a set of process streams with heating and cooling requirement has been known for long in literature (Floudas and Ciric, 1986; Yee and Grossmann, 1990). In HIWN, the process streams are the water streams and it is necessary to develop a water network design along with its corresponding HEN design. Thus, the main objective in the synthesis of HIWN is to design a water network with optimal freshwater consumption, total cost, and hot and cold utility consumption; thereby satisfying the flow, contaminant concentration and temperature needs of all the units in the water network.

Along with the conceptual approach based on graphical analysis, the superstructure based mathematical programming approach can be used to systematically design HIWNs either sequentially or simultaneously. In the sequential methodology, the model for the HIWN is hierarchically decomposed and solved as water network model and HEN model sequentially (Ahmetović and Kravanja, 2012; Bagajewicz et al., 2002; Boix et al., 2012; Chen et al., 2010; Feng et al., 2009; George et al., 2011; Liao et al., 2011; Liu et al., 2015; Polley et al., 2010; Sahu and Bandyopadhyay, 2012; Sharma and Rangaiah, 2014). In the simultaneous approach, as the name indicates, the water network and HEN are combined and solved as a single system (Ahmetović et al., 2014; Ahmetović and Kravanja, 2013, 2014; Bogataj and Bagajewicz, 2008; Dong et al., 2008; Ibrić et al., 2012, 2014a, 2014b; Leewongtanawit and Kim, 2008; Yan et al., 2016; Zhou et al., 2015). Recently, a comprehensive and systematic review of all the papers published in the field of HIWN synthesis till date (both sequential and simultaneous approaches) involving pinch analysis, mathematical programming and combination of both was done by Ahmetović et al. (2015). The advantage of the simultaneous approach is that, the appropriate interactions between the elements of water network (freshwater consumption, cost of treatment unit etc.) and HEN (hot and cold utility consumption, cost of heat exchangers) are captured holistically and the final network obtained has minimum cost. Such interactions are not captured in the sequential method and usually produce networks (solutions) with comparatively higher total costs than the simultaneous methodology due to higher freshwater and utility (hot and/or cold) consumption. The major drawback, however, of the simultaneous approach is in its model complexity that makes it computationally expensive and very difficult to solve. From the review of literature on both sequential and simultaneous approaches for HIWN synthesis, it can be understood that there is a need to develop a methodology (either sequential or simultaneous) that not only produces solutions of good quality (rightly exploring the trade-offs between water network and HEN to give minimum cost), but also provides these solutions within tractable computational time. This forms the motivation for this research work.

In this work, a new step-wise sequential solution strategy is developed for the design of HIWN. The step-wise sequential strategy consists of solutions of two mathematical models. The superstructure model for the HIWN synthesis has freshwater sources, process units, wastewater treatment units and discharge sinks. It can also handle multiple contaminants. All the streams in the HIWN superstructure can participate in heat integration thereby increasing opportunities for energy conservation. The first model determines the freshwater and energy consumption of the HIWN. From the solution of the first model, optimal flow rates and water network topology are ascertained. For this optimal flow rate and water network topology, heat integration is carried out and different HEN configurations are developed and evaluated in a sequential manner. The model for heat integration, second model in the sequential solution strategy, is the stage-wise heat exchanger network synthesis model (Yee and Grossmann, 1990). Both the models are non-convex MINLP in nature. As the HIWNs are evaluated in a sequential manner, a set of locally optimal solutions are produced from which the best one is chosen according to the selected objective. The proposed model and solution strategy is applied on small and medium sized examples in the literature. The usual drawback of most sequential strategies in HIWN synthesis, as mentioned earlier, is the poor or inferior quality of solutions obtained due to appropriate interactions not being considered between the elements of water network and HEN. But in the proposed step-wise sequential solution strategy, for an optimal water network topology, different HEN topologies (or configurations) are enumerated and evaluated in an exhaustive manner. For each of these evaluated HIWNs, the network with minimum TAC is selected as the optimal network. Although complete simultaneous interaction between water network and HEN is not considered in the proposed methodology, such exhaustive enumeration and evaluation approach can potentially find good HIWN designs whose TACs are nearly close to that of HIWN designs from simultaneous approaches especially for small and medium sized examples.

The contributions of this work are explained as follows. First, a novel step-wise sequential methodology has been developed for the synthesis of HIWN. The attractive feature of this methodology is that it introduces two new classification metrics in HIWN synthesis namely Type 1 and Type 2 networks (definition and significance explained later in Sections 5 and 6 respectively). Second, this work is one among few other works (Ahmetović et al., 2014; Bogataj and Bagajewicz, 2008; Chen et al., 2010; Dong et al., 2008; Ibrić et al., 2014a; Liao et al., 2011) in the literature which considered HIWN synthesis including wastewater treatment units. Most works in the area of HIWN had concentrated only on the water using units. By including the wastewater treatment units, the overall HIWN synthesis problem now consists of water using units, wastewater treatment units along with heat exchange units (HEN). Thus, the HIWN synthesis problem now involves reuse, recycle and regeneration (wastewater treatment) of water streams thereby minimizing freshwater usage, wastewater generation and utility consumption; ensuring that the quality of wastewater effluent discharged into the environment complies with suitable environmental and legislative restrictions. HIWN design considering wastewater treatment option increases the model complexity and size and consequently results in longer solution time. The proposed sequential solution strategy is in a position to handle the same and produces good quality optimal solutions for the small and medium sized problems. Third, using the approaches in the literature (Jagannath et al., 2012; Jagannath et al., 2014; Jagannath and Almansoori, 2014), the bilinear terms (related to the product of flow and temperature) are considerably reduced in the MINLP models (explained later in Section 3). This, to some extent, reduces the effect of nonlinearity in the MINLP models and makes them relatively easier to solve.

The structure of the rest of this paper is organized as follows. Section 2 formally describes HIWN problem followed by the superstructure considered. Section 3 provides a brief description of the mathematical models considered in this paper. The detailed explanation of the models considered in this paper are given in Appendix A. The sequential solution strategy is described in Section 4. Section 5 reports and analyzes the results when the proposed model and sequential solution strategy are applied on some of the literature examples. The features of the proposed model and solution strategy such as computational time, model statistics, features and shortcomings are highlighted in Section 6. The conclusions from this work and some specific directions for future work are highlighted in the final section (Section 7). Appendix B lists the notations used in this work and Appendix C provides the variable bounds for one of the mathematical model (explained later) used in this