CHEMICAL ENGINEERING TRANSACTIONS

VOL. 35, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Varbanov, Jiří Klemeš, Panos Seferlis, Athanasios I. Papadopoulos, Spyros Voutetakis

ISBN 978-88-95608-26-6; **ISSN** 1974-9791

DOI: 10.3303/CET1335025

Automatic Synthesis of Alternative Heat-Integrated Water-Using Networks

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A novel sequential approach is developed in this work to identify alternative heat-integrated WUNs with four mathematical programming models. The proposed synthesis method can be implemented in two stages. In the first stage, the objective is to identify all alternative optimal configurations featuring the minimum freshwater usage, the minimum energy consumption and the minimum total interconnection number respectively. These structures can be determined by solving two distinct models in sequence. The possible WUN designs are identified exhaustively by adopting the 'solution pool' technique provided by Solver CPLEX in GAMS. The HEN designs are then generated in the second stage. From each candidate obtained in the first stage, the stream data can be readily extracted and utilized in the transshipment models for determining the minimum utility usage and the minimum number of heat transfer units. The advantages of this approach are twofold: (1) more than one alternative designs can be found, and (2) all model scales can be kept to manageable levels. A case study is provided in this paper to illustrate the effectiveness of the proposed method.

1. Introduction

Water is one of the most often-used utility in industrial processes (Bagajewicz et al., 2002). In addition to its quality, water temperature is often an important parameter for the water-using operations, e.g., hydrolysis reaction, absorption and steam stripping, etc. Thus, it is quite obvious that, for efficient energy and water management, the design tasks of water and heat-exchanger networks in a given process are inseparable. The study concerning integrated water-using network (WUN) and heat exchange network (HEN) has been initiated by Savulescu and Smith (1998). Savelscu et al. (2005a, 2005b) introduced a conceptual approach which can be applied in a two-stage procedure. A two dimensional grid diagram is first developed to explore different options for minimum water and energy consumption. The concept of a separate system is then adopted to decrease the number of heat transfer units of the HEN design. Subsequently, other conceptual design tools, such as the source-demand energy composite curves (Savulescu et al., 2002), the principles of non-isothermal merging or direct heat transfer (Feng et al., 2008), the heat surplus diagrams (Manan et al., 2009), and the water energy balance diagram (Leewongtanawit and Kim, 2009), were developed to further improve the HEN design evolutionarily. The key point of this problem is how to properly address the interaction between WUN and HEN. It is obvious that the concept-based approaches cannot fully address the influence of different WUN configurations on the subsequent energy integration target (Feng et al., 2009). Mathematical programming techniques have been used for addressing this issue. Reviews of the related works can be found in Dong et al. (2008) and Liao et al. (2011). The model-based method can be further classified into two types, i.e., the simultaneous and sequential search strategies. All possible network configurations are incorporated in the former model according to a superstructure (e.g., the state-space representation), but this model is often very large and thus calls for extensive computation resources and a global optimum may not be reachable (Dong et al., 2008). In the latter case, several relatively simple models are solved in sequence, and the obtained target and the constraints of one model may be incorporated as constraints in the subsequent model. Consequently, the model scale could increase rapidly in the solution procedure (Bagajewicz et al., 2002;

Please cite this article as: Bao-Hong Li, Zhen-Zhen Ruan, Chuei-Tin Chang, 2013, Automatic synthesis of alternative heat-integrated water-using networks, Chemical Engineering Transactions, 35, 151-156 DOI:10.3303/CET1335025

Liao et al., 2011). Recently, Boix et al. (2011, 2012) adopt sequential search strategies and mathematical programming formulations to minimize the water and energy consumptions, a compromise solution is aimed although several intermediate network configurations are produced during the design procedure. Chew et al. (2011, 2013) present a simultaneous optimization model aiming for water and energy saving for the Brown Stock Washing System (BSWS) in the pulp and paper mills, the proposed model of MINLP type results in signification reduction in energy and water consumption. Note that all available design methods are aimed to find only one optimum heat-integrated WUN and neglecting other attractive candidates if additional design criteria (i.e., safety and flexibility) are also considered.

A novel sequential approach is developed in this work to identify heat-integrated single-contaminant WUNs by solving a series of four linear models (GAMS Development Corporation, 2010). The proposed synthesis method can be implemented in two stages. In the first stage, the objective is to identify all alternative optimal configurations featuring the minimum freshwater usage, the minimum energy consumption and the minimum total interconnection number respectively. These structures can be determined by solving two distinct models in sequence. The possible WUN designs are identified exhaustively by adopting the 'solution pool' technique provided by Solver CPLEX in GAMS. The HEN designs are then generated in the second stage. From each candidate obtained in the first stage, the stream data can be readily extracted and utilized in the transshipment models for determining the minimum utility usage and the minimum number of heat transfer units. The advantages of this approach are twofold: (1) more than one alternative designs can be found, and (2) all model scales can be kept to manageable levels. A case study is provided in this paper to illustrate the effectiveness of the proposed method.

2. Problem definition

For the design problem under consideration, the process parameters of all essential elements in a given water-using network are assumed to be given. The fixed-load operations are specified by their contaminant loads to be removed, the corresponding maximum inlet and outlet concentrations, and also the operating temperatures; The sole freshwater source is specified by its contaminant concentration and temperature; The only wastewater sink is specified by its maximum allowable temperature; All heat transfer units are constrained by a given temperature approach. For simplicity, it is also assumed that direct heat transfer by non-isothermal mixing is not possible and there are no water and heat loss during each operation. It is the objective of this design task to search for *all* possible optimal network configurations, and each must feature (1) the minimum freshwater usage, (2) the minimum energy consumption, and (3) the minimum number of heat transfer units.

3. Design strategy

3.1 A threshold problem

Most heat-integrated WUN design problems discussed by the previous workers are of this type (Polley et al., 2010). It was shown that the water conservation problem and the heat recovery problem can be de-coupled and the water conservation options should be established first (Polley et al., 2010). Under the constraint of maximum heat recovery, the energy demand is a function of the water throughput and the difference between discharge and supply temperatures, i.e.

$$Q_h = mC_p(T_d - T_s) \tag{1}$$

where Q_h is the external heat load requirements of the network, *m* is the water mass flow rate, C_p is the heat capacity, T_d is the discharge temperature and T_s is the supply temperature of water. It is clear that the consumed energy can be minimized as long as the freshwater consumption reaches its minimum.

3.2 A Pinch problem

Eq(1) cannot be applied to a "pinched" system because the minimum temperature approach drives the energy consumption level higher. To realize the proposed design aim, the minimum freshwater consumption should also be determined first without considering the heat recovery as a "threshold" problem does. The effect of different water network configurations featured by the minimum freshwater consumption on the energy consumption can be taken into account by enforcing two constraints: (1) the stream outlet concentration of each water-using unit reaches the maximum outlet concentration, and (2) a stream is forbidden to be reused to a water using unit if its concentration is greater than the maximum outlet concentration of the process unit. These two constraints drive the energy consumption rate of the WUN to its minimum (Feng et al., 2009).

3.3 Four general LP/MILP models to find all alternative configurations

Four LP/MILP models have been developed to identify alternative WUN configurations for the “threshold” and “Pinch” problems. A LP model is adopted first to minimize the freshwater consumption rate (Li and Chang, 2011). The second model is a MILP which can be used to minimize the total connection number while keeping the freshwater consumption rate at the minimum level. By making use of the solution pool function in Cplex 11, all alternative solutions can be enumerated (Li and Chang, 2011). The constraints of this MILP model include the two suggested by Feng et al. (2009) and also those in the first model. The third model is the extended transshipment model proposed by Papoulias and Grossmann (1985). By solving this LP repeatedly, one can predict the minimum energy consumption levels required by the alternative WUN configurations identified with the second model. The fourth model, a MILP, is aimed to minimize the number of heat transfer units so as to reduce the equipment costs. Finally, it should be noted that the detailed model formulations are omitted here because of space limitation.

4. A case study

An example from Feng et al .(2008) is adopted to illustrate the application of the aforementioned models. Six water-using units are involved and their limiting data and operation temperature are given in Table 1. The freshwater is supplied at 20 ℃ and its contaminant concentration is zero. The discharged wastewater is required to be cooled to be below 30 ℃. The minimum temperature approach for heat recovery is 10 ℃. It is required to identify all alternative heat-integrated WUN network configurations.

Table 1: The limiting data and operation temperature of water using units

Process number	C_{in}^{max}(ppm)	C_{out}^{max} (ppm)	M/(g/s)	T(℃)
1	0	100	2	60
2	0	50	2	75
3	50	100	1	71
4	75	150	3	73
5	150	200	2	90
6	100	200	2	80

The minimum freshwater consumption can be determined as 60 kg/s by applying the first model, the minimum total connection number of the WUN is 9 and there are two alternative WUN configurations featured by the minimum freshwater consumption and the minimum total connection number, they are provided in Figure 1 and 2. Note that FW and WW in Figures 1 and 2 represent freshwater and wastewater separately, each cold stream is marked with C while hot stream with H, and the contaminant concentration of each water stream is given in brackets. The HEN configuration shown in Figure 3 can be obtained when the third and fourth models are applied to the first WUN configuration, and the minimum hot and cold utility consumptions are found to be 3024 kW and 504 kW, which are the same as those reported results by Feng et al.(2008), the pinch temperature for hot streams is 80 ℃, and the minimum number of heat transfer unit is 8.

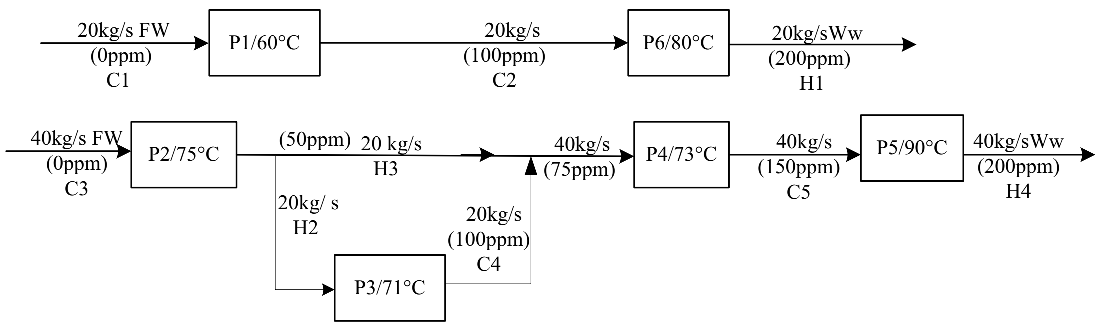

Figure 1: The first WUN configuration

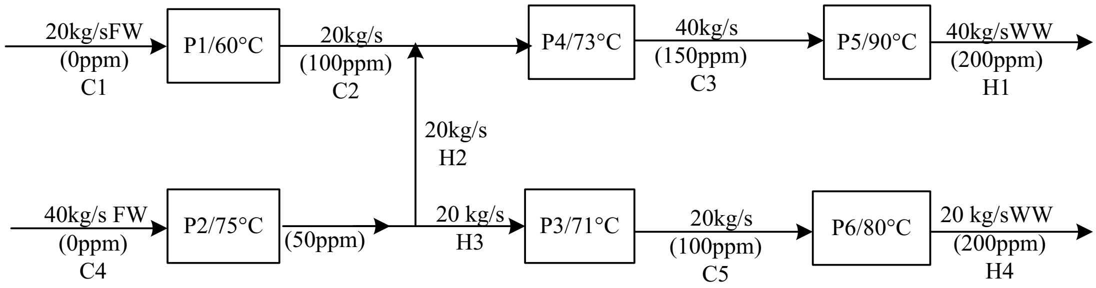

Figure 2: The second WUN configuration

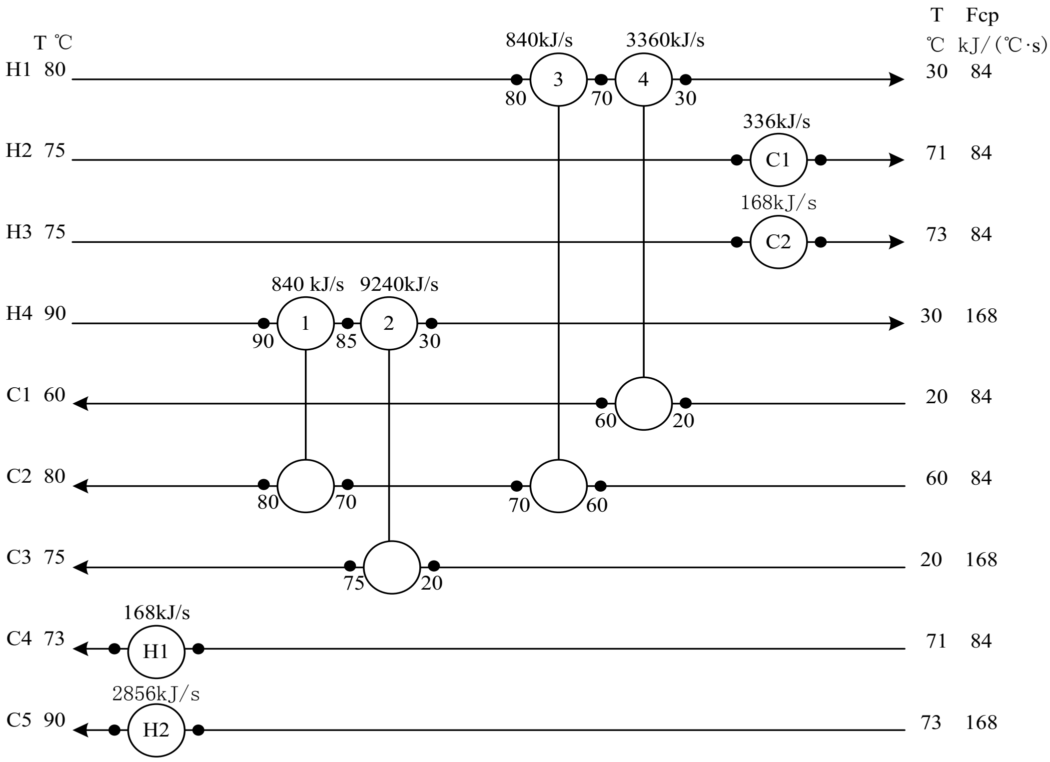

Figure 3: The HEN configuration of the first WUN

Similarly, the latter two models can be applied to the second WUN configuration in Figure 2. The minimum hot and cold utility consumptions and the pinch temperatures are just the same as those of the first WUN configuration. The corresponding HEN configuration is provided in Figure 4. Note that the minimum number of heat transfer units is 9, one more than that of Figure 3.

5. Conclusions

A novel sequential approach is presented in this paper to identify heat-integrated single-contaminant WUNs exhaustively. These alternative designs can be obtained by solving four mathematical programming models in sequence. The resulting solutions feature the minimum freshwater and energy consumption rates. A case study from literature is adopted to illustrate the effectiveness of the proposed approach.

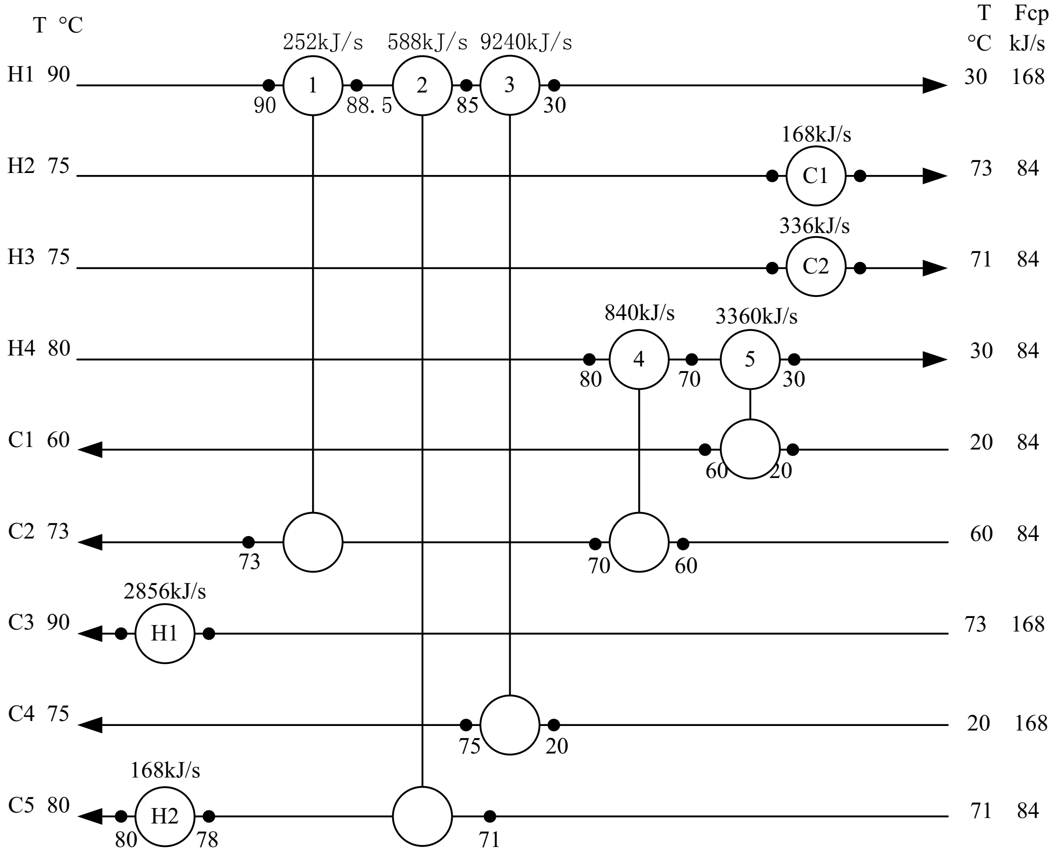

Figure 4: The HEN configuration of the second WUN

6. Acknowledgments

Financial support provided by Program for Liaoning Excellent Talents in University (LNET) (under Grant No. LJQ2012113) and Fundamental Research Funds for the Central Universities (under Grant No. DC110104) is gratefully acknowledged.

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