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A heuristic approach based on a single-temperature-peak design principle for simultaneous optimization of water and energy in fixed flowrate systems

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HIGHLIGHTS

- A single-temperature-peak design principle for simultaneous optimization of water and energy is proved.
- A new heuristic method is proposed to optimize the fixed flowrate problem.
- This approach is applicable for simultaneous optimization in multiple contaminants system.

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ABSTRACT

Methods of process integration could be classified in to two categories: the mathematical and conceptual method. The former is outstanding to solve the overall simultaneous synthesis problems, but sometimes, complex calculations will be needed. The conceptual method also could be employed to solve the problem about simultaneous optimization of water and energy but few of them could deal with the multiple contaminants problems. In this paper, a new heuristic approach is proposed to optimize simultaneously the water allocation and heat-exchange network (WAHEN) with both single and multiple contaminants in a fixed flowrate (FF) system. In order to build up this approach solidly, a principle of the single-temperature-peak design is proved through pinch analysis which discloses the interactions between water allocation network (WAN) and energy exchange network (HEN). When WAN only has a single-temperature-peak for each sub-stream, the heat recovery problem of this system could be a threshold problem requiring less energy. As a trade-off between water and energy consumption is established in this design principle, the water and energy consumption could be optimized at one step. Based on this single-temperature-peak design, a novel heuristic approach including two main designing steps, the design of WAN and HEN, is established. A graphical method is employed to design the original water allocation network to ensure it to be a single-temperature-peak type. Next, based on this WAN, WAHEN structures are further generated, which employs a method ensuring that the total energy consumption equals to the minimal value calculated by the first step. Graphical visualization is the advantage of this methodology, and it does not need complex mathematical calculations. Four literature examples are employed to check this new method. That the obtained optimization results are better than those of other works proves its effectivity and advantage. Currently, this paper mainly focuses on the water-reusing network, not the total network which will be investigated in our next work.

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1. Introduction

Nowadays, water and energy play important roles in process industries, especially for chemical industries. In general, they are consumed in a large mass. However, under the situation that the shortage of water and energy becomes more serious, process industries cannot use them in the most efficient way. Recently, process integration develops rapidly and becomes a good tool to reduce the consumption of water and energy. The methods of process integration are classified into two categories: mathematical methods and conceptual methods. During the integration process, water is not only a carrier of mass but also a carrier of

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Nomenclature

C	contaminant concentration (ppm)
C_{in}	limiting inlet concentration (ppm)
C_{out}	limiting outlet concentration (ppm)
C_p	heat capacity of streams (kJ/kg K)
T_i	temperature of process i (°C)
T_{in}	inlet water temperature of operation (°C)
T_{out}	outlet water temperature of operation (°C)
T_d	temperature of discharge stream (°C)
T_s	temperature of supply water (°C)
ΔT_{min}	minimum temperature difference (°C)
ΔT	the heat transfer temperature difference (°C)
$\Delta T_{threshold}$	the value of ΔT at which one utility target falls to zero (°C)
$T_{p,i}$	the highest process temperature (peak temperature) of one sub-stream (°C)
Q_m	minimum energy consumption (kW)
Q_h	consumption of hot utility (kW)
Q_c	consumption of cold utility (kW)
D_j	demand j
S_i	source i
$R_{i,j}$	maximum quasi-allocation amount
$C_{D_j,k}^{lim}$	limiting concentration of contaminant k in D_j (ppm)
$C_{S_i,k}$	concentration of contaminant k in S_i (ppm)
$_{Pi}$	process i
P_j	process with the lowest CPD order within the unperformed ones
$P_{p,i}$	peak process
F_{si}	flow rate of S_i (kg/s)
F_{Di}	flow rate of D_i (kg/s)
F_w	total freshwater consumption (kg/s)
H	heater
E	heat exchanger
m	total inlet flow rate of the external source (kg/s)
CP	heat capacity flow rate (kJ s/°C)
FF	fixed flowrate
FL	fixed mass load
CPD	concentration potential of demand
CPS	concentration potential of source
ND	number of demands
NC	number of contaminants
FW	freshwater
DS	discharge unit
RKC	the reuse key contaminant
TCOCC	temperature and concentration order composite curves
WAN	water allocation network
HEN	heat exchange network
WAHEN	water allocation heat exchange network
LP	linear programming
IHEN	indirect heat exchange networks
DHEN	direct heat exchange networks
MILP	mixed integer linear programming
MINLP	mixed integer non-linear programming

energy, and it is also a bridge of water allocation networks and heat exchange networks. Thus, the water allocation network and the heat exchange network are not two independent systems. It is necessary to disclose the interaction between WAN and HEN and also reduce the consumption of water and energy by the simultaneous optimization of them to obtain the global optimal results.

Conceptual methods based on pinch analysis are good to show the design process of WAHEN and also could be used to optimize the water and energy simultaneously. However, it is essential to analyze the interactions between WAN structures and heat recovery. Savulescu and Smith (1998) firstly used a graphical method to minimize the consumption of water and energy simultaneously with isothermal mixing and pointed out that the structure of WAN will affect energy consumption. This graphical method based on pinch technique was named Two Dimensional Grid Diagram and could solve the threshold problem with one freshwater source and single contaminant. In order to reduce the number of heat exchangers in the networks, Savulescu et al. (2002) introduced the non-isothermal mixing in the heat exchange network with no additional energy consumption. In 2005, Savulescu et al. (2005a, 2005b) presented a conceptual methodology which based on the work of Savulescu and Smith (1998) to obtain simultaneously the optimal targets of water and energy consumption. This method includes direct and indirect heat transfers which in order to reduce the number of heat exchangers. In the partI (Savulescu et al., 2005a), this method is suitable for systems with no water re-use; in the part II (Savulescu et al., 2005b), a two-dimensional grid diagram is introduced to expand the method to the system with water re-use and also to reduced complexity of the energy and water network. However, energy implication during the choice of water re-use is not considered fully. Leewongtanawit and Kim (2008) improved the method of Savulescu et al. (2005a, 2005b) to fix that problem. A water and energy balance diagram is proposed to analyze the simultaneous optimization of water and energy and the number of heat exchangers is reduced by this method. However, their method was a mathematical method. Manan et al. (2009) combined numerical and graphical tools to minimize the consumption of water and energy simultaneously. The optimized tool is named heat surplus diagram. It shows the insights on the energy demand and the stream matching choice when the water allocation heat exchange network (WAHEN) is designed. Almost at the same period, Polley et al. (2009, 2010) concentrated on the complexity of the heat recovery network which could be determined before designing any heat recovery network. This work tried to make the generated network simple and practical by selecting the better water conservation option with the simultaneous minimum water and energy consumption. Their method was to design a simple WAN at the first step by water pinch to get the minimum water consumption and then, decomposed the network into sub-systems to finish energy integration. In 2011, Martínez-Patiño et al. (2011) also focused on the design simplicity and operational flexibility. They proposed a design approach based on a temperature *vs.* concentration diagram. However, the proposed method which could be employed in the system with non-isothermal mixing would cause the energy penalty. In the next year, Martínez-Patiño et al. (2012) proposed an improved method to reduce the shortages of the one proposed by them in 2011. This method was based on the analysis of interaction between water and energy, which also used temperature *vs.* concentration diagram as the tool to ensure simultaneous optimization of water and energy and could get better results in the reduce of energy consumption and number of heat exchangers.

On the other hand, mathematical method is also an effective way to conduct simultaneous optimization. Bagajewicz et al. (2002) first presented a mathematical programming to design water allocation networks with an efficient consumption of energy. In this method, the state-space representation (Bagajewicz

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