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Design Energy Efficient Water Utilization Systems Allowing Operation Split*

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Abstract This article deals with the design of energy efficient water utilization systems allowing operation split. Practical features such as operating flexibility and capital cost have made the number of sub operations an important parameter of the problem. By treating the direct and indirect heat transfers separately, target freshwater and energy consumption as well as the operation split conditions are first obtained. Subsequently, a mixed integer non-linear programming (MINLP) model is established for the design of water network and the heat exchanger network (HEN). The proposed systematic approach is limited to a single contaminant. Example from literature is used to illustrate the applicability of the approach.
Keywords water utilization network, heat integration, wastewater minimization, operation split

1 INTRODUCTION

Energy and water are important resources to process industries. Since the modern society faces energy shortage and water scarcity problems, considerable attention has been paid to reduce energy and water consumption.

For water using operations such as absorption, extraction, and washing, it is required to operate at particular temperature levels. The water streams need to be heated up or cooled down to satisfy the temperature requirements of the operations. Under such circumstances, energy consumption should be considered in the design of water utilization systems.

During the past decade, considerable design techniques have been developed to minimize the energy and water consumption simultaneously. Conceptual design tools such as two dimensional grid diagram [1-3], separate system [1-3], source-demand energy composite curve [4], and graphical thermodynamic rule [5] have been introduced to design the water network and the corresponding heat exchanger network (HEN). Mathematical programming techniques have also been used for the problem. Bagajewicz et al. [6] proposed two sequential linear programming (LP) problems to determine the minimum water usage and energy consumption targets. Once these targets are identified, a mixed integer linear programming (MILP) model is generated to obtain the detailed network. Zheng [7] considered the multi-contaminant situation and obtained different water networks under different economic targets. Other researchers [8-11] treated the water network and the HEN sequentially. Since the water network obtained in the first step was not unique, the resulting HEN may not be optimal. Du *et al.* [12] introduced genetic algorithm and simulated annealing algorithm to solve the problem simultaneously. Leewongtanawit *et al.* [13, 14] developed a mixed integer non-linear programming (MINLP) model that relies on the combining of water superstructure and HEN superstructure to provide an overall network design. Recently, Liao *et al.* [15] introduced a modified transshipment model that treats direct and indirect heat transfers separately.

Kuo and Smith [16] first addressed that for particular processes such as extracting and washing, the operations are allowed to split, as seen in Fig. 1. They applied these split options to further reduce the freshwater usage. Later, Xu *et al.* [17] developed a mathematical programming model, which allows operation split for the water network with regeneration reuse. When the energy aspect is taken into account, the split of operations may further reduce the energy consumption. Consider now a two operation example of Table 1 to see how the operating cost can be decreased by operation split. Given that the water and energy cost are specified at 1.5 RMB Yuan·t^{-1} and 38 Yuan·GJ^{-1}, the approach of Liao *et al.* [15] is applied to this problem. The resulting minimum utility cost is 1114.6 RMB Yuan·h^{-1}, with the corresponding network shown in Fig. 2. If operation 1 is allowed to split at the concentration of 83.67 μg·g^{-1}, then a network with 999.6 RMB Yuan·h^{-1} utility cost can be obtained as shown in Fig. 3. On the other hand, the split of operations may cause additional equipment cost. Therefore, the tradeoffs between capital cost increasing and operating cost reducing should be evaluated.

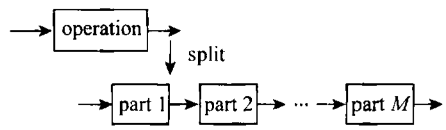

Figure 1 Split of original operation

The designer now faces the question of whether a better network may be possible using a different design strategy. What is really the correct utility target?

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Table 1 Data for Example 1

Process number	Mass load of contaminant /g·s^{-1}	$c_{\text{in}}^{\max}$ /μg·g^{-1}	$c_{\text{out}}^{\max}$ /μg·g^{-1}	Temperature /°C
1	5	25	100	45
2	2.5	50	100	70

Note: Temperature of freshwater: T_{w}=20°C; temperature of wastewater: $T_{1,\text{out}}$=30°C, $T_{2,\text{out}}$=70°C, $\Delta T_{\min}$= 10°C.

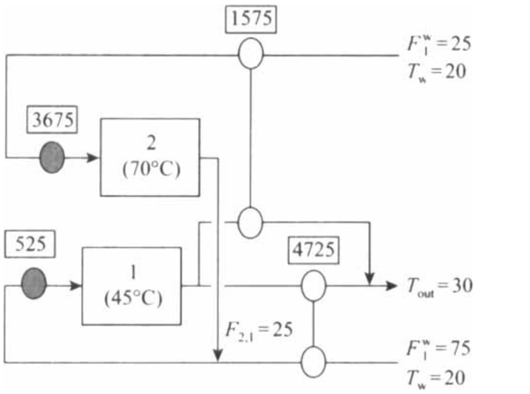

Figure 2 Solution for Example 1 not allowing operation split

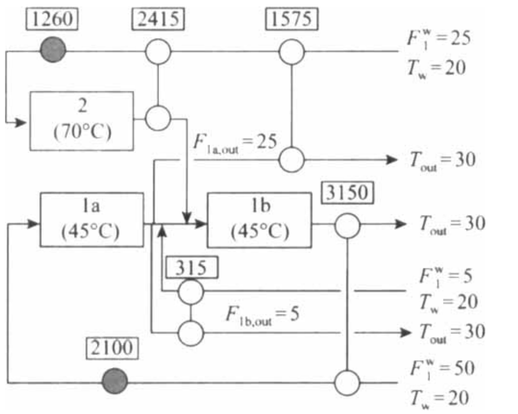

Figure 3 Solution for Example 1 allowing operation split

How many number of splits are required to achieve this? It should be noted that when operation split is allowed in the water network design, the design variables will increase rapidly. For example, if the maximum number of N is permitted to split in one operation, the total number of streams increases from N_{M}^2 to $(N_{\text{M}}N)^2$, where, N_{M} is the number of operations. In this article, an effective two step procedure is introduced to deal with such a problem. In the first step, a rigorous determination of the targets including utility consumption and the number of the operation splits is obtained. Once these targets are identified, the detailed network design is carried out in the second step by an MINLP formulation.

2 PROBLEM STATEMENT

Given are a set of water-using/water-disposing processes, which require water of a certain quality and temperature. It is desired to determine a network of water-stream interconnections among the processes and to design a network of heat exchangers between these streams. The objective is the simultaneous minimization of the freshwater usage and the energy consumption of the whole system. Several assumptions are specified: ① all operations operate isothermally; ② the contaminant load is fixed and is independent of the flow rate; ③ the operations are allowed to split by concentration; ④ the water flow rate does not change through an operation; ⑤ single contaminant is permitted.

3 MODEL DEVELOPMENT

3.1 Targeting procedure for operation split

Let us consider the general case of N_{M} operations. Without loss of generality, assume operation q is allowed to split into several sub operations, the maximum number of which is given by N_q. Indeed, these sub operations divide the whole operation into several concentration intervals. Let q^m denote the mth sub operation of operation q. Also, let L_q be the mass load of q^m, $c_{q^m,\text{in}}^{\max}$ and $c_{q^m,\text{out}}^{\max}$ be the maximum inlet and outlet concentrations of q^m respectively. Assume that the mass load distribution is proportional to the concentration distribution:

$$\frac{L_{q^m}}{L_q}=\frac{c_{q^m,\text{out}}^{\max}-c_{q^m,\text{in}}^{\max}}{c_{q,\text{out}}^{\max}-c_{q,\text{in}}^{\max}} \tag{1}$$

Given that the first sub operation q^1 has the lowest concentration and the potential sub operations are arranged in the concentration increasing order:

$$c_{q^{m-1},\text{out}}^{\max}=c_{q^m,\text{in}}^{\max} \qquad q\in P,\ m\in E_q \tag{2}$$

Consider the following general binary variables:

$$Y_{q^m}=\begin{cases}1, \text{sub operation } q^m \text{ exist}\\ 0, \text{otherwise}\end{cases} \tag{3}$$

These binary variables are related to the variables L_{q^m} through the inequalities:

$$L_{q^m}-L_qY_{q^m}\leqslant 0 \qquad q\in P,\ m\in E_q \tag{4}$$

Note that when Y_{q^m} takes a zero value, q^m does not exist, but when it is set to one, any amount of L_{q^m} that does not exceed L_q can exist.

To account for the capital cost of sub operations, all cost causing factors such as the flow rate, the concentration gradient, and the number of sub operations should be considered. However, this will likely strongly increase the computational effort required. Therefore, the capital costs of the sub operations are assumed to be fixed as e_3 in this article.

An MINLP problem based on the preceding binary variables to solve the operation split case is then proposed: