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Design of Water-Using Network with Single Internal Water Main for Process Plants

Ying Li

Institute of Environmental and Chemical Engineering, Dalian Jiaotong University, Dalian 116028, China
liying630@sina.com

A simple water-using network with single internal water main based on water pinch analysis is presented. The processes are arranged as sources of the internal water main according to the relative outlet concentration. First, the initial water-using network is set using the processes below and at the pinch as sources of internal water main. Then, the sources are added or reduced according to the relative outlet concentration until the restricted process is determined. Finally, fresh water consumption of water-using network is minimized when the amount flowing into the internal water main equals to the reused water allocated to the sinks. The Case studies show that the designs in this work are comparable to that reported in the literature. Comparing with other design methods, the presented method is simple and effective.

1. Introduction

The shortage of water resources and water pollution has attached importance to water system integration (Samanaseh et al., 2017; Madzivhandila and Chirwa, 2017). In the conventional water-using network, the design and control of the piping network is very complex for a large water network system. The network has limited flexibility to adapt to changes in process limiting data. To address this, Feng and Seider (2001) introduced a new structure with internal water mains to simplify the piping network. Wang et al. (2003) proposed a new concept (the “water-saving factor”) for multiple-contaminant water networks with a single internal water main. The procedure was complex and the results were not optimal. Zheng et al (2006) proposed a universal methodology to simplify the network structure with internal water mains using a new superstructure and a mixed-integer nonlinear programming strategy. This methodology necessitated an optimization algorithm. Based on an understanding of the physical insights of water networks with internal water mains, Ma et al. (2007) presented a rule-based design methodology. The final network was designed by adjusting and simplifying the original water network using a basic mathematical programming model and heuristic rules. The concentration potential concept and a trial- and -error approach were proposed by He et al. (2010) to design water networks with internal water mains. Su et al. (2012) designed the initial structure of a water-using network based on the conventional network, and the internal water main was formed by the sources with low concentration potential values. The final design was obtained by adjusting the amount of the internal water main in a few iterations. For large scale water-using network design, the arbitrary estimation of the water amount for the internal water main will result in excessive iterations. Zhao et al. (2014) presented the same method to design the water-using network with two internal water mains.

Appropriate settings for the position of the internal water mains can reduce the complexity of water-using networks, as well as facilitate their control and operation. Generally, the design of a water-using network with one internal water main can achieve clear water-saving effects. In this paper, water-using network design with a single internal water main is studies using water pinch analysis. The determination of the source streams of the internal water main is the key to the design. For a water-using network with single contaminant, the source streams of the internal water main can be arranged in an ascending order according to the processes’ outlet concentrations. However, it is often difficult to select sources streams for the internal water main for a water-using network with multiple contaminants. In this paper, a relative outlet concentration based pinch is presented to evaluate the potential of processes as source streams of the internal water main. The initial water-using network was obtained based on the pinch concentration.

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2. Design principle

In this paper, sources are defined as processes that supply water to the internal water main, and sinks are defined as processes that gain water from the internal water main. Thus, sources only use fresh water. Feng and Seider (2001) pointed out that the water flowing into and out of the internal water main must be sufficiently large. The concentration of the internal water main was usually close to the pinch concentration for single contaminant system. In their study, Feng and Seider (2001) set the processes below the pinch as sources for the internal water main. However, the flow rate and concentration of the internal water main were not optimized, and the work was not extended to multiple contaminants system.

According to pinch rules, some processes with outlet concentrations below the pinch concentration must use fresh water and are the best candidates for stream sources for the internal water main. For a single contaminant water-using network, the source streams of the internal water main can be arranged according to the ascending order of their outlet concentrations. The pinch concentration of each contaminant reflects the extent of the driving force restriction. The higher the outlet concentration compared to the pinch concentration, the lower the possibility that the process is set as a stream source. For a multiple contaminants system, the order of the outlet concentration for each contaminant is different. It is difficult to set an order for water-using processes as sources in systems such as single contaminant systems. However, the relative values of outlet concentration to pinch concentration represent the same possibility as the sources, and the sum of all contaminants (Eq. (3)) decides the order of water using processes. We calculated the relative outlet concentration values for all the processes when only freshwater is used. For a water-using network with single internal water main, the outlet streams of the processes which use freshwater will simply constitute the internal water main. For a single contaminant system, the outlet concentration of process *i* equals its maximum outlet concentration. For a multiple contaminant system, the outlet concentration of contaminant *j* in process *i* (Eq.(2)) equals, or is less than, its maximum outlet concentration, which depends on the maximum fresh water consumption of process *i* when it only uses fresh water. Relative outlet concentration is also applied for a single contaminant system to maintain consistency with the multiple contaminant system.

$$f_i^{\max} = \max \frac{\Delta m_{i,j}}{C_{i,j,out}^{\max}} \tag{1}$$

$$C_{i,j,out} = \frac{\Delta m_{i,j}}{f_i^{\max}} \tag{2}$$

$$\mathrm{ROC_i} = \sum_j \frac{C_{i,j,out}}{C_j^{pinch}} \tag{3}$$

where $f_i^{\max}$ is the fresh water consumption by process *i* when only fresh water is used, and $\Delta m_{i,j}$ is the mass load of contaminant *j* in process *i*. $C_{i,j,out}^{\max}$ is the limiting outlet concentration of contaminant *j* in process *i*, and $C_{i,j,out}$ is the outlet concentration of contaminant *j* in process *i*. C_j^{pinch} is the pinch concentration of contaminant *j*. ROC_i is the relative outlet concentration of process *i* considering the total effect of all contaminants. For a single contaminant system, the order of process as sources expressed by ROC_i is the same as that expressed by the limiting outlet concentration. For multiple contaminant systems, this provides the means for measuring the capability of process *i* as sources of the internal water main. The design of water-using network with single internal main are performed according to the pinch rules and the sequence of ROC_i from low to high.

3. Case studies

Example 1 is taken from Feng and Seider (2001), with the limiting data shown in Table 1. This is a single contaminant system with 10 processes.

Water pinch occurs at a contaminant concentration of 100mg·L^{-1}. The relative outlet concentration values of processes as sources are shown in Table 2.

Process 1 and 2 below the pinch, as well as 4 and 8 at the pinch, were selected as sources for the internal water main. The gaining amount for the internal water main was 97t·h^{-1}. The initial water-using network is shown in Figure 1, and is the same as the optimal result of Zheng et al. (2006) obtained using mathematical programming approach. The internal water main was assumed to be a new water source to supply water to the remaining sinks. The amount of water from the internal water main was insufficient (the amount of water required by the sinks from the internal water main was 107.72t·h^{-1}).

Table 1: Limiting process data of example 1

process	$C^{max}_{i,j,in}$ (mg·L^{-1})	$C^{max}_{i,j,out}$ (mg·L^{-1})	$\Delta m_{i,j}$ (g·h^{-1})
1	25	80	2000
2	25	90	2880
3	25	200	4000
4	50	100	3000
5	50	800	30000
6	400	800	5000
7	200	600	2000
8	0	100	1000
9	50	300	20000
10	150	300	6500

Table 2: Relative outlet concentration values of sources for example 1

Sources	1	2	8	4	3	9	10	7	5	6
ROC	0.8	0.9	1	1	2	3	3	6	8	8

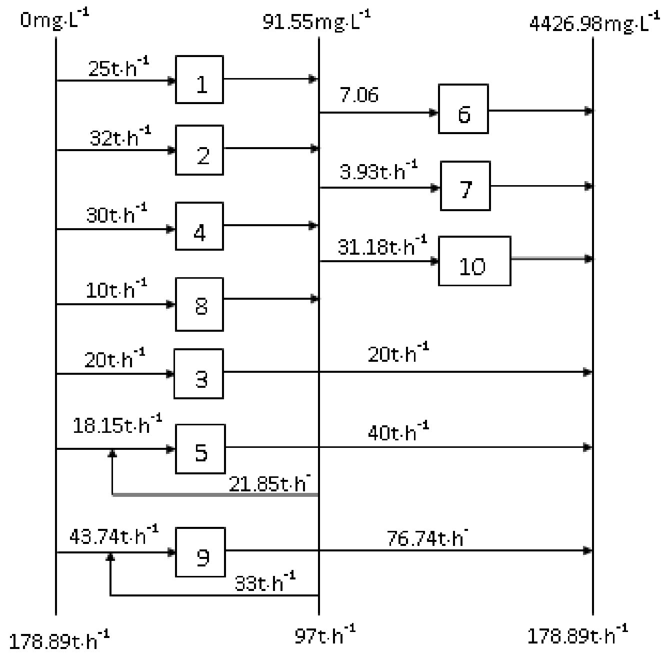

Figure 1: Initial water using network design with single water main for example 1

Process 3, with the lowest relative outlet concentration (except for process 1, 2, 8 and 4), was added to the internal water main. This supplied, 117t·h^{-1}, while the amount of water required from the internal water main was 100.06t·h^{-1}. The final sources of the internal water main were confirmed as process 1, 2, 8, 4, and 3. Process 3 is the restricted process of example 1. Thus, the sources for the internal water main are known, and the fresh water consumption is fixed for these sources. The amount for the internal water main is in surplus. This amount is reduced by decreasing the amount of water from process 3 flowing into it; the concentration for the internal water main is also decreased and the amount of water required from the internal water main is increased. When only 7.10t·h^{-1} from process 3 is supplied to the internal water main, the amount for the internal water main is used up. The optimal main concentration was attained and the fresh water consumption was minimized. The optimal water-using network with the internal water main is shown in Figure 2. A fresh water consumption of 176.35t·h^{-1} was achieved by one adjustment step. The same result was obtained by Ma et al. (2007). However, their result was obtained using conventional water-using network and heuristic rules to guide their design of a water-using network with single internal water main. The conventional water-using network is not unique for the specified limiting process data. There are uncertainties present and the design process is complex.

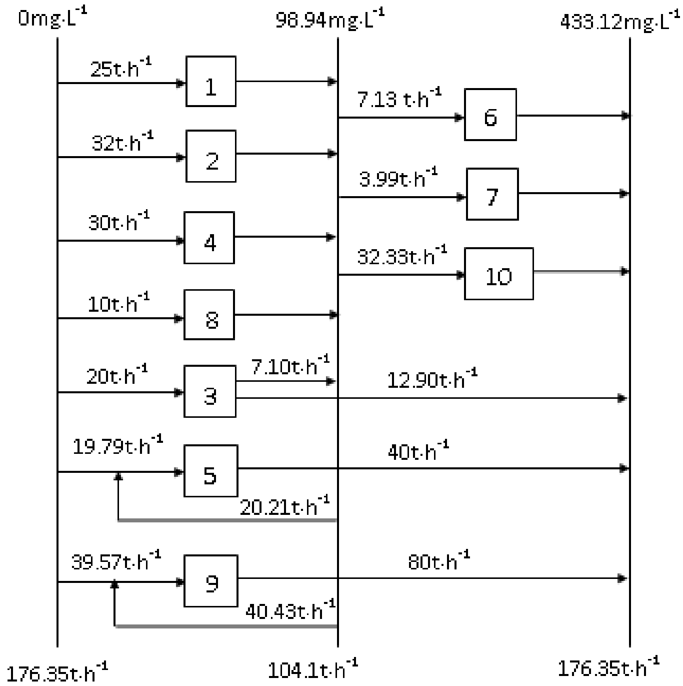

Figure 2: Optimal water using network design with single water main for example 1

Example 2 is taken from Wang et al. (2003), with the limiting data shown in Table 3. This example is a multiple contaminants system with 7 processes and 3 contaminants.

Table 3: Limiting process data of example 2

process	$C^{max}_{i,j,in}$ (mg L^{-1})	$C^{max}_{i,j,out}$ (mg L^{-1})	$\Delta m_{i,j}$ (g h^{-1})
1	0	50	1250
	0	100	2500
	0	50	1250
2	0	100	7000
	0	300	21,000
	0	600	42,000
3	20	150	4550
	50	400	12,250
	50	800	26,250
4	50	600	22,000
	110	450	13,600
	200	700	20,000
5	20	500	3840
	100	650	4400
	200	400	1600
6	500	1100	30,000
	300	3500	160,000
	600	2500	95,000
7	150	900	22,500
	700	4500	114,000
	800	3000	66,000

We found that water pinch occured at contaminant concentrations of 100,300 and 600 mg·L^{-1}. When the processes used fresh water only, the relative outlet concentrations of processes as sources are as shown in Table 4.

Table 4: Relative outlet concentration values of sources for example 2

Sources	1	2	3	4	5	6	7
ROC	0.92	3	3.96	8.15	7.26	21.69	28.22

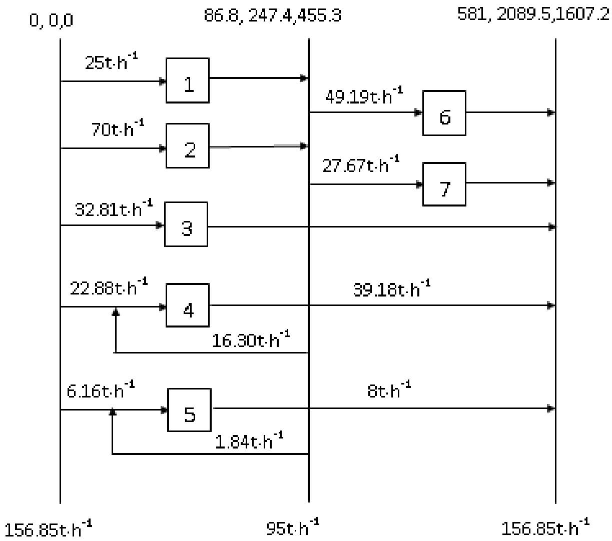

Figure 3: Initial water using network design with single water main for example 3

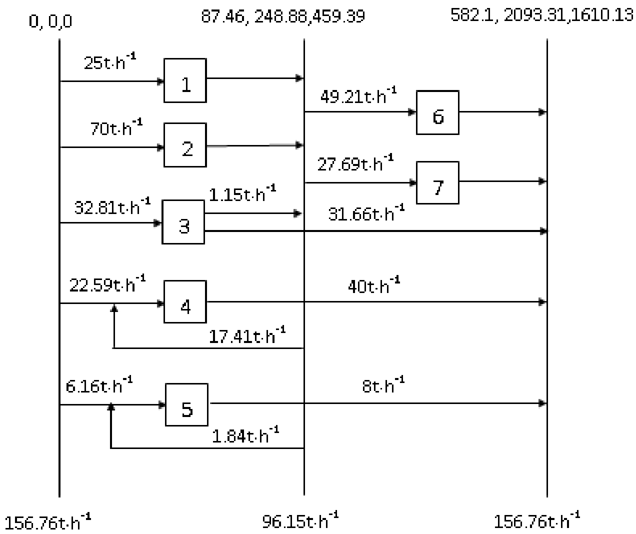

Figure 4: Optimal water using network design with single water main for example 3

Process 1 below the pinch and process 2 at the pinch were selected as sources for the internal water main. The gaining amount for the internal water main was 95t·h^{-1}. The initial water-using network shown in Figure 3 is the same as the optimal result of Zheng et al. (2006) obtained using a mathematical programming method. We assumed that the internal water main was a new water source to supply water to the remaining sinks. We found that the amount for the internal water main was insufficient (the required water amount from the internal water main was 96.27t·h^{-1}). Process 3, with the lowest relative outlet concentration except for process 1 and 2, was added to the internal water main, so that the amount supplied to the internal water main was 127.81t·h^{-1}, and the required water amount from the internal water main was 94.12t·h^{-1}. The final chosen sources for the internal water main were process 1, 2 and 3. Process 3 is the restricted process for example 3. Thus, the sources of the internal water main are known and the fresh water consumption is fixed for these sources. We know that the amount of the internal water main is in surplus. To reduce the amount in the internal water main by decreasing water flowing in the internal water main from process 3, the contaminant concentration in the internal water main was also decreased and the required water amount for the sinks was increased. When only1.15 $t \cdot h^{-1}$ from process 3 was supplied into the internal water main, the surplus from the internal water main was eliminated. The optimal main concentration was attained and the fresh water consumption was minimized. The optimal water-using network with single internal water main is shown in Figure 4. The fresh water consumption is 156.76$t \cdot h^{-1}$. Unlike the method of Su et al. (2012) for the same design, the method we present does not require iterations.

4. Conclusions

In this paper, a simple design method was presented for water-using networks with single internal water main. The method is based on water pinch analysis. An initial water-using network was obtained using pinch rules and a new concept of relative outlet concentration to pinch concentration was proposed to determine the order of the processes as sources of the internal water main. A comparison with published examples showed that our approach yielded results for the initial water-using network that were close to the optimal design. The optimal design of the final water-using network can be obtained through a simple calculation. The presented method can be applied to single and multiple contaminants system.

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