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Graphical Method for Optimizing a Single Contaminant Regeneration Heat-Integrated Water Network

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The shortage of energy and water is a critical issue in various industrial sectors especially in chemical engineering industry. Using the system integrated method can greatly reduce the fresh water and public utility consumption. The integration of water network and heat exchange network can merely optimize the usage of water and energy respectively, but the optimization of heat-integrated water networks can reduce not only the water consumption but also the energy and heat exchangers. This paper introduced the regeneration of wastewater into a single contaminant heat-integrated water networks, and improved the temperature-concentration graphical method. The optimization here presented the design method for heat-integrated water networks considering the regeneration recycling of wastewater and the regeneration reuse of wastewater. Compared to the earlier method, this method reduces the consumption of fresh water from 90 kg/s to 20 kg/s, and it also reduce the minimum heating utility consumption from 4,165 kW to 1,929 kW. The improved temperature-concentration graphical method of wastewater regeneration recycling system is better than that of wastewater regeneration reuse system. Considering the regeneration of the wastewater to optimize the heat-integrated water network, the consumption of fresh water and minimum heating utility decreases greatly and the result of water-saving and energy-saving is obvious.

1. Introduction

Water resources and energy are valuable resources for human life and industrial production. But nowadays, society is facing serious water and energy shortage, especially for the chemical process. At first, Linnhoff et al. (1982) applied the Pinch Technology to the field of Energy Integration in the process industry and has promoted the development of energy-saving. Wang and Smith (1994) put forward the concept of Water Pinch. Then Ravagnani et al. (2003) studied and improved the Pinch Method considering the pressure drop and heat transfer coefficient. From then on, like the Water Cascade Curve (Manan, 2004), the graphical method of water network has been developing rapidly.

In industry, the water network and heat exchange network always coexist. The optimization for water network and heat exchange network should be carried out simultaneously. Savulescu et al. (2005) studied the optimization of heat–integrated water network without reusing waste water, and using the maximum amount of reused water respectively. Later, various methods such as water and energy balance graphical method (Leewongtanawit, 2009), non-isothermal mixing rules (Feng et al., 2009) and temperature-concentration diagram method (Martínez-Patiño, 2011) have been proposed. Yang et al. (2014) presents a modified Lagrangean-based decomposition algorithm in order to solve the resulting nonconvex mixed-integer nonlinear programming (MINLP) problem efficiently. Liu et al. (2015) carried out a new methodology for simultaneous integration of water and energy in heat-integrated water allocation networks. Hong et al. (2016) did the simultaneous optimization considering the wastewater treatment.

Based on the previous research results, these design methods can be divided into two steps, the first step is to determine the water network with minimum amount of fresh water, the second step is to pick up the hot and cold stream data based on the water network in order to design the heat exchange network. However, when designing the water networks, these studies all reuse the waste water directly to optimize the networks, without considering the regeneration of waste water.

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Unlike the previous study, the regeneration recycling and regeneration reuse of waste water are introduced into the heat-integrated water network with single-contaminant in this paper, as well as the improved temperature-concentration graphical method, which can reduce the consumption of fresh water and public utility.

2. The design method of Heat-integrated Water Network

2.1 The improved temperature-concentration graphical method of the waste water regeneration recycling system

Compared with the single water network, there is more than one temperature variable in the heat-integrated water network. The temperature includes not only the operating temperature of every target unit, but also the fresh water's temperature and the discharge temperature of waste water. This kind of optimization can achieve the minimization of fresh water consumption, public utility consumption and the heat exchanger number. Martínez-Patiño et al. (2011) used the temperature-concentration graphical method to optimize the heat-integrated water network with single-contaminant, which reuse the waste water directly. That method is simple and easy to implement, but the final network has too large public utility and it has not considered the regeneration and recycle of the waste water. The improved temperature-concentration graphical method takes the regeneration recycling of waste water into account and adds the regeneration unit. The regeneration unit can recycle and make use of the waste water, which can save much water resources, as well as the consumption of public utility. The specific design steps for the regeneration unit are as follows:

(1) The inlet concentration of the regeneration unit should be the best regeneration concentration, which can be calculated from the question table of regeneration recycling water system;

(2) The water entering the regeneration unit is directly mixed, and is supplied by several water units with higher temperature. The unit with higher temperature and that can satisfy the requirement should be matched firstly.

(3) When matching the outlet water of regeneration unit, the water unit with higher temperature is in priority when it satisfies the inlet concentration and flow requirement.

After having the regeneration unit, then the whole water network can be designed. The specific steps are as follows:

(1) The unit whose limiting inlet concentration is 0 can merely use the fresh water;

(2) The water entering the water unit should meet its concentration and flow rate requirements, and in the subsequent water unit, try not to use fresh water;

(3) Matching the middle water unit to the unit with different temperature from the higher side, until it's finished.

Figure 1 shows the specific steps to design the whole water network using the improved method:

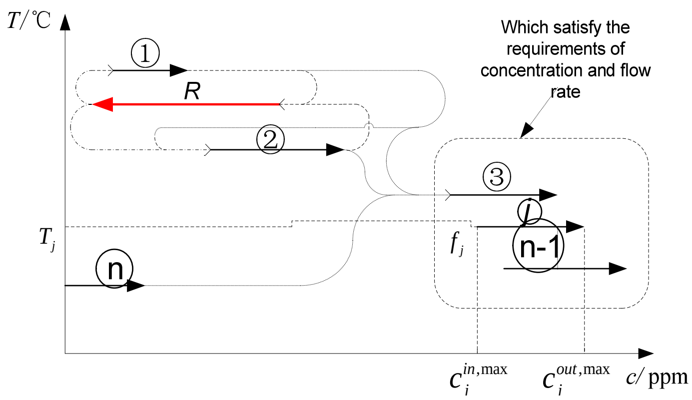

Figure 1: Design the whole water network using improved temperature-concentration graphical method of waste water regeneration recycling system

The water network obtained from the improved method does not necessarily meet the temperature demand of each water unit. Therefore, the water network also need heat exchange. When designing the heat-integrated water network, the heat transfer network is divided into two parts, one is the heat exchange inside the water network and the other is that outside. The specific design steps are as follows:

(1) Distinguish the hot and cold stream of the whole water network, and the minimum consumption of heating

utility and cooling utility of the system can be calculated using the Pinch Method.

(2) Under the premise of having no effect on the consumption of the system's public utilities, mix and exchange the heat directly as far as possible to reduce the use of heat exchangers.

(3) Use heat exchangers, heaters and condensers so that all the temperature can satisfy the requirement.

2.2 The improved temperature - concentration graphical method of the waste water regeneration reuse system

The method considering the regeneration reuse of the waste water does not allow the water unit to discharge the waste water to the regeneration unit while receiving the supply from the regeneration unit. Therefore, some of the water units need to be decomposed. The specific steps of designing the regeneration unit:

(1) The inlet concentration of the regeneration unit should be the optimal regeneration concentration, which can be calculated from the question table of the regeneration reuse water system;

(2) The water entering the regeneration unit is directly mixed, and is supplied by several water units of higher temperature. If some of the water units with the highest temperature cannot meet the requirements of concentration and flow, then the decomposition is needed.

(3) The outlet of the regeneration unit was supplied to the water unit which is in need.

Figure 2 shows the specific steps.

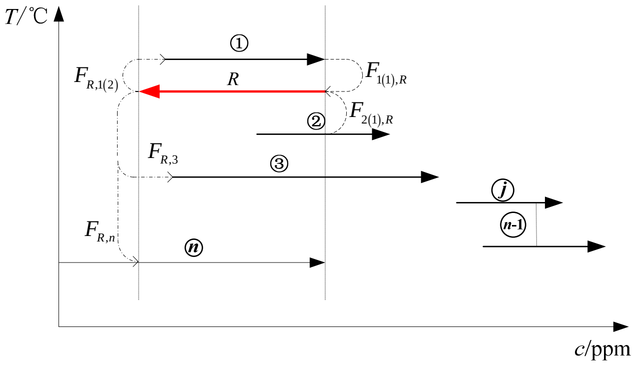

Figure 2: Design the regeneration unit using the improved temperature-concentration graphical method of waste water regeneration reuse system.

Then the whole water network and later the heat-integrated water network can be designed. All the method and steps are similar to that of the improved waste water regeneration recycling temperature-concentration graphical method.

3. Case studies

This case is selected from Wang and Smith (1994). The limiting data of the process is shown in Table 1.

Table 1: The limiting data of the process

Water unit	Impurity load, g/s	Limiting inlet concentration, ppm	Limiting discharge concentration, ppm	Operating temperature, °C
1	5	50	100	100
2	30	50	800	75
3	4	400	800	50
4	2	0	100	40

3.1 Using the improved waste water regeneration recycling temperature-concentration graphical method to design the heat-integrated water network

Using the water Pinch Method of regeneration recycling water system with single contaminant, the concentration after regeneration is 20 ppm and then the question table of regeneration recycling water system can be obtained, as shown in Table 2.

After that, design the regeneration unit. The inlet concentration of the regeneration unit was 305.71 ppm and the flow rate was 87.5 kg/s. According to the matching rules, the water network structure of the regeneration unit can be obtained as shown in Figure 3.

Table 2: The question table of regeneration recycling water system

Concentration ppm	Water using unit 1	2	3	4	Impurity load, g/s	Cumulative load, g/s	Fresh water flow rate, kg/s	Regenerated water flow rate, kg/s	Regeneration concentration, ppm
0						0	0	—	—
					0.4				
20						0.4	20	—	—
					0.6				
50						1	20	0	—
					8				
100						9	90	87.5	100
					12				
400						21	52.5	—	168.57
					20				
800						41	51.25	—	305.71

Then the structure of the water network can be designed and the possible connections that meet the requirements are shown in Figure 4.

Each water unit and the regeneration unit are sequentially marked in the improved waste water regeneration recycling temperature-concentration diagram. Match the water unit according to the specific rules of improved graphical method. After obtaining the water network structure, the data of hot and cold stream in the water network can be picked up. According to the information of flow, take the minimum heat transfer temperature difference as 10 °C and then the Total Composite Curve of heat and cold stream can be drawn. It can be seen from the total composite curve, the average temperature of Pinch Point is 95 °C (heat stream temperature of 100 °C, cold stream temperature of 90 °C), the minimum heating public utility is 1,929 kW, the minimum cooling public utility is 1,088 kW.

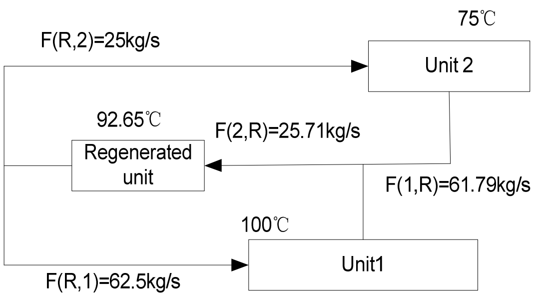

Figure 3: The regeneration unit structure designed by the regeneration recycling temperature - concentration graphical method

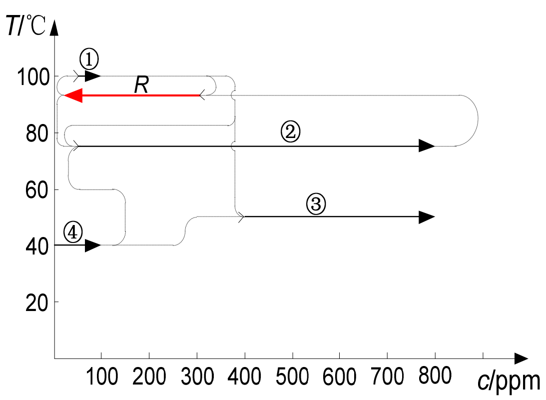

Figure 4: Possible connections that meet the requirements

After having all the data, design the heat exchange network according to the matching rules. Keep in mind that the direct heat transfer process is in priority.
The final heat-integrated water network is shown in Figure 5. There is a heater, a cooler and two heat exchanger of the process stream. The minimum fresh water consumption and the minimum regenerated water flow rate is 20 kg/s and 87.5 kg/s and the minimum heating public utility and the minimum cooling public utility is 1,929 kW and 1,088 kW.

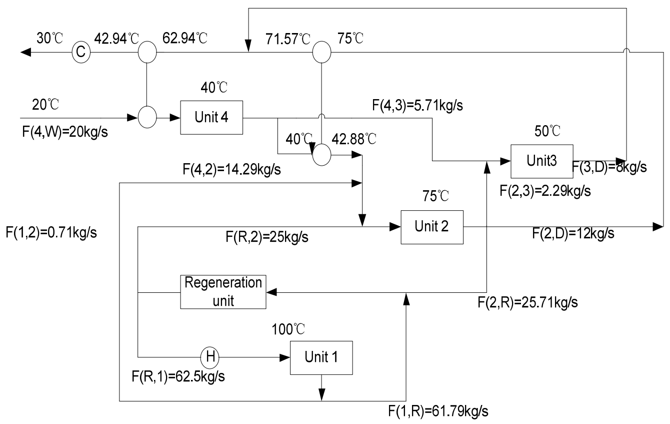

Figure 5: The structure of Heat Integrated Water Network designed using the regeneration recycling temperature-concentration graphical method

3.2 Using the improved waste water regeneration reuse temperature-concentration graphical method to design the Heat Integrated Water Network

When using the Water Pinch Method of regeneration reuse water system with single contaminant, set the concentration after regeneration as 20 ppm, then the main parameters of the system can be determined as follows: the minimum fresh water flow rate is 50 kg/s, the minimum regenerated water flow rate is 50 kg/s, and the optimum regeneration concentration was 100 ppm.
The structure of the regeneration unit water network can be obtained according to the above data. Finally, the whole water network and heat exchange network are designed in turn, and the final heat-integrated water network can be obtained, as shown in Figure 6.

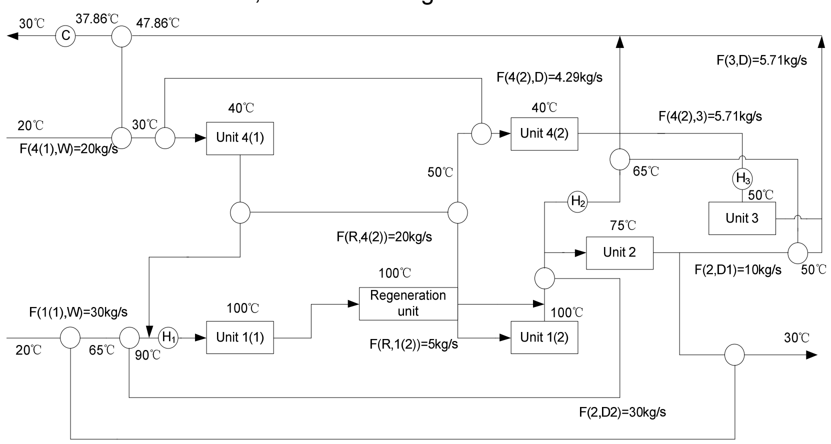

Figure 6: The structure of the Heat Integrated Water Network designed using the regeneration reuse temperature-concentration graphical method

The heat-integrated water network designed in this paper is compared with that in literature, the result is shown in Table 3, in which the Heat Integrated Water Network in the literature (Leewongtanawit, 2009) and literature (Martínez-Patiño, 2011) was designed using the water and energy balance graphical method and the temperature-concentration graphical method. It can be seen from Table 4 that the heat-integrated water network designed using the improved waste water regeneration recycling temperature-concentration graphical method and that method of the waste water regeneration reuse system can reduce the fresh water consumption and heating utility of the system greatly. At the same time, the results obtained by the improved waste water regeneration recycling temperature - concentration graphical method are better than those obtained by the improved waste water regeneration reuse temperature - concentration graphical method.

Table 3: Comparison of results

Method	The minimum freshwater consumption, kg/s	The minimum heat utility, kW	The minimum cool utility, kW	The number of the heat exchanger
Leewongtanawit (2009)	90	3,780	0	4
Martínez-Patiño (2011)	90	4,165	385	5
Regeneration recycling temperature-concentration graphical method	20	1,929	1,088	4
Regeneration reuse temperature-concentration graphical method	50	2,760	660	10

4. Conclusion

For the water network with Heat Integration, the waste water regeneration is considered in this paper. The improved temperature-concentration graphical method of waste water regeneration recycling system and the method of regeneration reuse system were used to design the Heat Integrated Water Network. The specific design order is: design the water network of regeneration unit first, and then design the total water network and at the final, design the heat exchange network. The design method is simple and easy to operate. For the Heat Integrated Water Network designed considering the regeneration, the fresh water and heating utility consumption is reduced substantially, and the results of water-saving and energy-saving is obvious.

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