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Graphical Approach of Two-Stage Regeneration Recycling Water Networks with Parallel Structure

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Two-stage regeneration recycling water networks can effectively reduce regeneration cost without increasing freshwater consumption. The graphical approach can intuitively show the relationship between system parameters. However, existing researches only focus on the two-stage regeneration water network with series structure. In this paper, the two-stage regeneration recycling water network with parallel structure has been studied, and the graphical approach has been established to determine the targets, including the optimal flowrates and the optimal regeneration concentrations. The optimal flowrates containing freshwater and regenerated water of all stages, determined in order from good to bad according to water quality. A case study shows that regardless of the relative level of the regeneration concentrations in the first and second stages, the optimal flowrate targets are the same, but the optimal regeneration concentrations are different. Water networks with higher second stage regeneration concentration have lower regeneration cost.

1. Introduction

Water system integration plays an important role in industrial water-saving and emission reduction, in which the water network with regeneration recycling can do those to the maximum extent.

There are two research approaches for water system integration: graphical approach and mathematical programming. For a single-contaminant system, the graphical approach can reveal the relationship between parameters in the system, and provide ideas for the application of water system integration and further research on mathematical programming.

In recent years, scholars have never stopped studying the water system integrated considering regeneration cycle. Li et al. (2017) and Fan et al. (2018) reviewed the design and optimization methods of water networks with regeneration recycling. Fan et al. (2016) proposed new calculation formulas for the regeneration recycling water network based on the graphical method. Li and Guan (2016) presented a stepwise design method for regeneration of recycling water networks. Deng et al. (2018) carried out an industrial water network model suitable for multi-water resources. Nikolakopoulos and Kokossis (2018) used a new coordinated transhipment model to optimize water networks with regeneration recycling. Zhang et al. (2018) applied a multi-scale optimization model to the water network optimization of iron and steel plants with outstanding results. But these studies are all based on water networks with one stage regeneration recycling.

The two-stage regeneration recycling water network can effectively reduce the regeneration cost of the water network without increasing the freshwater consumption, so has high industrial application value. Ding and Feng (2018) gave a method for constructing the optimal composite water supply line according to the graphical method in the study of the two-stage regeneration recycling water network with a series structure, determined the calculation formulas of the optimization targets, and proposed construction method of the problem table. However, during the research, the regeneration system of the water network was defaulted to be composed of multiple regeneration units connected in series and did not involve a parallel structure.

In industrial practice, there are often several parallel regeneration units. In such parallel structures, all regeneration units are independent and treat wastewater separately to produce regenerated water. Such parallel structure provides a higher degree of freedom and possibility for the design of the water network, but the network is more complicated than that with series structure. The design method of the water network with series structure

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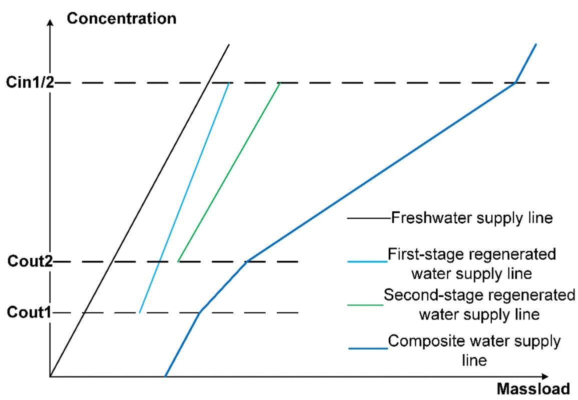
cannot be directly applied to that with parallel structure. Therefore, it is imperative to study the water network with parallel regeneration structure.

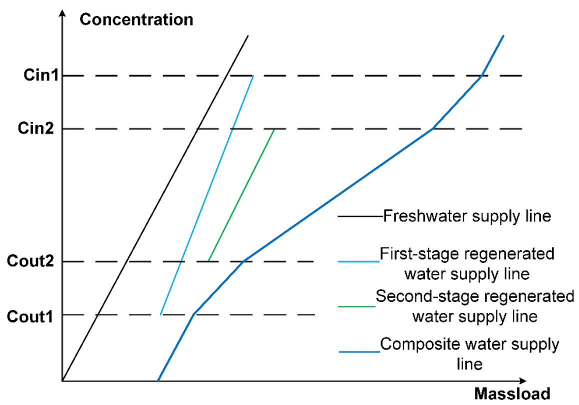
The two-stage regeneration recycling water network with parallel structure means that in the network the regeneration system is composed of two parallel regeneration units, and there is no direct correlation between them. In this paper, the graphical approach is used to study the single-contaminant two-stage regeneration recycling water network with a parallel structure to determine flowrate and regeneration concentration targets. The water loss of the water network is ignored.

2. Three kinds of relative relations of regeneration concentrations

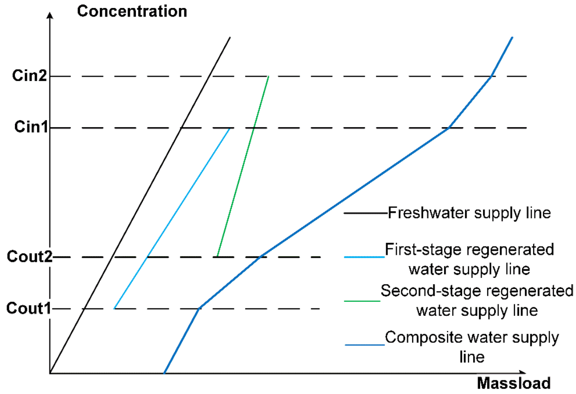
The two-stage regeneration recycling water network with parallel structure contains two kinds of regenerated water, one with a lower post-regeneration concentration and the other with a higher post-regeneration concentration. In order to facilitate the research, the regenerated water with a lower concentration is referred to as the first stage regenerated water and that with a higher concentration as the second stage regenerated water. There are three possible cases of the relative relationship between the regeneration concentrations of the two regenerated water: the regeneration concentrations are the same, the regeneration concentration of the first stage regenerated water is higher, and the regeneration concentration of the second stage regenerated water is higher. The three cases on the concentration-mass load (C-M) diagram is shown in Figure 1.



a. Regeneration concentrations are the same



b. First stage regeneration concentration is higher



c. Second stage regeneration concentration is higher

Figure 1: Three cases of parallel structure

3. Construction method of optimal composite water supply line

For the case with the same regeneration concentrations, the C-M diagram is divided into four concentration intervals by the first stage post-regeneration concentration, the second stage post-regeneration concentration, and the regeneration concentration. The intervals are numbered from low to high by the concentration. The freshwater supply line spans four concentration intervals (The part in the uppermost concentration interval referred to as the discharge line), the first stage regenerated water supply line spans the second and third concentration intervals, and the second stage regenerated water supply line spans the third concentration interval. Therefore, a composite water supply line in this case appears as a polyline with three inflection points, as shown in Figure 1a. Comparing the polyline in Figure 1a with the composite water supply line with a series regeneration structure (Ding and Feng, 2018), it is found that the composite water supply lines are completely the same. Therefore, the optimal composite water supply line construction method under the series structure is suitable for water network with the parallel structure with the same regeneration concentrations.

For the case in Figure 1b, the C-M diagram is divided into five concentration intervals by the first stage post-regeneration concentration, the second stage post-regeneration concentration, the first stage regeneration concentration and the second stage regeneration concentration. The freshwater supply line spans five concentration intervals, the first stage regenerated water supply line spans the second, third, and fourth concentration intervals, and the second stage regenerated water supply line spans only the third concentration interval. The composite water supply line in this case is a polyline with four inflection points. In the polyline, the first and fifth segments have the same slope, and the second and fourth segments have the same slope. The first and fifth segments have the largest slopes and the third segment have the smallest slopes. The composite water supply line is as shown in Figure 1b.

For the case in Figure 1c, the C-M diagram can also be divided into five concentration intervals. The freshwater supply line spans all five concentration intervals, the first stage regenerated water supply line spans the second and third concentration intervals, and the second stage regenerated water supply line spans the third and fourth concentration intervals. The composite water supply line in this case is a polyline with four inflection points. In the polyline, the first and fifth segments have the same and the largest slope, the third segment has the smallest slope. Besides, the slopes of the second and fourth segments are affected by the two kinds of regenerated water flowrates. The composite water supply line is shown in Figure 1c.

3.1 Optimization objectives

For the network, the parameters that will be optimized consist of freshwater flowrate, two regenerated water flowrates, two post-regeneration concentrations, and two regeneration concentrations. Among them, the two post-regeneration concentrations are mainly affected by economic factors and cannot be optimized using the graphic method, and their optimization is not considered in this paper. Therefore, the optimization objectives are the freshwater flowrate, two regenerated water flowrates, and two regeneration concentrations.

3.2 Construction of optimal composite water supply lines

The optimal composite water supply lines for the three cases are shown in Figure 2.

For the case with the same regeneration concentrations, the optimal composite water supply line construction method can refer to that of the network with serial regeneration structure (Ding and Feng, 2018), and they are completely the same.

For the case in Figure 1b, the construction method is as follows.

Step 1. In the first concentration interval, set the point where the mass load is 0 and the concentration is the same as that of freshwater as the starting point, and determine the straight line with the largest slope under the water composite curve.

Step 2. In the second concentration interval, set the point where the concentration on the straight line in step 1 is the first stage post-regeneration concentration as the starting point, and determine a straight line with the largest slope under the water composite curve.

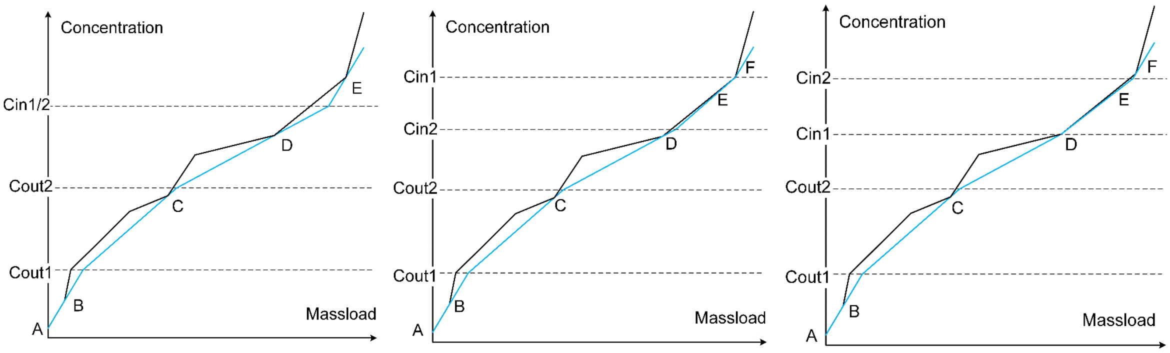
Step. 3. In the third concentration interval, set the point where the concentration on the straight line in step 2 is the second stage post-regeneration concentration as the starting point, and determine a straight line with the largest slope under the water composite curve.

Step 4. Using the bottom intersection of the straight line and the water composite curve in step 3 as the lower boundary, make sure that the straight line has an intersection with the upper water composite curve and is completely below the water composite curve, which has the same slope as the straight line in step 2. During the process, the concentration corresponding to the intersection point is as low as possible;

Step 5. Using the bottom intersection of the straight line and the water composite curve in step 4 as the lower boundary, determine the straight line that has an intersection with the upper water composite curve and is completely below the water composite curve having the same slope as the straight line in step 1. The abscissa of the line's right endpoint is the same as that at the right endpoint of the water composite curve. During the process, the concentration corresponding to the intersection point is as low as possible.

The optimal composite water supply line can be determined by steps 1-5 above. The concentration corresponding to the intersection point made in step 4 is the optimal second stage regeneration concentration,

and the concentration corresponding to the intersection point made in step 5 is the optimal first stage regeneration concentration.
For the case in Figure 1c, steps 1-3 of the construction method is the same as those for the case in Figure 1b, but the subsequent steps are different as follows.



a. Regeneration concentrations are the same *b. First regeneration concentration is higher* *c. Second regeneration concentration is higher*

Figure 2: Optimal composite water supply line

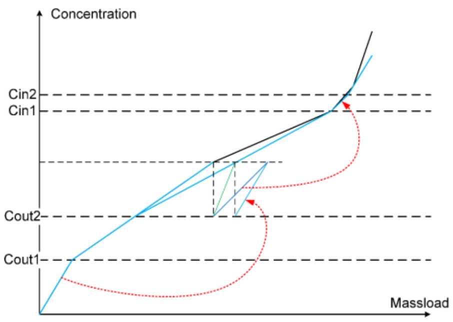


Figure 3: Determining slope of composite water supply line in fourth concentration interval for case in Figure 1c

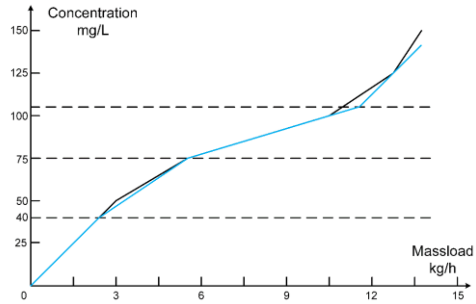
Step 4. Determine the second stage regenerated water supply line. In the third concentration interval, extend the composite water supply line made in the second concentration interval to the third concentration interval, and make a horizontal line at an appropriate concentration, so that the straight line intersects with the extension line and the straight line made in step 3. Take the intersection on the left as a starting point, make a straight vertical downward line which has an intersection with the second stage regeneration concentration line, and connect the new intersection with the right intersection. The connected line is the second stage regenerated water supply line.
Step 5. Combine the two straight lines determined in step 4 and step 1 to determine the slope of the composite water supply line in the fourth concentration interval. Take the right intersection point in step 4 as the starting point and make a straight vertical downward line. This line has an intersection point with the second stage regeneration concentration line. Using this intersection point as the starting point, make a straight line with the same slope as the straight line in step 1, which has an intersection with the horizontal line made in step 4. Connect the new intersection with the left intersection of the second stage regenerated water supply line made in step 4.
Step 6. Using the bottom intersection of the straight line and the water composite curve in step 3 as the lower boundary, determine the straight line that has an intersection with the upper water composite curve and is completely below the water composite curve with the same slope as the straight line in step 5. During the process, the concentration corresponding to the intersection point is as low as possible.
Step 7. Using the bottom intersection of the straight line and the water composite curve in step 4 as the lower boundary, determine the line that has an intersection with the upper water composite curve and is completely below the water composite curve with the same slope as the straight line in step 1. During the process, the concentration corresponding to the intersection point is as low as possible.
Steps 4 and 5 above are shown in Figure 3.

4. Case study

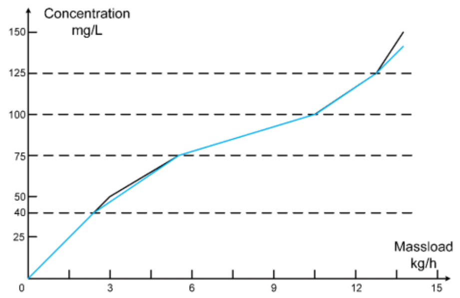
To illustrate the approach mentioned above, a case studied is used (Ding and Feng, 2018). The limiting data of water using units are shown in Table 1. The two post-regeneration concentrations are set to 40 mg/L and 75 mg/L, respectively. The optimal composite water supply line of the three cases can be determined based on the approach above, as shown in Figure 4. The corresponding networks are shown in Figure 5.

Table 1: Limiting data of water using units

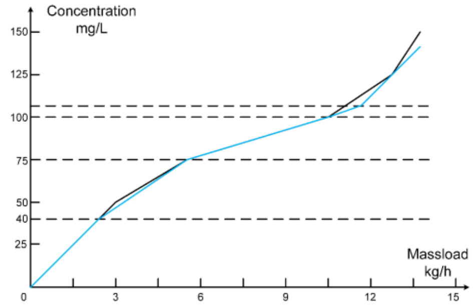
Unit	Limiting input concentration/(mg/L)	Limiting output concentration/(mg/L)	Mass load/(kg/h)
1	0	100	6
2	50	150	4
3	75	100	2.5
4	100	125	1.25



a. Case with same regeneration concentration



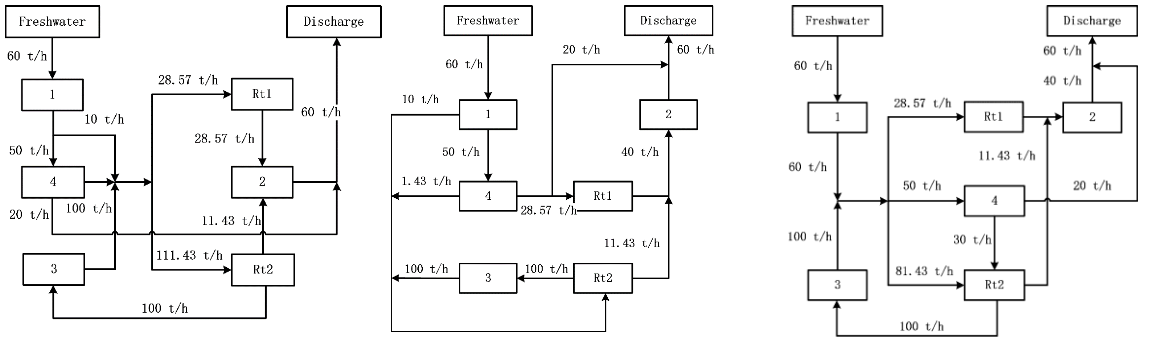
b. Case with a higher first stage regeneration concentration



c. Case with a higher second stage regeneration concentration

Figure 4: C-M diagram of the case study

By disassembling the first three segments of the optimal composite water supply line, the freshwater supply line and two regenerated water supply lines can be obtained, and then the optimal flow rates can be obtained.
For this water system, the optimal flow rates of the three cases are the same. The optimal freshwater flow rate is 60 t/h, the optimal first stage regenerated water flow rate is 28.57 t/h, and the optimal second stage regeneration water flow rate is 111.43 t/h. However, the optimal regeneration concentrations of different cases are different. The optimal regeneration concentration of the network with the same regeneration concentration is 105.36 mg/L, the optimal regeneration concentrations of the network with a higher first stage regeneration concentration are 100.32 mg/L and 125 mg/L, and the optimal regeneration concentrations of the network with a higher second stage regeneration concentration are 100 mg/L and 106.75 mg/L.
According to the calculation formula of the regeneration cost proposed by Feng and Chu (2004), it can be found that the regeneration cost of the water network with a higher first stage regeneration concentration, with a higher second stage regeneration concentration and with the same regeneration concentration are 448.87 mu/h, 346.03 mu/h and 366.43 mu/h, respectively (mu stands for currency unit).



a. Case with same regeneration concentration

b. Case with a higher first stage regeneration concentration

c. Case with a higher second stage regeneration concentration

Figure 5: Water networks of the case study

5. Conclusion

In this paper, a graphical approach for targeting the single-contaminant two-stage regeneration recycling water network with parallel structure has been studied. Three cases with correlations between two regeneration concentrations have been considered. Parameters, including the freshwater flow rate, two regenerated water flow rate and two regeneration concentrations, are determined as the optimization objectives. The construction method for the optimal composite water supply line has been presented to target those objectives. A case study shows that regardless of the relative level of the first and second stage regeneration concentrations, the optimal freshwater flow rate, the optimal first stage regenerated water flow rate, and the optimal second stage regenerated water flow rate are the same, but the optimal regeneration concentrations are different. Water networks with higher second stage regeneration concentration have lower optimal regeneration concentrations, which means lower regeneration costs.

The graphical method proposed in this paper can effectively reveal the insight of the water network, but cannot be applied to the water network with multi-contaminants. In our future work, the mathematical programming method for two-stage regeneration recycling water networks with parallel structure will be studied, which can deal with not only multi-contaminant systems, but also problems such as uncertainty.

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