R&D NOTES

A Simple Method for Design of Distributed Wastewater Treatment Systems with Multiple Contaminants

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Introduction

Water scarcity and stricter environmental regulations have pushed forward the researches in wastewater minimization. Being an effective technology for saving freshwater and reducing wastewater, water process integration has become the research focus recently. In water-using network design, it is necessary to allocate water streams in each water-using unit reasonably so as to maximize water-reusing and minimize wastewater discharge. In 1980, Takama et al.[1] presented a seminal article on water network design by using superstructure optimization approach. However, the research on water networks was not active until 1994, when Wang and Smith[2] proposed the approach of water-pinch analysis. Since then, many methods have been proposed for design and targeting of water networks. From the point of view of the number of contaminants, the systems investigated include single contaminant systems[3–11] and multiple contaminant systems.[1,2,12–27] Three review articles on water networks[28–30] were also published recently.

As pointed out by Foo[28] the work reported for wastewater treatment design and targeting is relatively less as compared to that in water reuse/recycle, as well as regeneration. Traditionally, the wastewater streams are treated in a centralized facility, in which all the effluent streams from the various processes are collected and treated in a common centralized facility. The feature of a centralized treatment system is that the wastewater streams will be mixed before treatment. This often leads to processing of large volumes of wastewater with low concentrations of contaminants. Eckenfelder et al.[31] Lankford et al.[32] and Higgins[33] addressed that distributed wastewater treatment could have significant advantages over centralized effluent treatment, because distributed wastewater treatment segregates effluent streams for treatment where appropriate and mixes them where appropriate.

For wastewater treatment systems, as pointed out by McLaughlin et al.[34] capital and operating costs of most wastewater treatment operations are proportional to the total flow rate of wastewater which flows through the treatment. Therefore, the costs increase with the decreasing concentration for a given mass load of contaminant. In addition, the number of treatment units also affects the costs. Therefore, in order to obtain a design with minimum cost, it is necessary to consider the following factors: (a) reduce the treatment flow rates of the processes, especially the expensive ones, and (b) reduce the number of treatment units, if possible.

For wastewater treatment system design and targeting, the methods proposed can be classified into pinch-based methods and mathematical programming methods. The first work on pinch-based method is proposed by Wang and Smith.[35] In the work of Wang and Smith[35] a general methodology for the design of distributed effluent treatment systems was presented. The minimum flow rate targets were determined before design of the distributed effluent treatment systems. Several design rules were proposed to achieve the targets. The method of Wang and Smith[35] provides valuable insights into the design of distributed effluent treatment systems. However, the method has some drawbacks as pointed out by Kuo and Smith.[36] Kuo and Smith[36] presented a modified method for the design of distributed effluent treatment systems and extended the method to retrofit cases. They[36] introduced the concept of mixing exergy loss, which provides a

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measurement of the extent in the wastewater degradation when the streams are mixed. However, it is necessary to design many subsystems to calculate the mixing exergy loss. This will increase calculation effort significantly for larger systems. Other pinch-based approaches for treatment system design and targeting include the work of Li et al.[37] Bandyopadhyay and Cormos,[38] Ng et al.[39,40] One of the advantages of the pinch-based methods is that the problem can be described graphically, which makes it easy to be understood.

The mathematical programming methods are also very important because they can deal with complex systems compared to the pinch-based methods. Takama et al.[1] used a nonlinear programming approach to optimize distributed wastewater treatment systems. Galan and Grossmann[41] introduced a superstructure optimization approach for the design of distributed effluent treatment systems. Hernandez-Suarez et al.[42] presented a superstructure-based optimization approach for the synthesis of distributed wastewater treatment networks with no stream recycles or recirculations. They decomposed a typical complex network superstructure into a set of basic network superstructures. The best treatment network was determined by solving a set of linear programming problems. Karuppiah and Grossmann[17] addressed the problem of optimal synthesis of an integrated water system, which combined water using processes and water treatment operations into a single network. A superstructure that incorporated all feasible design alternatives for water treatment, reuse and recycle, was proposed. The authors formulated the optimization of this structure as a nonconvex nonlinear programming (NLP) problem, which was solved to global optimality. Statyukha et al.[43] used water pinch analysis and wastewater degradation concepts to develop an initial structure of wastewater treatment networks, first. The initial structure was used to create a superstructure for nonlinear optimization. Castro et al.[44] presented an approach for the optimal design of wastewater treatment systems. They proposed an algorithm that can be divided in two parts for finding global optimal solutions to the problem. The first part generated multiple starting points by a linear program. The best solution of the several nonlinear problems that were solved was taken as the "global optimal solution". Karuppiah and Grossmann[18] addressed the problems of uncertainty of multiscenario mixed integer nonlinear programming models arising in the synthesis of integrated water networks. The other approach includes the expert method proposed by Freitas et al.[45]

This article presents a new method for designing of distributed wastewater systems. For the systems with multiple contaminants, a new concept, the total treatment flow rate potential (TTFP), is proposed, which can reflect a measurement of the minimum total flow rate of a treatment process to remove a contaminant in the streams to be treated to meet the environmental regulations. The value of the TTFP is calculated based on the bypassing fraction of a stream with single contaminant when it is treated by a treatment process. In order to reduce the total treatment flow rate, the treatment process with the minimum value of the TTFP should be performed first, if the total flow rate is directly proportional to the treatment cost. When the treatment cost is not directly proportional to the treatment flow rate, a few heuristic rules are proposed to determine the process sequences. The design method proposed is illustrated by a few literature examples.

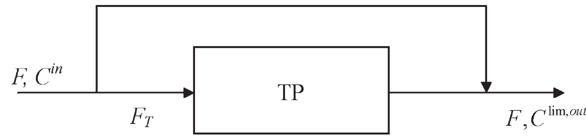

Figure 1. Bypassing and treatment fraction.

Problem Statement

The distributed effluent treatment system design investigated in this article can be stated as follows. Given are a set of effluent streams of different flow rates S_i, which are polluted by a set of contaminants ($j = 1, 2\ldots, NC$). To meet the environmental discharging limits, partial or total of the contaminants in the effluent streams must be removed in a set of treatment processes $\boldsymbol{P}$. Each of the processes is able to remove, to some extent, a subset of the contaminants in the effluent streams. It is assumed that there is no flow rate loss in the treatment processes. The design task includes: determining the performing order of the treatment processes, and segregating effluent streams for treatment where appropriate and mixing them where appropriate. The objective of the design is to reduce the total cost of the system as much as possible.

Calculation of bypassing fraction of a stream with single contaminant

Now, we will introduce a simple equation to calculate the bypassing amount for a stream with single contaminant when it is treated by a treatment process as shown in Figure 1. For the system shown in Figure 1, we have the following mass balance of the contaminant

$$(F - F_T)C^{in} + F_T C^{in}(1 - RR) = FC^{\mathrm{lim,out}} \tag{1}$$

where F_T is the minimum treatment amount to meet the environmental regulations, RR is the removal ratio of the treatment process (Wang and Smith[35]) as shown in Eq. 2

$$RR = \frac{f^{in}\,C^{in} - f^{out}\,C^{out}}{f^{in}\,C^{in}} \tag{2}$$

From Eq. 1 we have

$$F_T = F \times (C^{\mathrm{in}} - C^{\mathrm{lim,out}})/(C^{\mathrm{in}}RR) \tag{3}$$

Then, we have

$$F_T = F(C^{\mathrm{in}} - C^{\mathrm{lim,out}})/(C^{\mathrm{in}}RR) = F(m^{in} - m^{\mathrm{lim,out}})/\left(m^{in}RR\right) \tag{4}$$

Equation 4 can be written as

$$F_T = F(1 - C^{\mathrm{lim,out}}/C^{in})/RR \tag{5}$$

The bypassing fraction BF will be

$$\begin{aligned} BF = 1 - F_T/F &= 1 - (1 - C^{\mathrm{lim,out}}/C^{in})/RR \\ &= 1 - (1 - m^{\mathrm{lim,out}}/m^{in})/RR \end{aligned} \tag{6}$$

The value of $(C^{in} - C^{lim,out})/C^{in}$ is the ratio of the contaminant which should be removed to meet the requirement. From Eq. 4, it can be seen that if the value of $(C^{in} - C^{lim,out})/C^{in}$ is the same as the value of RR, we have $F_T = F$. This means that the bypassing fraction will be zero. Bypassing fraction will be larger than zero when the value of $(C^{in} - C^{lim,out})/C^{in}$ is smaller than that of RR.

Design for the systems of multiple contaminants: considering total treatment flow rate only and each process removing one contaminant

In this section, we will take the total treatment flow rate of the processes as the main factor for the design, and the treatment cost is considered as being directly proportional to the treatment flow rate. In the design procedure, the treatment process sequence will be determined first. The allocation of the streams will be considered, then. In the design, the streams might be mixed to reduce the number of treatment units, or split to reduce the treatment flow rate for some treatment processes. Because the treatment cost is often proportional to the total flow rate, we need an indicator which directly relates to the treatment flow rate to determine the process performing order.

Let us consider the situation when contaminant j in stream i is treated by process k, without considering the influence of the other streams and other contaminants. For this situation, the pseudo-minimum treatment flow rate (PMTF) $F^k_{i,j}$, can be calculated by the minimum treatment flow rate as Eq. 4

$$F^k_{i,j} = F_T = F_i(C^{in}_{i,j} - C^{lim,out}_{i,j})/(C^{in}_{i,j}RR) \quad (7)$$

It should be pointed that, when the PMTF is calculated, there are three situations

1. If $C^{in}_{i,j} > C^{lim,out}_{i,j}$, the PMTF should be calculated by Eq. 7. When $C^{in}_{i,j} \times (1 - RR) > C^{lim,out}_{i,j}$, the value of $(C^{in}_{i,j} - C^{lim,out}_{i,j})/(C^{in}_{i,j}\ RR)$ will be larger than unity. Then, the PMTF value will be larger than the flow rate of the stream. However, the value of $(C^{in}_{i,j} - C^{lim,out}_{i,j})/(C^{in}_{i,j}\ RR)$ will rarely be larger than 2.
2. If $C^{in}_{i,j} = C^{lim,out}_{i,j}$, contaminant j needs not to be treated, the PMTF value will be zero.
3. If $C^{in}_{i,j} < C^{lim,out}_{i,j}$, the value of $(C^{in}_{i,j} - C^{lim,out}_{i,j})/(C^{in}_{i,j}RR)$ will be negative. This means that the stream should not be treated. Instead, the treatment flow rate of the other stream can be reduced. The negative value of the PMTF can reflect this point. However, if $C^{in}_{i,j}$ is very small, the value of $|(C^{in}_{i,j} - C^{lim,out}_{i,j})/(C^{in}_{i,j}\ RR)|$ will be very large. In order to avoid the magnitude of the PMTF being too large, we assume that $|(C^{in}_{i,j} - C^{lim,out}_{i,j})/(C^{in}_{i,j}\ RR)| \le 1$.

From the aforementioned discussion, it can be seen that although the value of PMTF is not the ***real*** required treatment flow rate for process k to remove contaminant j in stream i, it can reflect the real required treatment flow rate in some way. The sum of the PMTFs for process k to remove contaminant j in all the streams will be as follows

$$FP^k_j = \sum_{i=1}^{NS} F^k_{i,j} \quad (8)$$

We call FP^k_j as the total treatment flow rate potential (TTFP) of process k to remove contaminant j. The TTFP value can reflect a measurement of the total minimum flow rate required to remove contaminant j in all the streams by using process k. The larger of the TTFP value, the larger of the total flow rate of process k to remove contaminant j. The value of the TTFP is taken as an indicator for treatment flow rate and will be used in the design of distributed wastewater system design.

Table 1. Data for Example 1

(a) Stream data

Stream	Flowrate (t/h)	Concentration (ppm) A	B	C
S_1	20	600	500	500
S_2	15	400	200	100
S_3	5	200	1000	200

(b) Treatment process data

Process	Removal ratio for contaminant (%) A	B	C
TPI	90	0	0
TPII	0	99	0
TPIII	0	0	80

In order to reduce treatment cost as much as possible, the treatment process with the largest treatment flow rate should be performed last. The reason is that if the process with the largest treatment is performed earlier, it might be necessary to mix the streams to be treated by the process. This would increase the treatment flow rate of the downstream processes.

Then, the following rule is proposed for the design of treatment systems if the total flow rate is directly proportional to the treatment cost: *the smaller of the value of TTFP of a process, the earlier the process should be performed.*

Let us show how to use the rule proposed to design a distributed wastewater system by using a literature example.

Example 1

The data for Example 1 are shown in Table 1, taken from Kuo and Smith.[36] The environmental limit for each contaminant is 100 ppm.

From Table 1, it can be seen that contaminant A in stream 1 should be treated by TPI. From Eq. 7, we have

$$\begin{aligned} F^I_{1,A} &= F_1 \times (C^{in}_{1,A} - C^{lim,out}_{1,A})/(C^{in}_{1,A}RR) \\ &= 20 \times (600 - 100)/(600 \times 0.9) = 18.52(\text{t/h}) \end{aligned}$$

Then, the PMTF value for process TPI to remove contaminant A in stream 1 is 18.52 t/h. Similarly, the other PMTF values can be calculated. The PMTF matrix for this system is as follows

$$\begin{bmatrix} F^{I}_{1,A} & F^{II}_{1,B} & F^{III}_{1,C} \\ F^{I}_{2,A} & F^{II}_{2,B} & F^{III}_{2,C} \\ F^{I}_{3,A} & F^{II}_{3,B} & F^{III}_{3,C} \end{bmatrix} = \begin{bmatrix} 18.52 & 16.16 & 20.00 \\ 12.50 & 7.58 & 0.00 \\ 2.78 & 4.55 & 3.13 \end{bmatrix} \quad (9)$$

The TTFPs for the treatment processes are as follows

$$\begin{bmatrix} FP^I_A & FP^{II}_B & FP^{III}_C \end{bmatrix} = \begin{bmatrix} 33.80 & 28.28 & 23.13 \end{bmatrix} \quad (10)$$

Table 2. The Streams After Treatments for Example 1

(a) The streams after TPIII

Stream	F (t/h)	Concentration (ppm) A	B	C
S'_1	23.13	545.95	567.57	91.89
S_2	15	400	200	100
S'_3	1.88	200	1000	200

(b) The streams after TPII

Stream	F (t/h)	Concentration (ppm) A	B	C
S''_1	1.51	545.95	567.57	91.89
S_2	15	400	200	100
S''_3	23.49	518.33	6.02	100.5

(c) The streams after TPI

Stream	F (t/h)	Concentration (ppm) A	B	C
S_2	5.83	400	200	100
S'''_3	34.17	48.78	82.93	100

where $FP_A^I = 18.52 + 12.50 + 2.78 = 33.80$ t/h. The other values in formula (10) can be obtained similarly.

From formula (10), it can be seen that the value of TTFP for TPIII is the smallest, and that for TPI is the largest. According to the rule proposed, TPIII should be performed first, and TPI should be performed last.

Process TPIII is performed to treat S_1 and 3.13 t/h of S_3. The streams data after TPIII are listed in Table 2a. In Table 2a, stream S'_1 is the outlet stream of TPIII.

Then, TPII will be performed to treat the rest of S_3 and 21.62 t/h of the outlet stream of TPIII. The treatment flow rate for TPII is 23.49 t/h. TPI is performed last. The treatment flow rate for TPI is 34.17 t/h. The streams after TPII and those after TPI are listed in Table 2b and 2c, respectively. The total treatment flow rate for the whole system is 80.8 t/h. The final design is shown in Figure 2 (1).

We also calculate the total treatment flow rates for all the possible sequences, as shown in Table 3. The detailed designs of the processes are shown in Figure 2, which are the same as that obtained by Kuo and Smith.[36] From the data shown in Table 3, it can be seen that: when the process with the maximum TTFP (TPI) is performed last, the total flow rate will be small (sequences 1 and 2 in Table 3 and Figure 2); when the process with the maximum TTFP is performed second, the total flow rate will be medium (sequences 3 and 4 in Table 3 and Figure 2), when the process with the maximum TTFP is performed first, the total flow rate will be large (sequences 5 and 6 in Table 3 and Figure 2). For the sequences in which TPI is performed in the same order (say sequences 1 and 2), when the process with the larger TTFP (TPII) is performed first, the total flow rate will be larger. Similar situations can be found in sequences 3 and 4, and sequences 5 and 6. From this example, it can be seen that the method proposed in this article is effective, and the calculation of this work is simpler compared to the literature method. From the earlier discussion, it can be seen that the TTFP value is a good indicator to reflect the total treatment flow rate.

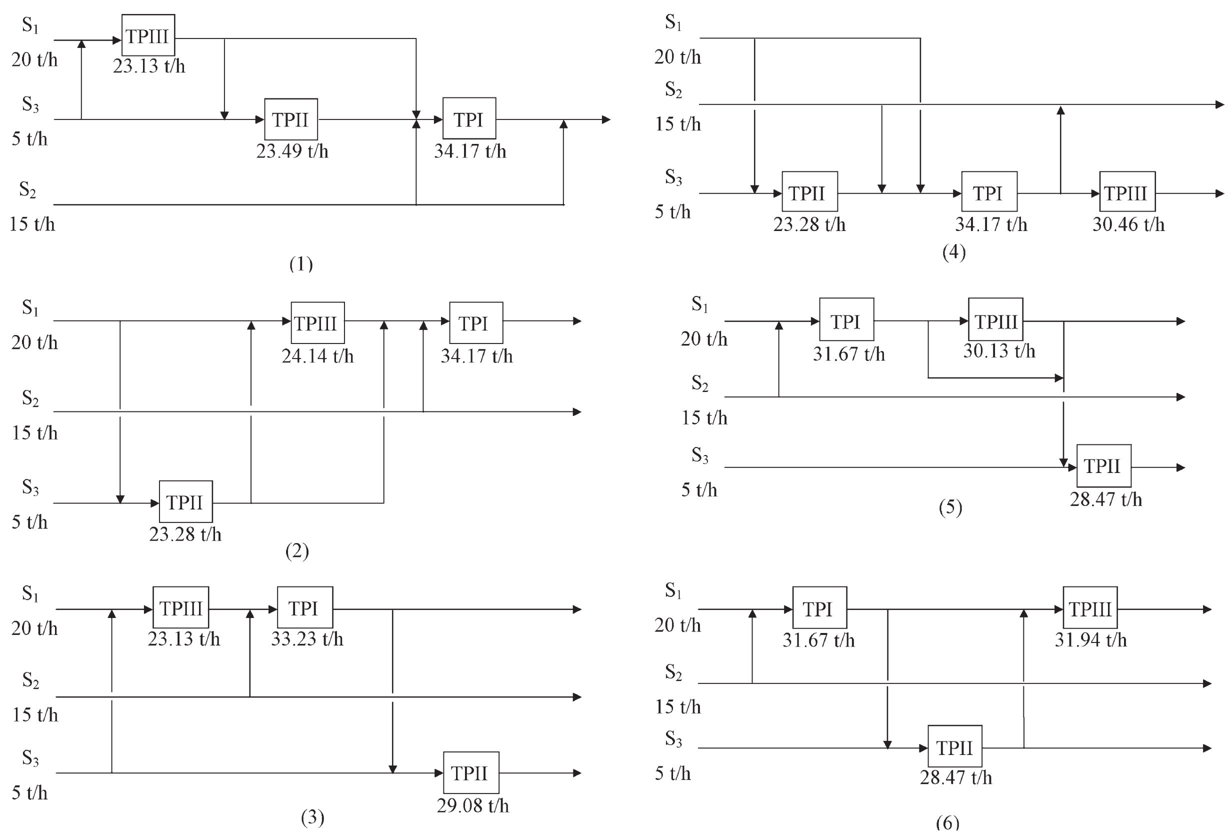

Figure 2. Designs for Example 1.

Table 3. The Total Treatment Flow Rates of Different Sequences for Example 1

Sequence		Total treatment flowrate (t/h)	Note
Number	Detailed		
1	TPIII, TPII, TPI	80.8	Minimum
2	TPII, TPIII, TPI	81.6	
3	TPIII, TPI, TPII	85.4	
4	TPII, TPI, TPIII	87.9	
5	TPI, TPIII, TPII	90.3	
6	TPI, TPII, TPIII	92.1	Maximum

Design for treatment processes which can remove multiple contaminants

In the aforementioned discussion, the total treatment flow rate of the processes is considered as the main factor, the treatment cost is assumed as directly proportional to the total flow rate of the processes, and we assume that each treatment process can only remove one contaminant. When the relationship between the treatment cost and the treatment flow rate is not directly proportional, the design of distributed wastewater treatment processes is more complex. Generally speaking, if possible, the expensive process should be performed first to avoid increasing its treatment flow rate. This is different from the situation for the process synthesis with single feed. For the process synthesis with single feed (say, synthesis of distillation sequence with single feed), the process with higher cost should be considered last while economic process should be performed first. However, for distributed wastewater treatment systems, there are a few ‘‘feed’’ streams. If the process with higher cost is performed last, it has to treat larger amounts of wastewater. This will increase the total treatment cost. The cheap process can be performed any time because this will not affect the total cost too much. If each treatment process can remove multiple contaminants, the situation will also be more complex. In order to meet the environmental limit of each contaminant, the TTFP of a treatment process should be the maximum value of the TTFPs for the contaminants treated by the process. We will show this in Example 2.

For design of a distributed treatment system when the treatment cost is not directly proportional to the total flow rates, we use the following rules:

1. Select the process performed earlier carefully;
2. Perform the expensive treatment process(es) early to avoid increasing its treatment flow rate;
3. Perform the treatment process with the smallest TTFP first;
4. If the expensive treatment process has higher TTFP, detailed calculation should be carried out to determine the sequence.

The process performed early will play a more important role in determining the topological structure of the system, compared to the process performed later. If the expensive treatment process has higher TTFP, rules 2 and 3 contradict each other. Therefore, a detailed calculation is necessary to determine the sequence. Similar design procedure has been used successfully in the synthesis of distillation sequences (Liu and Xu[46]).

Table 4. Data for the Case Study

(a) Stream data

Stream	Flowrate (t/h)	Concentration (ppm) A	B	C
S_1	13.1	390	10	250
S_2	32.7	16780	110	400
S_3	56.5	25	100	350
Sum	102.3			

(b)Treatment process data

Treatment Process	Removal ratios (%) H_2S	Oil	Suspended solids
TP I	99.9	0	0
TPII	90	70	98
TPIII	0	70	50

(c) Cost functions for the treatment processes

TPI	Capital ($)	$16{,}800\times f^{0.7}$
	Operating ($/h)	$1.0\times f^{0.7}$
TPII	Capital ($)	$12{,}600\times f^{0.7}$
	Operating ($/h)	$0.0067\times f^{0.7}$
TPIII	Capital ($)	$4{,}800\times f^{0.7}$
	Operating ($/h)	0

Note: Annual rate of return = 10%.
Operating hours = 8600 h/yr.
f = flow rate treated t/h.

Example 2

Let us consider the case study example of Kuo and Smith,[36] with the data shown in Table 4. The environmental limits of the concentrations of contaminants A, B and C are 5, 20 and 100 ppm, respectively.

For TPI, TPII and TPIII, the PMTF matrices are shown in Table 5. It should be pointed out that in Table 5a, only the PMTF values for contaminant A are listed, because TPI can

Table 5. TTFP Calculation for the Treatment Processes of the Case Study

(a) For TPI

Stream	PMTF (t/h) Contaminant A
S_1	12.94
S_2	*32.72*
S_3	45.25
Sum	90.91

(b) For TPII

Stream	PMTF (t/h) A	B	C
S_1	*14.37*	*−13.1*	8.02
S_2	*36.32*	38.22	25.03
S_3	50.22	*64.57*	41.18
Sum	100.91	89.69	74.23

(c) For TPIII

Stream	PMTF (t/h) B	C
S_1	*−13.1*	15.72
S_2	*38.22*	*49.05*
S_3	*64.57*	*80.71*
Sum	89.69	145.48

Table 6. The Data of the Streams after Treatment of the Case Study

(a) The streams after TPI

Stream	Flowrate (t/h)	Concentration (ppm)			Mass load (kg/h)		
	F	A	B	C	A	B	C
S_1'	8.08	390	10	250	3.15	0.08	2.02
S_2'	37.72	14.60	96.70	380.04	0.55	3.65	14.34
S_3	56.5	25	100	350	1.41	5.65	19.78
Sum	102.3				5.12	9.38	36.13

(b) The streams after TPIII

Stream	Flowrate (t/h)	Concentration (ppm)			Mass load (kg/h)		
		A	B	C	A	B	C
S_1'	8.08	390	10	250	3.15	0.08	2.02
S_2'	37.72	14.60	96.70	380.04	0.55	3.65	14.33
S_3'	19.96	25	100	350	0.50	2.00	6.99
S_3''	36.54	25	30	175	0.91	1.10	6.40
Sum	102.3				5.12	6.82	29.74

only treat contaminant *A*. Similarly, for TPIII, only the PMTFs for contaminants *B* and *C* are listed. It should be noticed that from the discussion about calculation of PMTF in the section of ''Design for the systems of multiple contaminants: considering total treatment flow rate only and each process removing one contaminant'', the PMTF values for process TPII to remove contaminant *B* in S_1 will be -13.1 t/h, because the inlet concentration of *B* in S_1 is lower than the limiting outlet concentration. On the other hand, when TPI and TPII are used to treat S_2, the outlet concentration will be higher than the limiting outlet concentration. That means, the concentration of contaminant *A* in S_2 is too high. Therefore, the PMTF values for TPI and TPII to remove contaminant *A* in S_2 will be larger than the value of S_2. Similarly, there are a few PMTF values in Table 5 are not ''normal'' and they are printed in italics format.

From Table 5b, it can be seen that for TPII, the TTFPs for contaminants *A*, *B* and *C* are 100.91, 89.69 and 74.23 t/h, respectively. To meet the environmental limits for all the contaminants, the maximum TTFP 100.91 t/h, will be taken as the TTFP for TPII. Similarly, the TTFP for TPIII is taken as 145.48 t/h.

From Table 5, it can be seen that the TTFP of TPI is the smallest. On the other hand, TPI is the most expensive one. From rules 2 and 3, TPI should be performed first. Because TPIII is the cheapest process, it can be performed any time. From the mass balance of the contaminants, it can be seen that all the streams should be treated by TPII, when TPI is performed first. Therefore, TPII should be performed last, and this will reduce the treatment flow rate of TPIII. The process sequence is TPI, TPIII and TPII.

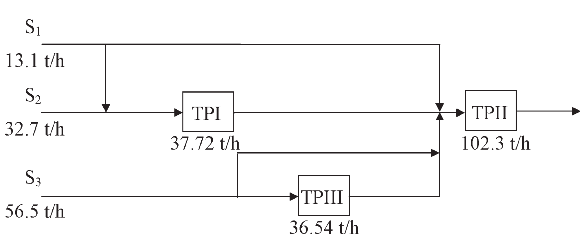

Figure 3. Design for Example 2.

Process TPI can remove contaminant *A* only. The concentration of contaminant *A* in S_2 is the highest. Therefore, S_2 should be treated by TPI totally. From mass balance of contaminant *A*, it can be seen that S_3 can be bypassed totally and S_1 should be treated partially by TPI. The streams after TPI are shown in Table 6a.

For TPIII, S_3 should be treated partially. The treatment flow rate of S_3 can be obtained from mass balance of the contaminants, which is 36.54 t/h. The streams after TPIII are shown in Table 6b. All the streams after TPI and TPIII should be treated by TPII, and its treatment flow rate is 102.3 t/h.

The final design obtained in this work is shown in Figure 3, which is the same as that obtained by Kuo and Smith.[36] However, the design procedure proposed is simpler than that of Kuo and Smith.[36]

Conclusion

This article presents a new method for design of distributed effluent treatment systems. For the multiple contaminants systems in which the treatment cost is directly proportional to the total treatment flow rate, a new concept, total treatment flow rate potential (TTFP), is proposed, which can reflect a measurement of the minimum total flow rate of a treatment process to remove a contaminant in the streams to be treated to meet the environmental regulations. The treatment process with the minimum TTFP should be performed first. For the treatment whose cost is not directly proportional to the treatment flow rate, a few heuristic rules are proposed. The illustrated examples show that the method proposed in this work is simple, and the results obtained are comparable to that obtained in the literature.

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Notation

BF = bypassing fraction

$C_{i,j}^{\text{in}}$ = inlet concentration of contaminant j in stream i, ppm

$C_{i,j}^{\text{lim,out}}$ = outlet environmental limiting concentration of contaminant j in stream i, ppm

F = flow rate, t/h

$F_{i,j}^{k}$ = pseudo-minimum treatment flow rate of process k to remove contaminant j in stream i, as shown in Eq. 7

FP_{j}^{k} = value of the TTFP for process k to remove contaminant j, as shown in Eq. 8

F_T = treatment flow rate, t/h

m = mass load, kg/h

PMTF = pseudo-minimum treatment flow rate, as shown in Eq. 7

RR = removal ratio

TTFP = total treatment flow rate potential, as defined in Eq. 8

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