Chin. J. Chem. Eng., **15**(3) 361—368 (2007)

Synthesis of Water Utilization System Using Concentration Interval Analysis Method (Ⅰ) Non-Mass-Transfer-Based Operation

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Abstract A strategy for water and wastewater minimization is developed for continuous water utilization systems involving fixed flowrate (non-mass-transfer-based) operations, based on the fictitious operations that is introduced to represent the water losing and/or generating operations and a modified concentration interval analysis (MCIA) technique. This strategy is a simple, nongraphical, and noniterative procedure and is suitable for the quick yields of targets and the identification of pinch point location. Moreover, on the basis of the target method, a heuristic-based approach is also presented to generate water utilization networks, which could be demonstrated to be optimum ones. The proposed approaches are illustrated with example problems.

Keywords water minimization, water utilization network, targeting method, concentration interval table

1 INTRODUCTION

Water is extensively used in process industries. Water-using operations can be typically classified into two broad categories[1—4]. One is the fixed contaminant load (mass-transfer-based) operations (*e.g.*, washing, scrubbing, and extraction), which are quality controlled and considered mass transfer units with water as the only mass separating agent[5,6]. The other is the fixed flowrate (non-mass-transfer-based) operations, which need quantity control (*e.g.*, reactors, boilers, and cooling towers). For the latter category, the units have specified inlet and outlet flowrates, which may not necessarily be equal and therefore can account for water losses or generations[3,4].

Current water scarcity and the ever-tightening environmental regulations on industrial effluent have motivated the research on the minimization of water usage and wastewater. Conceptual-based methods have been successfully used in the optimization of water utilization network to avoid the complex mathematical formulations and the corresponding solutions. These methods, also known as target methods, are the extended methods of the pinch analysis techniques for heat and mass exchanger networks. These include the graphical methods[1—3,7,8] and design procedure[9] on the basis of concentration interval analysis (CIA), also named as mass problem table (MPT)[10]. Although by using these approaches, the minimal consumption of freshwater could be effectively identified, yet there are some limitations. The first limitation comes from the graphical nature itself. The second is that they cannot simultaneously handle the problems associated with the two types of operations. To overcome these limitations, Manan *et al.*[4] proposed a method, namely, water cascade analysis technique, which can simultaneously handle the problems associated with the two types of operations. The third limitation is that there is no clear roadmap for these approaches to generate an optimal network.

In contrast to the work of Manan *et al.*[4], this article proposed an approach to simultaneously solve the problems associated with the two types of operations. The approach is mainly based on the conversion of problems by the introduction of fictitious operations, which is similar to those proposed by Zheng *et al.*[11], and on a modified CIA approach. The proposed strategy has the basic features of CIA, and it rapidly give the targets and identify the pinch point location of water utilization systems without using the graphical technique. Consequently, the utilization of CIA principle in the present article can avoid the complexity introduced by the concept of water purity level. Another major difference to the work of Manan *et al.*[4] is that a design method is proposed based the target approach developed in the present paper. For this, the design method proposed by Wang and Smith[5] on the basis of the concept of minimum number of water sources is extended to give a clear roadmap for the generation of an optimal water utilization network involving fixed flowrate operation unit, and this method is much simplified by avoiding loop identification and handling.

2 FICTITIOUS OPERATIONS

Unlike the fixed contaminant load operations, where upper bounds values are given to limit the inlet and outlet concentrations of the contaminant of the streams, the fixed flowrate operations have specified outlet (maximum) concentrations. Therefore, according to the optimum necessary conditions for fixed contaminant load operations[12], they have the same inlet and outlet concentration constraints for the water minimization problems of single contaminant operations. However, unlike the fixed contaminant load operations, the fixed flowrate operations have specified inlet and outlet flowrates, which may not necessarily to be equal.

On the basis of the above features, the operation types involving water loss or generation can be homogeneously represented by two fictitious water-using

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Received 2006-05-23, accepted 2006-11-27.

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operations: type 1 and type 2, as demonstrated in Fig.1. Operation type 1 is an operation whose limited water flowrate is equal to the inlet flowrate of the fixed flowrate operations with the same concentration constraints (limited inlet and outlet contaminant concentration). Operation type 2 is an operation whose limited water flowrate is equal to the quantity of lost or generated water in the fixed flowrate operation, and whose limited inlet and outlet concentration are equal to the outlet concentration of the fixed flowrate operation and the maximum outlet concentration of the whole water-using system, respectively. In other words, the operation type involving water loss can be fictitiously regarded as the water stream that is used to remove the mass load of the fictitious operation, and the operation system involving generated water can be fictitiously regarded as the (interior) water source rejected by the fictitious operation, which is used to remove the mass load of other operations.

By introducing the fictitious operations as shown in Fig.1, the problem associated with fixed flowrate operations could be converted to those of equivalent fixed contaminant load operation, and it could be solved using the modified CIA, and it is described in the next section.

Compared with the fictitious operations proposed by Zheng *et al.*[11], upon the above definition, the fictitious operations used for the generation of water have different inlet and outlet concentration. As a result, the modified CIA can directly acquire the minimum fresh water for the water system, and the deduction of fictitious freshwater consumptions conducted by Zheng *et al.*[11] can be avoided.

3 MODIFICATION OF CIA TECHNIQUE

The purpose of introducing fictitious operations is to convert the fixed flowrate operation problems into fixed contaminant load operation problems so that the CIA technique can be effectively applied. However, to solve the problems associated with the water-generation operations, the following modification should be made for the CIA method.

According to the CIA technique[10], the total limiting water flow rates in every interval j should be defined. However, if there is a fictitious operation derived from the operation type involving the generation of water, the generated water considered as an interior water source, should be preferably used by other operation unit. Then the total limiting water flow rates crossing interval j, F_j is given by the following expression

$$F_j = \sum_{i\in I, i\notin M, i\notin N} f_i + \sum_{m\in M} f_{\mathrm{l},m} - \sum_{n\in N} f_{\mathrm{g},n} \qquad (1)$$

where f_i , $f_{\mathrm{l},m}$, and $f_{\mathrm{g},n}$ represent the flowrate that crosses the interval j of the water-using operation i, the flowrates of the fictitious operation derived from the operations involving the loss and generation of water, respectively.

Note that, the modified CIA technique retains all the features of CIA, which is simple and numerically efficient to identify the minimum freshwater usage and the location of pinch or multiple pinch (if any).

4 EXAMPLES AND ILLUSTRATION OF THE APPROACH

4.1 Example 1

This example is taken from the studies of Polley *et al.*[1], which consists of four operation units; all are fixed flow rate operations (non-mass-transfer operation). The data provided in Table 1 shows that operations types 3 and 4 involve water losses.

According to the strategy proposed in the previous sections, each operations involving water loss is composed of two fictitious operation units: fictitious operation 3′ for operation 3, and fictitious operation 4′ for operation 4, respectively. Then, the corresponding limiting water data and concentration constraints given in Table 1 are turned equivalently into those given in Table 2.

The corresponding concentration interval table (CIT) is given as Table 3. Note that, because of the outlet concentration, operation unit 4′ has reached the maximum concentration of the entire water system, this fictitious unit doesn’t appear in the CIT. From Table 3, it can be seen that the minimum fresh water

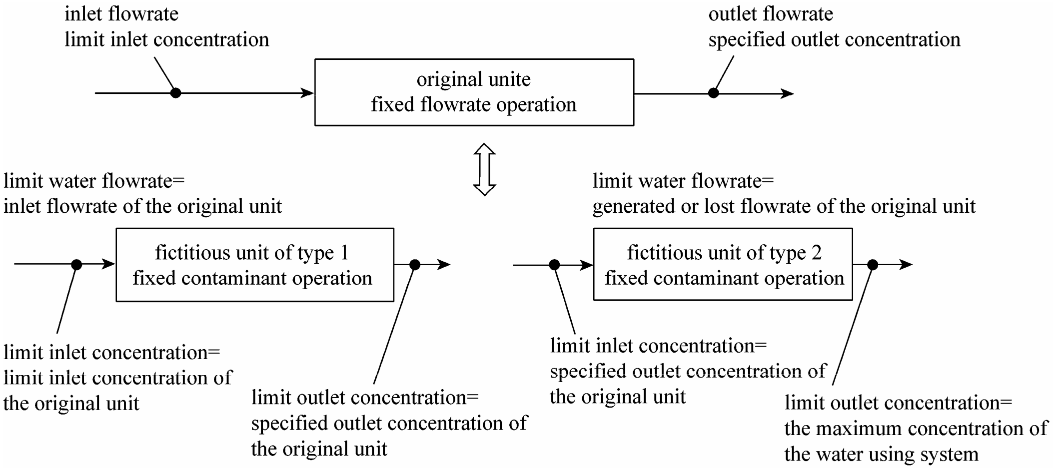


Figure 1 Schematic illustration of the conversion of fixed flowrate operation into fictitious operations

Table 1 Limiting water data for Example 1

Process number	$C_{\text{in}}^{\text{limit}}$, mg·L^{-1}	$C_{\text{out}}^{\text{limit}}$, mg·L^{-1}	Demand flowrate, t·h^{-1}	Water loss, t·h^{-1}
4	200	250	70	10
3	100	150	80	10
2	100	100	100	—
1	20	50	50	—

Table 2 Modified limiting water data for Example 1

Process number	$C_{\text{in}}^{\text{limit}}$, mg·L^{-1}	$C_{\text{out}}^{\text{limit}}$, mg·L^{-1}	Demand flowrate, t·h^{-1}	Water loss, t·h^{-1}
4′	250	250	10	—
4	200	250	70	—
3′	150	250	10	—
3	100	150	80	—
2	50	100	100	—
1	20	50	50	—

flow rate is 70t·h^{-1}, and the pinch point is at 150mg·L^{-1}, which is the upper limit of the concentration interval that lead to the maximum fresh water flowrate, as obtained from literatures[1,3,4]. In addition, the CIA technique can also identify the stream of operation unit 3 as the pinch-causing stream. The total flow rate of the wastewater discharged is 50t·h^{-1}, and it is calculated using the following expression

$$f_{\text{wastewater}} = f_{\text{fw}} - f_{\text{wl}} + f_{\text{wg}} \qquad (2)$$

where f_{fw} is the minimum freshwater flowrate of the water system, which is calculated using CIA technique , f_{wl} and f_{wg} are the flowrate of water loss and water generation in the total water system, respectively, $f_{\text{wasterwater}}$ is the flowrate of the discharged water from the total water system.

4.2 Example 2

Example 2 is from the studies of Sorin and Bedard[7], and it is the one involving multiple pinch points and mixed (mass-transfer-based and non-mass-transfer-based) operations. The limiting data for this example is showed in Table 4. Note that, the water used in operation 3 is totally lost. The limiting inlet and outlet concentrations for the corresponding fictitious operation are equal to the limiting inlet concentration of the operation and the limiting outlet concentration of the problem, respectively.

Table 4 Limiting water data for Example 2

Process number	$C_{\text{in}}^{\text{limit}}$, mg·L^{-1}	$C_{\text{out}}^{\text{limit}}$, mg·L^{-1}	Demand flowrate, t·h^{-1}	Water loss, t·h^{-1}
6	240	250	195	—
5	170	230	80	—
4	140	180	140	—
3	50	—	80	80
2	50	140	80	—
1	0	100	120	—

Table 5 shows the CIT for this problem. This extreme case, where the water used by unit 3 is completely lost, clearly demonstrates the physics of the introduced fictitious unit. Fictitious unit 3′ means that the water used in unit 3 could no longer be reused, or it cannot remove the load of any other “real” units. The minimum fresh water consumption calculated using modified CIA is 200t·h^{-1}, the wastewater target is 120t·h^{-1}, and this is similar to the previous studies of Sorin and Bedard[7] and Hallale[2]. Table 5 also shows that two pinch points exist in this problem at 100mg·L^{-1} and 180mg·L^{-1}, respectively, which is consistent with the results of other methods, such as water surplus diagram[2].The out stream of operation 1 was identified as the water source that causes pinch because its concentration is just the first pinch point concentration (100mg·L^{-1}), and the stream of operation 4 was also identified as the pinch-causing water source that leads to the second pinch (180mg·L^{-1}).

Table 3 The CIT for Example 1

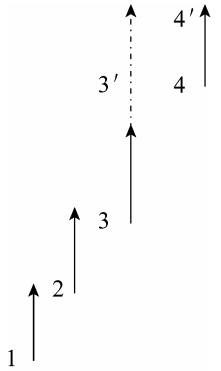
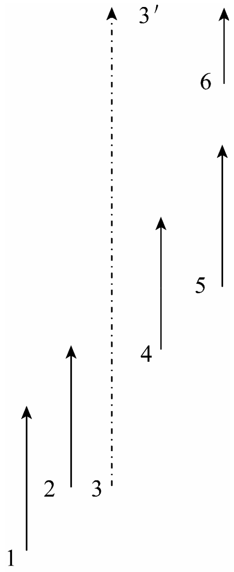
Interval	C_i, mg·L^{-1}	Operations	F_j, t·h^{-1}	Δm_j, kg·h^{-1}	$\Delta m_{\text{cumulative},j}$, kg·h^{-1}	$f_{\text{w},j}$, t·h^{-1}
	250					
5			80	4	15	60
	200					
4			10	0.5	11	55
	150					
3			80	4	10.5	70
	100					
2			100	5	6.5	65
	50					
1			50	1.5	1.5	30
	20					

Table 5 The CIT for Example 2

Interval	C_j, mg·L^{-1}	Operations	F_j, t·h^{-1}	Δm_j, kg·h^{-1}	$\Delta m_{\text{cumulative},j}$, kg·h^{-1}	$f_{\text{w},j}$, t·h^{-1}
	250					
8			275	2.75	47.55	190.2
	240					
7			80	0.8	44.8	186.6667
	230					
6			160	8	44	191.3043
	180					
5			300	3	36	200
	170					
4			220	6.6	33	194.1176
	140					
3			160	6.4	26.4	188.57
	100					
2			280	14	20	200
	50					
1			120	6	6	120
	0					

4.3 Example 3

This example is taken from the studies of Manan *et al.*[4], it consists of six operation units; and all are fixed flow rate operations (non-mass-transfer operation). The data are given in Table 6. Note that all operations types involve either the generation or loss of water. Similar to operation 3 in Example 2, the introduction of fictitious operation units for each of the operations can convert a fixed flowrate operation problem into an equivalent fixed contaminant load operation problem.

Table 6 Limiting water data for Example 3

Process number	$C_{\text{in}}^{\text{limit}}$, mg·L^{-1}	$C_{\text{out}}^{\text{limit}}$, mg·L^{-1}	Demand flowrate, t·h^{-1}	Water loss, t·h^{-1}	Water generation, t·h^{-1}
6	—	34	0	—	1.4
5	—	25	0	—	5.9
4	—	14	0	—	5
3	—	0	0	—	0.8
2	10	—	5.8	5.8	—
1	0	—	1.2	1.2	—

Table 7 shows the CIT for the problem. The minimum fresh water target calculated using modified CIA is 2.057t·h^{-1}, the wastewater target is 8.157t·h^{-1}, and these results are similar to the previous studies of Manan *et al.*[4]. Table 5 also shows that one pinch point exist in this case at 14mg·L^{-1}, which is consistent with the results of Manan *et al.*[4].The stream of operation 4 was identified as the pinch-causing water source.

5 WATER ALLOCATION AND NETWORK DESIGN WITH MINIMUM FRESHWATER TARGETS

In his section，water networks design approach based on the modified CIA technique, and the assumption that the mass transfer rate is a linear function of the concentration[5] are discussed. First, the water allocations in every concentration intervals are determined. Then, heuristic rules are used to determine freshwater and wastewater flowrates for each operation units.

5.1 Water allocation in every concentration interval

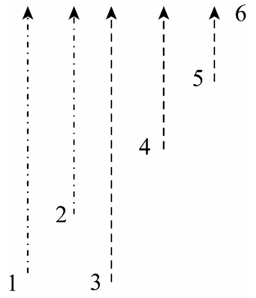
According to the pinch principles[5,6], below the pinch, *i.e.* for the streams with concentrations lower than the pinch value, only freshwater is used; and above the pinch, *i.e.* for the streams with concentrations higher than the pinch value, only wastewater is used. This means that sufficient wastewater discharged from the pinch point to remove the remaining contaminant mass. Therefore, water allocation to the intervals above the pinch can be considered as a novel problem. The minimum amount of water (wastewater) $f_{\text{ww},l}$ up to the concentration interval l can be calculated using the following expression[10]:

$$f_{\text{ww},l}=\left(\frac{\Delta m_{\text{cumulative},l}-\Delta m_{\text{cumulative,pinch}}}{C_l-C_{\text{pinch}}}\right) \tag{3}$$

where C_l is the upper limit concentration of interval l that is above the pinch, C_{pinch} is the pinch concentration, $\Delta m_{\text{cumulative, pinch}}$ and $\Delta m_{\text{cumulative},l}$ are the cumulative load up to the pinch and interval l, respectively. However, there may be more than one pinch points. Therefore, while calculating $f_{\text{ww},l}$, concentration, C_{pinch} and cumulative load $\Delta m_{\text{cumulative,pinch}}$ should be selected as the nearest pinch point.

In the water-using system, water is used to remove the mass load. Therefore, according to the assumption that the mass transfer rate is a linear function of the concentration, for the concentration intervals

Table 7 The CIT for Example 3

Interval	C_j, mg·L^{-1}	Operations	F_j, t·h^{-1}	Δm_j, kg·h^{-1}	$\Delta m_{\text{cumulative},j}$, kg·h^{-1}	$f_{w,j}$, t·h^{-1}
	34					
4			−4.7	−0.0423	−0.0003	−1.24
	25					
3			1.2	0.0132	0.042	1.68
	14					
2			6.2	0.0248	0.0288	2.057
	10					
1			0.4	0.004	0.004	0.4
	0					

-·-·-·-·-·-·-➤ Fictitious operation units derived from the water loss operation

--------➤ Fictitious operation units derived from the water generation operation

below the first pinch (the pinch with the lowest concentration), with the increase in the mass load to be removed, the amount of freshwater required will increase with the increase in the number of concentration intervals. Then, the increase in the use of freshwater $f_{\text{interval},j}$ for every interval j at the interval below the first pinch can be calculated using

$$f_{\text{interval},j} = f_{\text{w},j} - f_{\text{w},j-1} \qquad (4)$$

where f_{wj} is the fresh water using amount up to interval obtained by CIA, specially $f_{\text{w},0}$ is equal to 0. $f_{\text{interval},j}$ given by Eq.(4) gives in fact the amount of fresh water allocated to interval j.

Similarly, between the two pinch points and above the pinch point, the wastewater allocation (water reuse) in every concentration interval can be obtained by considering it as a separated problem.

Note that, to consider water re-use during the freshwater allocation, the interval immediately above the end point of an operation unit and all the intervals below the next end point of an operation, as shown in Table 3, the concentration interval 2 and 3, and interval 4 and 5 in Table 5, should be merged and regarded as one interval. While calculating the water allocation using expression (4) and in the following sections, the intervals are numbered in accordance with the merged intervals.

5.2 Network design rules

According to the CIA technique described above, freshwater is used to remove the mass load, and at the intervals below the first pinch, with the increase in the amount of mass load to be removed, the amount of freshwater needed increases until the pinch point, the amount of water used at this point is the minimum amount of fresh water required for the whole water system. This also means that, at one interval below the pinch, the wastewater is preferably used, freshwater usage is more preferred for the entire water system.

On the basis of the linear assumption of mass transfer, the amount of water used in an operating unit which is once determined, can satisfy the requirement of removal of the corresponding contaminant load for all the intervals it crosses. So during the determination of the amount of water use (freshwater or wastewater) of each operation in an interval, the operation unit crossing the interval will not be considered. In other words, in each interval, only the operation that start from the interval will use the freshwater allocated to the interval or the water leaving certain operation units from an above concentration interval. By this strategy, the water is allocated to the intervals, where it is needed, and thereby, the problem of loop marked and broken elaborated in the approach given by Wang and Smith[5] can be avoided.

Furthermore, on the basis of the modified CIA technique, if there is a fictitious operation derived from water generation operation, the generated water that is considered as an interior water source, should be preferably used by other operation unit. Therefore, the investigation with regard to amount of water used in the operation in each interval is needless to consider the fictitious operation unit for generated water.

On the basis of the above analysis, Rules 1 and 2 can be used to determine the water-using flowrate of each operation except the fictitious operation unit for generated water, and all the fictitious operation will be combined together to obtain the final water network.

Rule 1: Operation units prefer the use of wastewater that leaves certain operation units of lower concentration interval for minimizing the freshwater. Specially, an operation unit crossing a concentration interval uses the water from itself in the previous interval, such as the operation units 1 in concentration interval 2 of Table 5. Similarly, the fictitious operation prefer to use the water discharged from the fictitious operation that discharged from the same fixed flowrate operation.

Rule 2: If the mass load of one concentration interval can't be completely removed by applying Rule 1, the fresh water allocated to the interval will be used. There are three different cases to calculate the amount of water used by the operation units of corresponding concentration interval.

Case 1:

If no water is coming from the lower concentration interval other than the water from the operating unit itself, the freshwater allocated to the interval will be used by the operation unit that is starting from the interval, which is proportional to the limiting water flowrates[5]. So the amount of fresh water for each operation unit $f_{\mathrm{w},i}$ can be calculated using the following expression,

$$f_{\mathrm{w},i} = f_{\mathrm{interval},j} \frac{f_i}{\sum_{h \in H} f_h} \qquad i, h \in H \tag{5}$$

where the operation units indicated by i and h are the operation units starting from the interval j. f_i or f_h is the limiting water flow rate of the operation units in the interval.

For example, in interval 2 of Table 5, according to the rule, the amount of freshwater use in operation type 2 and 3 are 40t·h^{-1}.

Case 2:

If the stream of water coming from the lower concentration interval can be used，and there is only one operation unit that starts from the concentration interval, then the operation unit will use all freshwater allocated in the concentration interval, such as operation units 1, 2, 3, 4 in the respective concentration interval of Table 3 and operation stream 4 in the concentration interval 4 of Table 5.

Case 3:

If one or more streams of water coming from the lower concentration interval can be used, and there is more than one operation unit that starts from the concentration interval, then the identification of the water reuse matches between wastewater coming from lower concentration intervals, and the operation unit in the current interval is very simple. Here, instead of the minimum driving forces rule[5] to identify the matches, the following sub-rule is used to determine the matches.

Sub-rule 1: favor the match giving the smallest gap between the load to be removed in the interval of an operation unit and the load that can be removed by the water coming from the lower intervals.

If the water coming from the lower intervals by rule 1 is not enough to remove the mass load of certain operation unit i, the freshwater allocated to the interval will be used, and the amount $f_{\mathrm{w},i}$ can be calculated using the following expression,

$$f_{\mathrm{w},i} = \frac{m_i - m_{\mathrm{p},i}}{C_j - C_{\mathrm{w}}} \tag{6}$$

Where m_i is the load to be removed in the interval j of the operation unit i, $m_{\mathrm{p},i}$ is the mass load that can be removed using Rule 1, C_j is the concentration up to the concentration interval j, and C_{w} is the concentration of water source.

Finally, the remained freshwater that allocated in the interval will be allocated to other operation units in the interval according to the load proportion that need to be removed in the interval.

Note that, similar to the water allocation, for the operation units, which locate in the interval above the pinch and between the pinches, both Rules 1 and 2 can be applied to obtain their corresponding water using flowrate by considering it as a separated problem.

For the fixed flowrate operation units, the water using flowrate obtained by the above two rules can not always satisfy their flowrate requirements. As a result, additional water must be reused for satisfying the fixed flowrate requirement. Here, on the basis of the network design method (nearest neighbors algorithm) proposed by Ravi Prakash[3], the Rule 3 is introduced to identify the final water flowrate of these operations.

Rule 3: If the above two rules can't satisfy the demand of flowrate for a fixed flowrate operation, then the recycled water from the operation itself[8] or the discharged water from another operation whose outlet concentration is the maximum inlet concentration of corresponding fixed flowrate operation will be used to satisfy the flowrate requirement. The water stream is selected according to the following sub-rule.

Sub-rule 2: first**,** the water stream with high concentration should be selected for reducing the discharge amount.

For Example 1, operation 4 can reuse the water from itself and that discharged operation 3 According to sub-rule 2, only the water from itself is reused to reduce the amount of discharge.

Note that, for minimizing the environmental impact by minimizing the contaminant discharge, the selection of water stream for satisfying the requirement of fixed flowrate operation is a complicated optimization sub-problem[3]. Rule 3 proposed in this paper is just a heuristic and simplified approach to the optimum.

It should be pointed out that, as a heuristic approach, the proposed rules have some limitations. This approach is only suitable for single contamination water network designs; and for the problem associated with fixed flowrate operation, all fictitious operation must be combined to get the final water network.

5.3 Example analysis

According to the above water allocation approach and rules, the fresh water is first allocated for those operation units below the pinch. For Example 1, the amount of water allocated in the intervals 1, 2, and 3 is equal to 30, 35, and 5t·h^{-1}, respectively. Second, above the pinch, the problem is treated as a separated problem, where the wastewater with concentration of 150mg·L^{-1} is reused, and the amount of wastewater allocated in interval 4 and 5 is equal to 10 and 35t·h^{-1}, respectively.

Next step is the establishment of water allocation network. First, in every concentration interval, there is only one operation unit starting from the corresponding concentration interval. Therefore, according to Rule 2, apart from the reuse of water from the above interval, the operation unit will use the whole amount of water that are allocated to the corresponding interval. Consequently, the fresh water used in operations 1, 2, and 3 are 30, 35, and 5t·h^{-1}, respectively; the amount of wastewater at pinch point concentration of 150mg·L^{-1} from operation unit 3 used by operation unit 3′ and 4 is 10 and 35t·h^{-1}, respectively, and the wastewater discharged from operation unit 1 and 2 is

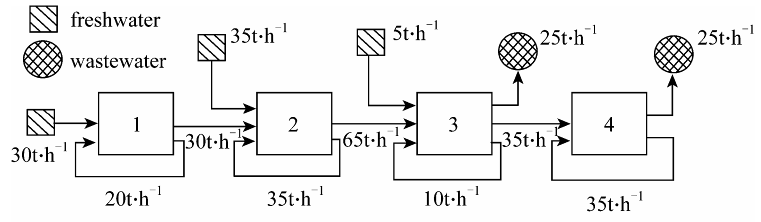


Figure 2 Water network design for Example 1

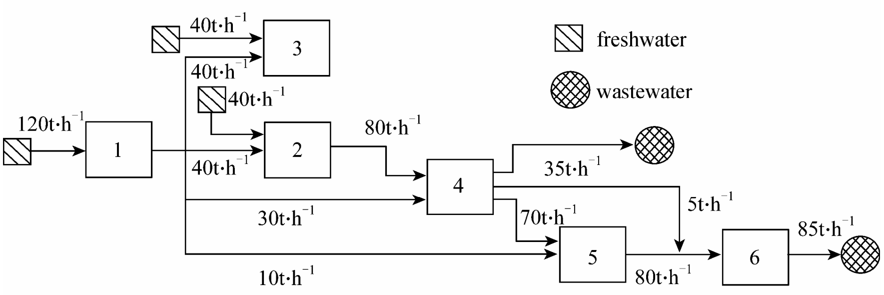


Figure 3 Water network design for Example 2

entirely reused by the subsequent operation units 2 and 3, respectively. Second, to satisfy the demand of fixed flowrate, according to Rule 3, operation units 1, 2, 3, and 4 also must reuse the water discharged from themselves, and the amounts of discharged water are: 20, 35, 10, and 35t·h^{-1}, respectively. Finally, the network design is obtained, and it is shown in Fig.2, which is similar to those obtained by Prakash[3].

In the same manner, the network designs for Examples 2 and 3 are also obtained, which are shown in Figs.3 and 4, respectively.

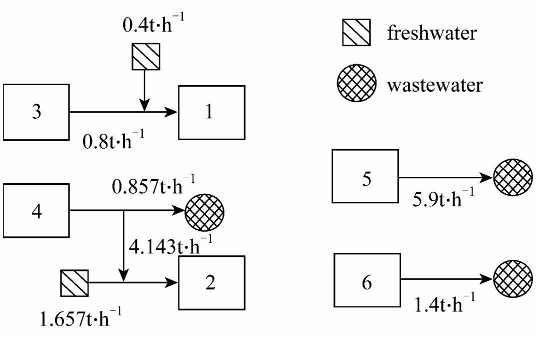


Figure 4 Water network design for Example 3

6 CONCLUSIONS

An approach for establishing the minimum fresh water and wastewater targets for continuous water-using system involving non-mass-transfer-based operations is proposed. This has been achieved by introducing fictitious operations so that the problem can be equivalently converted to that of traditional mass-transfer-based, which can be handled using CIA approach. This approach is a nongraphical, noniterative numerical technique, and it yield accurate targets and pinch point locations for the problems associated with non-mass-transfer-based operation as well as mass-transfer-based operations.

On the basis of the target method and the linear assumption of mass transfer, a heuristic-based approach is presented to generate water utilization networks. Using this approach, the problem of loop marked and broken elaborated in the approach given by Wang and Smith[5] can be avoided, and the network design with less contaminant environment discharge can be obtained for the design problem involving fixed flowrate operation.

NOMENCLATURE

C_j	the concentration up to the concentration interval j, mg·L^{-1}
C_w	the concentration of water source, mg·L^{-1}
F_j	the sum of the limiting water flow rates through the interval j, t·h^{-1};
$f_{g,i}$	the limiting water flow of fictitious operation coming from water generation operation unit, t·h^{-1};
f_i	the limiting water flow rates of the operation units i, t·h^{-1}
$f_{\mathrm{interval},j}$	the amount of freshwater-used in the interval j, t·h^{-1};
$f_{l,i}$	the limiting water flow of fictitious operation coming from the operation unit involving water loss i, t·h^{-1};
$f_{w,i}$	the water-using operation unit i including the fictitious operation, t·h^{-1}
$f_{w,j}$	the amount of fresh water used up to interval j, t·h^{-1}
$f_{ww,l}$	the amount of water used up to the interval l from the pinch, t·h^{-1};
H	the set of operation units starting from the interval j
I	the set of operation units present in interval j
M	the set of fictitious operation units whose limited water flowrate is equal to the amount of lost water in the corresponding fixed flowrate operation
m_i	the load that can be removed in interval j of operation unit i, kg·h^{-1};
$m_{p,i}$	the mass load that can be removed using rule 1, kg·h^{-1};

$\Delta m_{\text{cumulative}, j}$	the cumulative mass transferred up to the concentration interval j, $\text{kg}\cdot\text{h}^{-1}$;
Δm_j	the amount of mass transferred in interval j, $\text{kg}\cdot\text{h}^{-1}$;
N	the set of fictitious operation units whose limited water flowrate is equal to the quantity of generated water in the corresponding fixed flowrate operation

Subscripts

h, i, m, n	operation unit
j, k, l	concentration interval

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