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Combined Water−Oxygen Pinch Analysis with Mathematical Programming for Wastewater Treatment

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Abstract: Water−oxygen pinch analysis is an effective method to decrease the wastewater quantity and improve the wastewater quality. But when multiple-contaminants are present, the method is difficult to be carried out. In this paper, the method that combines water−oxygen pinch analysis with mathematical programming is proposed. It obtains the general optimal solution and leads to the reuse stream that cannot be found only by pinch analysis. The new method is illustrated by an example, and the annual cost is reduced by 8.43% compared with the solution of literature.

Key words: water−oxygen pinch analysis; wastewater minimization; mathematical programming

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1 INTRODUCTION

In recent years, there has been considerable development of system engineering methods to achieve fresh water and wastewater minimization in industry. This is driven by the rising cost of fresh water and effluent treatment, as well as more stringent environmental legislation. At present, there are two main approaches used to design water utilization network, that is, conceptual approach and mathematical programming.

1.1 Conceptual Design Approach

In 1994, Wang et al.[1] introduced the important concepts of “water pinch” and “limiting water profile” and proposed a targeting procedure that allows the calculation of the minimum fresh water usage without the need of constructing a network. Although this approach is a major step in understanding water system design, it has several limitations. Dhole et al.[2] correctly pointed out that based on a mass transfer model was a large drawback and presented an alternative method. In 2000, Polley et al.[3] presented a similar representation with Dhole's and thus overcame the limitations based on the mass transfer-based approach. Hallale[4] presented a new graphical targeting method which introduced a new representation of water composite curves by “water purity” and the concept of “water surplus”. Besides water pinch, Zhelev et al.[5] presented oxygen pinch which was prior to designing the minimum oxygen consumption required by micro-organisms for waste degradation.

1.2 Mathematical Programming

Takama et al.[6] addressed an approach for optimal water allocation in a petroleum refinery based on a superstructure of all possible reuse and regeneration opportunities. Doyle et al.[7], Alva-Argáez et al.[8] as well as Huang et al.[9] also presented MINLP and NLP models in series. Savelski and Bagajewicz presented the necessary conditions of optimality of water utilization systems in process plants with single contaminant and multiple contaminants respectively to reduce a nonlinear program to a linear program, by inserting the maximum outlet concentration conditions[10,11]. In recent years, mathematical programming has been developed greatly by combining with advanced algorithms and optimizing approaches, such as, genetic algorithms, simulated annealing algorithm, particle swarm optimizations and neural network approach.

In all of above reports, it is rarely mentioned to combine water pinch with mathematical programming. At present, there is no any paper on combined water−oxygen pinch analysis with mathematical programming. This paper presents a new approach to solve the problems.

2 COMBINED WATER−OXYGEN PINCH ANALYSIS METHODOLOGY

The aim of this methodology is to enhance the cost effectiveness of wastewater treatment and decrease the pollution levels in wastewater treatment process. The factors contributing to the cost of wastewater treatment and pollution levels are the wastewater quantity and the wastewater quality. Water pinch analysis is focused on the decrease of the quantity of wastewater, but can't improve the wastewater quality. Oxygen pinch analysis

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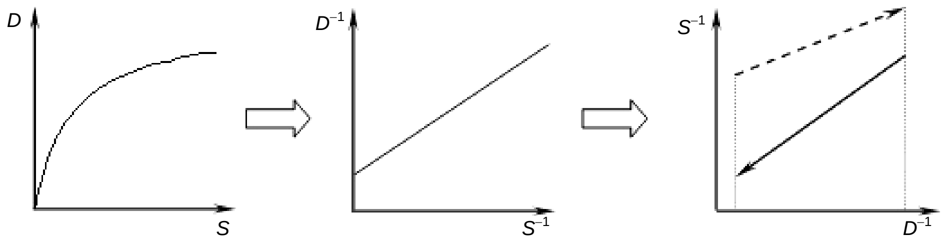
was found effective to solve the problem[5].

2.1 Oxygen Pinch Analysis

Since almost all wastewater can be treated biologically with proper environmental control, biological treatment has been widely used as core part of the treatment processes. In biological treatment, waste substances are oxidized and converted into simple end products, in which the oxidizer is oxygen transferred from air into the liquid. Oxygen demand is directly related to not only wastewater quality but also energy required. So oxygen pinch analysis was necessary to design the minimum oxygen consumption required by the micro-organisms for waste degradation and suggest flowsheet.

Oxygen demand D is proportional to substrate concentration S, the relationship between D and S is shown as Fig.1(a). Since the relation is usually not linear, it is difficult to use it in pinch analysis. However, the reciprocal of substrate concentration and the reciprocal of D follow a linear correlation. Oxygen pinch analysis is defined by graphical targeting method similar to water pinch analysis [shown in Fig.1(b) and 1(c)].

The oxygen pinch concept focuses on mass transfer pinch analysis but exceeds the classical pinch target expectations. It succeeds to set quantitative targets (oxygen solubility, residence time, oxidation energy load), as well as additional qualitative targets, namely the growth rate directly addressing the micro-organisms age and health. Water pinch and oxygen pinch are shown in Fig.2.



(a) Relationship (b) Linear trace (c) Oxygen pinch

Fig.1 Oxygen pinch stream definitions

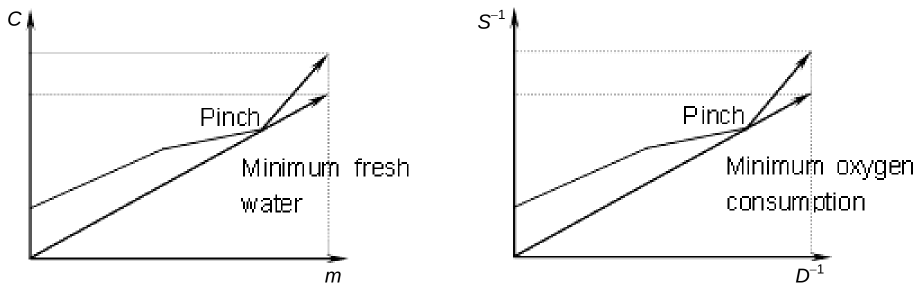


Fig.2 Water pinch and oxygen pinch analyses

2.2 Water−Oxygen Pinch Analysis

The factors contributing to the cost of wastewater treatment and pollution levels are the wastewater quantity and the wastewater quality. The wastewater quantity is directly related to the amount of energy required for the wastewater treatment, as well as pollution levels. Water pinch analysis was proposed to decrease the wastewater quantity thereby decreasing the cost of wastewater treatment and pollution levels. The wastewater quality was inversely proportional to the energy required for wastewater treatment as well as pollution levels. Oxygen pinch analysis was presented to improve the wastewater quality. Thus the overall effect of increasing the cost effectiveness of wastewater treatment was achieved by the application of a combined water−oxygen pinch analysis (shown in Fig.3). Moreover, the proposed combination method will allow to realize better management of fresh water and wastewater.

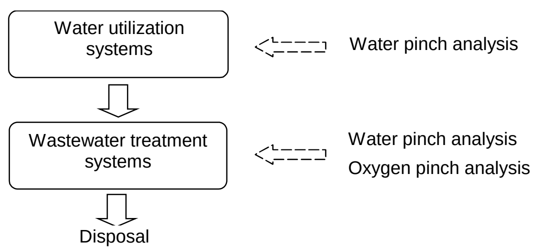


Fig.3 Water system with water−oxygen pinch analysis

The link between these two pinch analyses is the usage of COD, chemical oxygen demand, as the concentration variable in water pinch analysis. Water–oxygen pinch analysis can be simple as water pinch analysis with COD as concentration variable.

3 COMBINED WATER–OXYGEN PINCH ANALYSIS WITH MATHEMATICAL PROGRAMMING FOR WASTEWATER TREATMENT

The conceptual design approach leads to the minimum fresh water requirement of the entire process in a direct way, but when multiple-contaminants are present, graphical methods require additional assumptions to ease the implementation, some of which may be difficult to justify. The mathematical programming methods are effective in optimizing large-scale systems, but are difficult to interpret, giving designers fewer insights compared with graphical methods, and when the system is too large, it is also difficult to obtain the general optimal solution. These can be solved by combined pinch analysis with mathematical programming for wastewater treatment.

3.1 Setting up the Model of Wastewater Treatment Network

The wastewater treatment network is described as a system, in which wastewater can be treated more than once, including multiple streams and multiple wastewater treatment processes. The flowrate to each wastewater treatment process have been given. The removal ratio of each treatment process is constant.

Entering wastewater treatment network, each stream flows into a splitting node, where the stream can flow to all wastewater treatment processes. There is a mixing node in front of each treatment process, where all streams coming from other operation units are mixed. There is another splitting node behind each treatment process, in which stream may flow to discharge node or mixing nodes. And all wastewater streams flow to a mixing node at last, namely the discharge node, where the concentration of contaminant must satisfy the environmental regulations. In Fig.4, the superstructure model of wastewater treatment network includes three wastewater streams, three wastewater treatment processes and a discharge pool.

3.2 Decreasing Uncertain Parameter by Water–Oxygen Pinch Analysis

The water–oxygen pinch can be solved from the procedure presented by Zhelev et al.[5]. Furthermore, the

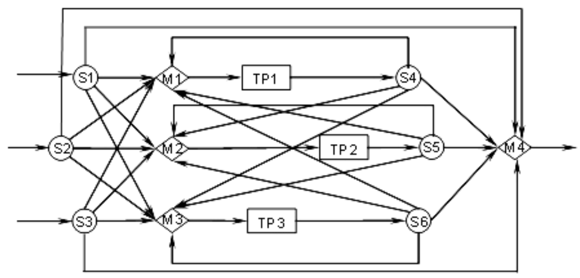


Fig.4 Superstructure model of wastewater treatment networks

water–oxygen pinch complies with the water pinch design rules. Streams whose contamination concentration is higher than that of the pinch are fully treated by the treatment process, those that are equal to the pinch are partially treated and partially bypass the treatment, and those that are lower than the pinch completely bypass the treatment. According to the design rule, the streams partially treated are regarded as parameters, while streams fully treated and completely bypass the treatment are regarded as constants. So the amount of uncertain parameters is deceased largely.

3.3 Setting up Mathematic Model

The capital cost and operating cost functions of treatment process are expressed by wastewater flowrate, and the mathematical model is shown as follows:

Objective function:

$$\mathrm{Min}\sum_{t}\left(\lambda A_t f_t^{\beta}+yB_t f_t\right). \tag{1}$$

Subject to:

(1) Mass balance of wastewater treatment process t:

$$\sum_{w} x_{t,w}=\sum_{w} x_{e,t}+w_b . \tag{2}$$

(2) Contaminant mass balance of wastewater treatment process t:

$$\left(1-R_{t,j}\right)\left(\sum_{k\neq t} x_{t,k}c_{k,j,out}\right)=\left(\sum_{k\neq t} x_{k,t}+w_b\right)c_{t,j,out} . \tag{3}$$

(3) Mass balance of wastewater stream w:

$$\sum_{t} x_{t,w}+x_{e,w}=f_w . \tag{4}$$

(4) Flowrate limiting of wastewater treatment process t:

$$\sum x_{t,w}\leqslant l_t. \tag{5}$$

(5) Limiting concentration of wastewater in discharge pool:

$$\sum_{t} x_{e,t}c_{t,j,out}+\sum_{w} x_{e,w}c_{w,j,out}\leqslant\left(\sum_{w} f_w\right)c_{e,j} . \tag{6}$$

It is often difficult to obtain the general optimum solution for non-linear programming by GAMS (General Algebraic Modeling System). Applying the rule of water–oxygen pinch analysis to decrease the number of uncertain parameters, the superstructure is easy to solve for the general optimum solution.

4 CASE STUDY

The case is taken from Kuo et al.[12]. Three wastewater streams are produced and must be treated before discharge. The flowrates of streams and the concentrations of contaminants involved are given in Table 1. The parameters of treatment processes, removal rates and the cost functions are given in Table 2, and the environmental limiting concentrations of the three contaminants are 5, 20, 100 mg/L, respectively.

Considering the minimum oxygen consumption required by the micro-organisms for waste degradation, the concentrations are turned into the COD as shown in Table 3, in which suspended solid can't be regenerated by biological treatment and is not necessary to turn into COD.

Table 1　Wastewater stream data for the case study

Stream number	Flowrate (t/h)	Contaminant concentration (mg/L)		
		H_2S	Oil	Suspended solid
1	13.1	390	10	250
2	32.7	16 780	110	400
3	56.5	25	100	350

Table 2　Removal rate and cost function for treatment process

Treatment process	Removal rate (%)			Cost	
	H_2S	Oil	Suspended solid	Capital cost ($)	Operating cost ($/h)
TPI	99.9	0	0	$16\,800f_t^{0.7}$	$1.0f_t$
TPII	90	70	98	$12\,600f_t^{0.7}$	$0.0067f_t$
TPIII	0	70	50	$4\,800f_t^{0.7}$	0
Annual rate of return (%)	λ=10				
Operating time (h/a)	y=8 600				

Table 3　COD concentration of wastewater stream

Stream number	Flowrate (t/h)	Contaminant concentration (mg/L)			
		COD (H_2S)	COD (Oil)	Suspended solid	Total COD
1	13.1	732.67	32.57	250	766.69
2	32.7	31 523.51	358.29	400	31 944.17
3	56.5	46.94	325.71	350	372.77

According to the given parameters and data, the superstructure and mathematical model are set up. Then, the water–oxygen pinch from the procedure presented by Zhelev et al.[5] is solved. The pinch of COD (H_2S) is at 732.67 mg/L, so stream 1 is considered as parameter and stream 2, 3 are considered as constants in the wastewater treatment. According to the procedure, other contaminants are similarly confirmed. The number of uncertain parameters is decreased greatly by water–oxygen pinch analysis and the superstructure is solved easily. We obtain the following optimal wastewater treatment network as shown in Fig.5. The optimal annual cost is $352 095.3772, lowed by 8.43%, as compared with the result by Kuo et al.[12], which was $384 489.7694.

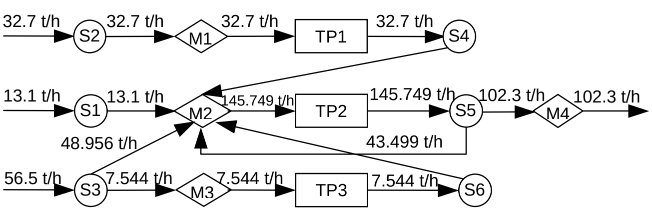


Fig.5 The optimal wastewater treatment network in this work

5 DISCUSSION

Compared with the result by Kuo et al.[12], the annual cost of the optimal wastewater treatment network in this paper is lowered by 8.43%. It can be learned that the two networks are mainly different in the flowrate of stream 1 to TP1 and the reused stream of TP2. Conceptual design approach adopted by Kuo et al.[12] failed to achieve the general optimal solution because they simplified the design procedure by rules and assumptions. Moreover, they did not consider the cost difference between the treatment processes. It is evidently that the operating cost of TP1 is much more than one of TP2 and the annual total cost can be reduced by decreasing the flowrate to TP1. Water–oxygen pinch analysis combined with mathematical programming can set up all possibilities of the network and get the optimal result.

6 CONCLUSIONS

The new design procedure that combines water–oxygen pinch analysis with mathematical programming is introduced to solve wastewater treatment network.

Firstly, water−oxygen pinch analysis is an effective method to decrease the quantity and improve the quality of wastewater. Then, the amount of uncertain parameter of superstructure and mathematical model is reduced greatly by pinch analysis. Finally, the method of water−oxygen pinch analysis combined mathematical programming can obtain the global optimal solution and find the stream that cannot be found by pinch analysis. The new method is illustrated by a case, and the annual cost is reduced by 8.43% compared with the solution by Kuo et al.[12].

NOTATIONS:

A_t	Capital cost coefficient of treatment process t ($/t)
B_t	Operation cost coefficient of treatment process t [$/(t·h)]
$c_{e,j}$	The environmental discharge limiting concentration of contaminant j (mg/L)
$c_{t,j,out}$	Concentration of contaminant j at outlet of treatment process t (mg/L)
$c_{w,j,out}$	Wastewater concentration of contaminant j (mg/L)
f_t	Flowrate of treatment process t (t/h)
f_w	Flowrate of wastewater stream w (t/h)
l_t	Limiting flowrate of water treatment process t (t/h)
$R_{t,j}$	Removal rate of contaminant j in treatment process t
w_b	Reuse flowrate of wastewater (t/h)
$x_{e,t}$	Discharge flowrate from treatment process to environment (t/h)
$x_{e,w}$	Discharge flowrate from wastewater stream to environment (t/h)
$x_{t,k}$	Flowrate from treatment process k to treatment process t (t/h)
$x_{t,w}$	Flowrate of wastewater stream w to treatment process t (t/h)
y	Annual operating time (h/a)
β	Exponential coefficient of capital cost of treatment process t
λ	Annual rate of capital cost return (%)

Subscribe

b	Reuse process	e	Environment
k, t	Treatment process	j	Contaminant
w	Wastewater stream	out	Outlet

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