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Design of Distributed Wastewater Treatment Networks

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Distributed wastewater treatment network (DWTN) has significant advantages over centralised one. This paper mainly reviews the methods proposed by our group for the design of DWTNs. Pinch analysis and mathematical programming methods are briefly discussed as well. By analysing the features of DWTNs, our group pointed out that it is very important to minimize unnecessary stream mixing to reduce the total treatment flowrate of a DWTN. Based on this insight, we proposed a series of design methods for both single and multiple contaminant systems. The constraints on the maximum inlet concentrations of treatment processes were considered as well. The methods of our group can handle complex problems with simple calculation and have clear engineering meaning.

1. Introduction

In a traditional wastewater treatment system, various streams are collected in a common sewer and then sent to central treatment facilities. Distributed (decentralised) wastewater treatment network (DWTN), in which streams are primarily segregated for treatment and only mixed when it is appropriate, has many advantages over centralized one (Wang and Smith, 1994). The DWTNs can not only improve treatment efficiency, reduce energy consumption, but also provide more chances to reuse the treated wastewater (Libralato et al., 2012). For municipal wastewater systems, life cycle assessment indicated that distributed treatment was preferable in environmental impacts (Opher and Friedler, 2016). There are mainly two kinds of methods for design of DWTNs, Pinch analysis methods and mathematical programming methods.

2. Pinch analysis methods for the design of DWTNs

Pinch analysis techniques, which have clear physical meaning, are effective tools for targeting and design of the DWTNs with single contaminant or simple ones with multiple contaminants. Wang and Smith (1994) introduced a graph-based Pinch approach for targeting of DWTNs and developed design rules for achieving the targets. Kuo and Smith (1997) improved the procedures of Wang and Smith (1994) by addressing some important features in designing multiple treatment processes for both single and multiple contaminant systems. They indicated that inappropriate mixing could result in wastewater degradation and introduced the concept of mixing exergy loss to measure the extent in the wastewater mixing. However, the design procedure of Kuo and Smith (1997) is complicated for complex systems. Bandyopadhyay (2009) proposed an algebraic approach based on pinch principle to target the minimum treatment flowrate for the wastewater systems with flow loss and provided a graphical representation with physical insight. Ng et al. (2007) introduced waste treatment pinch diagram for targeting the system of single contaminant with one treatment process. The method was extended by Soo et al. (2013) to the systems of one- or two-contaminant with multiple treatment processes.

3. Mathematical programming methods for the design of DWTNs

Mathematical programming methods are more robust in designing the DWTNs with multiple contaminants or achieving multiple-objective optimization. A mathematical programming procedure generally involved three steps: constructing a superstructure, formulating mathematical models, and solving the models. Table 1 lists the major development of mathematical programming methods in designing the DWTNs. In Table 1, columns

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2-4 correspond to the above three steps, respectively. The last column gives the remark on the solution obtained with the literature methods. For most methods, global optimal solution can be obtained with commercial global optimal solver, such as GAMS/BARON and LINDO WHAT'S BEST, but some simplifications might be adopted. A few modified algorithm were also developed for solving complicated models more effectively, such as Teles et al. (2012) and Yang et al. (2014).

Table 1: Mathematical programming methods in designing the DWTNs

Literature	Superstructure type	Model type	Solving strategy	Remark
Galan and Grossmann (1998)	Multiple contaminants	NLP	Relaxed LP providing start points for NLP	Global or near global optimal solutions
Hernandez-Suarez et al. (2004)	DWTN with no stream recycle or recirculation	LP	Superstructure decomposition and parametric optimization	Most certainly obtain global optimal solution
Liu et al. (2006)	Multiple contaminants	NLP/ MINLP	Particle swarm optimization	Obtaining global optimal solution without relying on an initial point
Castro et al. (2007)	Single and multiple contaminants	NLP	LP generated start points for NLP	Global optimal solution
Statyukha et al. (2008)	Single and multiple contaminants	NLP	Sequential approach: pinch technique created small superstructure, followed by a simple home-made optimizer	Cannot guarantee an optimal solution, but produce substantial improvements for existing networks
Ponce-Ortega et al. (2010)	Simultaneously consider the integration of mass & property, constraints & waste treatment	MINLP	Global optimal solver BARON	Obtaining global optimal solution without any numerical problems
Burgara-Montero et al. (2012)	Simultaneously optimize total cost and pollutant concentration for DWTN discharged into river	MINLP	Discretization approach was used to simulate each treatment unit before optimizing with GAMS/DICOPT solver	The accuracy of models, such as seasonality and stream properties, remained to be enhanced
Teles et al. (2012)	Water-using network and DWTN	MILP	Multiparametric disaggregation	Obtain global optimal solution rapidly compared to global solver BARON
Martinez-Gomez et al. (2013)	Optimization of environment, economy and safety	MINLP	GAMS solvers SBB/CONOPT/ CPLEX	Considered several simplifications, but it is effective to describe macroscopic systems in steady state
Yang et al. (2014)	Use more realistic models	MINLP	Modified Lagrangean decomposition algorithm	Obtain global optimal solution
Alnouri et al. (2015)	Industrial city water reuse network with central and DWTN	MINLP	LINDO WHAT'S BEST global solver	Converged fast
Sueviriyapan et al. (2016)	Retrofit wastewater network based on recycling/rerouting	MILP/ MINLP	GAMS solver CPLEX/DICOPT	Obtain solutions with effectively computational time
Li et al. (2016b)	DWTN	MILP	Multiparametric disaggregation and discretization	Obtaining global optimal solution

Generally speaking, mathematical programming methods can deal with complex problems, but they are complex in developing and solving the models. Moreover, it is difficult to adjust the solutions according to engineering practice, because the solution is often obtained with "black box" procedure.

4. The methods proposed by Liu's group

In a DWTN, the treatment cost is often proportional to treatment flowrate. Therefore, it is necessary to minimize the total treatment flowrate of DWTNs. Liu and his coworkers pointed out that it is unnecessary mixing of the streams, which is caused by irrational precedence order of the treatment processes, increases the total treatment flowrate. The key to minimize unnecessary stream mixing is to determine the reasonable precedence order of treatment processes (Liu et al., 2013). Based on this insight, Liu's group proposed a series of design methods including both heuristic rule-based ones and numerical indicator-based ones. The methods can be applied for the systems of both single contaminant and multiple contaminants with and/or without the maximum inlet concentration constraints for the treatment processes.

4.1 Design methods for the DWTNs without maximum inlet concentration constraints

To achieve the treatment flowrate target for the systems with one treatment process, Wang and Smith (1994) pointed out that all the streams above Pinch should be treated, the Pinch stream be partially treated, and all the streams below Pinch be bypassed. Based on the Pinch rules, Liu et al. (2012) concluded that if the stream which should be partially treated is identified, the Pinch can be determined. In this way, the design of the system can be obtained easily for the systems of single contaminant. The procedure to identify the Pinch is shown in Table 2, in which the streams are ranked in the descending order of concentration from S_1 to S_{nk}, f_i is the flowrate of S_i, c_i is the concentration of S_i, and $m_i = f_i\, c_i$. The residual mass load in S_i after treatment (m_i^{res}) can be obtained with Eq(1), and the cumulative mass load in all the discharged streams (CM_i^{res}) with Eq(2), where r_{TP} is the removal ratio of treatment process. When Eq(3) is met, S_P will correspond to the Pinch stream, where M_{env}^{lim} is the environmental limit discharging mass load.

$$m_i^{res} = \left(1 - r_{TP}\right) \times m_i \tag{1}$$

$$CM_P^{res} = \sum_{i=1}^{P} m_i^{res} + \sum_{i=P+1}^{nk} m_i \tag{2}$$

$$CM_{P-1}^{res} \geq M_{env}^{\lim} \geq CM_P^{res} \tag{3}$$

Table 2: The procedure to identify the Pinch stream

Stream	f_i	c_i	m_i	m_i^{res}	CM_i^{res}
S_1	f_1	c_1	m_1	m_1^{Res}	CM_1^{Res}
S_2	f_2	c_2	m_2	m_2^{Res}	CM_2^{Res}
S_{p-1}	f_{p-1}	c_{p-1}	m_{p-1}	m_{P-1}^{Res}	CM_{P-1}^{Res}
S_p	f_p	c_p	m_p	m_P^{Res}	CM_P^{Res}
S_{p+1}	f_{p+1}	c_{p+1}	m_{p+1}	m_{P+1}^{Res}	CM_{P+1}^{Res}
S_{nk}	f_{nk}	c_{nk}	m_{nk}	m_{nk}^{Res}	CM_{nk}^{Res}

The treatment flowrate of S_P is:

$$F_{TP,Pinch}^{treated} = \frac{CM_{P-1}^{res} - M_{env}^{\lim}}{r_{TP} \times c_P} \tag{4}$$

Then, the treatment flowrate of treatment process is:

$$F_{TP,in} = F_{TP,Pinch}^{treated} + \sum_{i=1}^{P-1} f_i \tag{5}$$

To simplify the design procedure of DWTNs with multiple contaminants, Liu's group usually considered only the main contaminant, which corresponds to the largest removal ratio of the process, to reduce calculation effort. The calculation procedure proposed by Liu et al. (2012) described above can serve as the basis for the design of the systems with multiple contaminants.

For the systems with multiple contaminants, more treatment processes are generally required. To avoid the complexity of considering all processes simultaneously, Liu et al. (2013) proposed a heuristic method. A three-process group is selected first. Then, the precedence order of the processes within this group is determined. To accomplish the grouping, Liu et al. (2013) analyzed the relationships between treatment processes, and calculated the minimum treatment flowrate of each process for its main contaminant. According to the minimum treatment flowrates and the relevance between treatment processes, the grouping can be carried out with a minimum-mixing rule: first, selecting the processes that will not cause any stream mixing; then, selecting the processes that will cause moderate stream mixing; lastly, selecting the processes that will cause serious stream mixing. The rules of determining the precedence order in a group is similar. The above procedure will continue till all the processes are designed. For some complex networks, the heuristic method of Liu et al. (2013) will encounter the difficulty of grouping or determining the precedence order of processes within the group. Therefore, it is essential to quantify the extent of stream mixing or the influence of stream mixing on the flowrates of downstream processes.

Shi and Liu (2011) proposed a numerical indicator to determine the precedence order of treatment processes. They used pseudo-minimum treatment flowrate (PMTF) to reflect the minimum treatment flowrate of process k to remove contaminant j in stream S_i, without considering the influence of other streams and other contaminants. The sum of the PMTF values, called as total treatment flowrate potential (TTFP), can serve as a measurement of the total minimum flowrate of process k to remove contaminant j for all the streams. When a process can remove multiple contaminants, the TTFP should be the maximum value of the TTFPs for all the contaminants to be treated. Shi and Liu (2012) addressed that to avoid unnecessary stream mixing, the process with the smallest TTFP should be performed first. The method of Shi and Liu (2011) can be used to design some DWTNs successfully. However, when the concentration of contaminant j in S_i is very low, the value of PMTF cannot appropriately reflect the minimum treatment flowrate of process k to remove contaminant j.

To overcome the weakness of the method of Shi and Liu (2011), Li et al. (2015) proposed another numerical indicator, total mixing influence potential (TMIP). In Eq(6), f_{TPj} is the minimum treatment flowrate of process j for removing its main contaminant, and $MI_{j,k}$ is the minimum treatment flowrate of downstream process k to remove its main contaminant for the outlet streams of process j. The value of $MI_{j,k}$ can directly reflect the influence of performing process j on the treatment flowrate of downstream process k. The sum of all the elements in the jth column vector of Eq(6), MI_j, as shown in Eq(7), can serve as an indicator to measure the influence of the stream mixing caused by performing process j on the total treatment flowrate of the system. Li et al. (2015) named MI_j as total mixing influence potential (TMIP) of process j. Li et al. (2015) determined the precedence order of the treatment process as follows: the process with the smallest TMIP value, say process q, would be performed first.

$$\begin{bmatrix} f_{TP_1} & \cdots & MI_{j,1} & \cdots & MI_{NT,1} \\ \vdots & & \vdots & & \vdots \\ MI_{1,j} & \cdots & f_{TP_j} & \cdots & MI_{NT,j} \\ \vdots & & \vdots & & \vdots \\ & \cdots & MI_{j,k} & \cdots & \\ \vdots & & \vdots & & \vdots \\ MI_{1,NT} & \cdots & MI_{j,NT} & \cdots & f_{TP_{NT}} \end{bmatrix} \tag{6}$$

$$MI_j = \sum_{i=1}^{NT} MI_{j,i} \tag{7}$$

The method of Li et al. (2015) is simple in calculation and easy to be programed in computer. More importantly, the calculation effort does not increase significantly with the increasing of numbers of streams, contaminants, and treatment units. Liu et al. (2017) presented a modified method for the design of DWTNs in which each process can remove multiple contaminants. An LP approach is combined with Pinch method to calculate the TMIP value.

4.2 Design methods for the DWTNs with maximum inlet concentration constraints

For the systems in which two processes are needed and constrained by maximum inlet concentrations, Liu et al. (2012) presented a two-step design procedure. The first step is to perform the processes according to the descending order of inlet concentration constraint, say TP_1, first. In the initial network, all the streams are treated by TP_1, and the outlet streams of TP_1 become the available streams treated by TP_2 whose treatment flowrate can be obtained by the Pinch method described in Section 4.1. The second step is to adjust the bypass amount of the streams with lower concentrations for TP_1 and establish the expressions of treatment flowrates for the two processes. The final network structure can be obtained by optimizing the treatment cost function shown in Eq(8), where K_{TP1} and K_{TP2} are the cost factors of TP_1 and TP_2, respectively.

$$E_{total} = F_{TP_1,in} \times K_{TP_1} + F_{TP_2,in} \times K_{TP_2} \quad (8)$$

For the systems with multiple treatment processes, Li and Liu (2016) presented a heuristic design method. The method includes three steps: (1) selecting treatment processes and determining the precedence order of the selected processes, (2) establishing an initial network, and (3) obtaining the final design. The first two steps can be achieved using the proposed heuristic rules by Li and Liu (2016). The implementation of the third step needs to consider the following issues simultaneously: contaminant mass load balance, Pinch method, and maximum inlet concentration constraints.

Li et al. (2016a) extended the method of Li and Liu (2016) to the systems of multiple contaminants with maximum inlet concentration constraints. The key contaminant(s), which corresponds to the maximum total treatment flowrate, needs to be identified when establishing the initial network. The final design can be obtained by adjusting the initial network for the key contaminant. Stream recycling might be adopted when either of the following situations is met: (1) the maximum inlet concentration constraint(s) of one or a few contaminants cannot be met in any available processes, and (2) the environmental regulation(s) of one or a few contaminant(s) cannot be met even if all the available processes are employed. In addition, the introduction of recycling structure in the process with the highest removal ratio for the key contaminant can improve the final design evidently, sometimes.

5. Conclusions

This paper reviews the methods for the design of DWTNs. Pinch analysis methods have clear physical significance but only are applicable for single-contaminant systems or simple multi-contaminant ones. Generally speaking, mathematical programming methods can handle complex problems, but it is difficult to develop and solve the models. Liu's group pointed out that it is very important to minimize unnecessary stream mixing to reduce the total treatment flowrate of a DWTN. This paper highlights the methods proposed based on this insight. The methods proposed by Liu's group have the following features: computational effort would not increase significantly with the increasing of the numbers of streams, treatment processes and contaminants. In addition, the methods proposed by Liu and his co-workers have clear engineering meaning. Although the methods cannot guarantee optimal solutions, they can provide near-optimal solutions in most cases. In the future, based on the insight of minimizing unnecessary stream mixing, the methods taking minimum treatment cost as objective function and that for the design of total water networks and for the interplant water systems will be developed.

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References

Alnouri S.Y., Linke P., El- Halwagi M., 2015, A synthesis approach for industrial city water reuse networks considering central and distributed treatment systems, Journal of Cleaner Production, 89, 231-250.

Bandyopadhyay S., 2009, Targeting minimum waste treatment flow rate, Chemical Engineering Journal, 152, 367-375.

Burgara- Montero O., Ponce- Ortega J.M., Serna- González M., El- Halwagi M.M., 2012, Optimal design of distributed treatment systems for the effluents discharged to the rivers, Clean Technologies and Environmental Policy, 14, 925-942.

Castro P.M., Matos H.A., Novais A.Q., 2007, An efficient heuristic procedure for the optimal design of wastewater treatment systems, Resources, Conservation and Recycling, 50, 158-185.

Galan B., Grossmann I.E., 1998, Optimal design of distributed wastewater treatment networks, Industrial & Engineering Chemistry Research, 37, 4036-4048.

Hernandez- Suarez R., Castellanos- Fernandez J., Zamora J.M., 2004, Superstructure decomposition and parametric optimization approach for the synthesis of distributed wastewater treatment networks, Industrial & Engineering Chemistry Research, 43, 2175-2191.

Kuo W.C.J., Smith R., 1997, Effluent treatment system design, Chemical Engineering Science, 52, 4273-4290.

Li A.H., Liu Z.Y., 2016, Design of distributed wastewater treatment networks of single contaminant with maximum inlet concentration constraints, CIESC Journal, 67, 1015-1021.

Li A.H., Yang Y.Z., Liu Z.Y., 2015, A numerical- indicator- based method for design of distributed wastewater treatment systems with multiple contaminants, AIChE Journal, 61, 3223-3231.

Li A.H., Zhang J., Liu Z.Y., 2016a, Design of distributed wastewater treatment networks of multiple contaminants with maximum inlet concentration constraints, Journal of Cleaner Production, 118, 170-178.
Li T., Castro P.M., Lv Z., 2016b, Models and relaxations for the wastewater treatment design problem, Chemical Engineering Research and Design, 106, 191-204.
Libralato G., Ghirardini A.V., Avezzù F., 2012, To centralise or to decentralise: An overview of the most recent trends in wastewater treatment management, Journal of Environmental Management, 94, 61-68.
Liu C.Z., Li A.H., Liu Z.Y., 2017, A modified method for design of distributed wastewater treatment systems: Each unit removing multiple contaminants, Chemical Engineering Transactions, 61, 1213-1218.
Liu Y.J., Luo Y.Q., Yuan X.G., 2006, Synthesis of distributed wastewater treatment networks based on particle swarm optimization, Journal of Tianjin University, 39, 16-20.
Liu Z.H., Shi J., Liu Z.Y., 2012, Design of wastewater treatment networks with single contaminant, Chemical Engineering Journal, 192, 315-325.
Liu Z.H., Shi J., Liu Z.Y., 2013, Design of distributed wastewater treatment systems with multiple contaminants, Chemical Engineering Journal, 228, 381-391.
Martinez- Gomez J., Burgara- Montero O., Ponce- Ortega J.M., Nápoles- Rivera F., Serna- González M., El-Halwagi M.M., 2013, On the environmental, economic and safety optimization of distributed treatment systems for industrial effluents discharged to watersheds, Journal of Loss Prevention in the Process Industries, 26, 908-923.
Ng D.K.S., Foo D.C.Y., Tan R.R., 2007, Targeting for total water network. 2. Waste treatment targeting and interactions with water system elements, Industrial & Engineering Chemistry Research, 46, 9114-9125.
Opher T., Friedler E., 2016, Comparative LCA of decentralized wastewater treatment alternatives for non-potable urban reuse, Journal of Environmental Management, 182, 464-476.
Ponce- Ortega J.M., Hortua A.C., El- Halwagi M., 2009, A property- based optimization of direct recycle networks and wastewater treatment processes, AIChE Journal, 55, 2329-2344.
Shi J., Liu Z.Y., 2011, A simple method for design of distributed wastewater treatment systems with multiple contaminants, AIChE Journal, 57, 3226-3232.
Soo S.S.T., Toh E.L., Yap K.K.K., Ng D.K.S., Foo D.C.Y., 2013, Synthesis of distributed wastewater treatment networks for one‐ and two‐contaminant systems, Chemical Engineering Research and Design, 91, 106-119.
Statyukha G., Kvitka O., Dzhygyrey I., Jeżowski J., 2008, A simple sequential approach for designing industrial wastewater treatment networks, Journal of Cleaner Production, 16, 215-224.
Sueviriyapan N., Suriyapraphadilok U., Siemanond K., Quaglia A., Gani R., 2016, Industrial wastewater treatment network based on recycling and rerouting strategies for retrofit design schemes, Journal of Cleaner Production, 111, Part A, 231-252.
Teles J.P., Castro P.M., Matos H.A., 2012, Global optimization of water networks design using multiparametric disaggregation, Computers & Chemical Engineering, 40, 132-147.
Wang Y.P., Smith R., 1994, Design of distributed effluent treatment systems, Chemical Engineering Science, 49, 3127-3145.
Yang L., Salcedo- Diaz R., Grossmann I.E., 2014, Water network optimization with wastewater regeneration models, Industrial & Engineering Chemistry Research, 53, 17680-17695.