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Optimal Design of Wastewater Treatment Network for Glass Container Plant

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This paper addresses design of wastewater treatment network (WWTN) with mathematical detailed models of treatment processes. The designing method is sequential and applies insight-based techniques followed by mathematical programming. First, water pinch analysis and wastewater degradation concept are employed to develop an initial structure. Then, a superstructure is created for WWTN. The solution from the first stage proved to be the good starting point for nonlinear optimization. Nonlinear programming problem is formulated on the basis of WWTN superstructure that uses stream split coefficients as variables. In the first stage typical crude model of treatment processes is used while in the second optimization stage detailed models of the operation are employed. Also, operation expenses and piping costs have been included into goal function. Hence, the approach accounts more rigorously for industrial requirements.

The design approach can be used for synthesis and also for retrofit of wastewater treatment networks. The aim of this paper is to present the extended approach and, also, to illustrate its industrial applications.

1. Introduction

Application of a distributed wastewater treatment systems is a key mean for reducing cost of treatment stations. A segregation or combination of separate wastewater streams in treatment systems is a crucial mean to reach the aim. The investment cost and treatment plant's operation costs depend on a proper choice of system structure and parameters of wastewater streams treated in various processes. In distributed wastewater treatment, streams are either treated separately or only partially mixed which reduces the flow rate to be processed when compared to centralized wastewater treatment systems. This, in turn, reduces total expenses because they, for most treatment operations, are proportional to the total flow of wastewater. This suggests that the design of effluent treatment systems should segregate the streams for treatment and only combines them if it is appropriate (Wang and Smith, 1994; Kuo and Smith, 1997).

The increasing importance of environmental regulations and changes in production for “veteran” plants in Ukraine designed and operated according to quite different economical and environmental regulations than those at present, motivates the need of retrofit of wastewater systems. Retrofit of wastewater system is possible not so much at the expense of processing units’ parameters changes as by reorganization of effluent treatment network into distributed one that has substantial advantages compared to centralized facility.

2. Basis of the approach to optimal WWTN design

The approaches to designing WWTN fall into two broad categories: insight-based and optimization-based. These from the first group do not guarantee cost optimal solution. Optimization-based methods most often use superstructure concept. Both types of approaches are usually limited to crude model of treatment operation defined by contaminant removal ratios. Solution of WWTN superstructure optimization model to (hopefully) global optimum requires great computation effort. For instance, Galan and Grossmann (1998) as well as Hernadez-Suarez et al. (2004) proposed complex linearization scheme, which requires exhaustive calculations by solving numerous LP problems.

A method addressed in this paper is the extension of hybrid approach from Statyukha et al., 2007. This approach combines insight-based techniques with rigorous optimization models and, also, detailed models of treatment processes. It consists of two stages: structure development stage and parameter optimization stage. Techniques applied in the first stage are based on “wastewater pinch” concepts developed by Wang and Smith, 1994 and Kuo and Smith, 1997.

Performing the stage of structure development gives the wastewater treatment network with fixed structure. Also, the flow rates are known. The structure is feasible solution to the problem. However, the flow rates have been calculated on the basis of exergy losses concept. Though the concept is generally valid but it does not minimize cost of treatment facility. The parameters, such as flow rates or split fractions in splitters attached to treatment processes should be adjusted so as to minimize total cost of WWTN. The second stage is aimed at refining the optimal solution. We applied mathematical optimization – solution of nonlinear programming (NLP) problem. NLP problem is formulated on the basis of WWTN superstructure that is represented by stream split coefficients. Overall goal function is the sum of wastewater treatment cost and piping cost. The piping costs are function of pipe length and wastewater stream flow rate. It is of importance that detailed models of treatment apparatus are used at this stage. The solution obtained in the first stage of the approach is applied as the starting point for optimization procedure. Since it is feasible and, usually, good solution the use of it ensures good convergence properties of a simple direct optimization technique applied.

3. Mathematical models of treatment processes

The novel feature of the method is the application of mathematical models of treatment processes. Majority of works published to date on WWTN design applied only fixed removal ratio as treatment process design model. The only exception is the contribution of Galan and Grossmann (1998) who, however, used the model of a specific membrane treatment process. Additionally, many authors assumed that removal ratio does not depend on contaminant concentration and treatment flow rate i.e. it is fixed for a process independent on its conditions. Another, often found assumption is the constant total flow rate via processes and, thus, within total WWTN. We apply mathematical models of treatment processes at the optimisation stage to take into account a relation between the removal ratio of a treatment process and treatment flow rate and/or contaminant concentration. Also, it allows considering flow rate changes due to removal of contaminants in a particular treatment process and, in result, changes of total flow rate in WWTN within design procedure.

Wastewater treatment facilities at Ukrainian plants built before the 1990 were designed according to procedures of calculations prescribed by the building code put into use all over the former USSR. Equations, relationships, tabular and graphical data from the building code allow designing particular treatment unit with engineering accuracy of calculation under necessary wastewater flow rate, treatment efficiency, operating regime etc. for steady state operation mode. We adapted these procedures for obtaining removal ratios of treatment processes depending on treatment flow rate and contaminant concentration under given treatment unit parameters in retrofit cases. Simulation models of treatment processes have been developed to take into account possible changes of treatment process removal ratio because of flow rate and contaminant concentration changes while designing distributed WWTN.

These models allow considering not only removal ratio changes but also to reckon specific parameters of treatment process in, e.g. water loss in the network with sediment from settler, with froth from flotation or coagulation unit, additional constraints at the units inlet and so on. The models of treatment processes require inlet treatment flow rate, contaminant concentration and properties, constructional and process parameters of the particular treatment unit as the data. For these parameter the treatment process removal ratio of the given contaminant and the outlet flow rate from treatment process are determined.

4. Case study

The application of the developed approach is illustrated here for the case of retrofitting industrial centralized wastewater treatment system of the glass container factory. There are three wastewater streams from: production department, assembling department, and ceramic department. The effluents are treated by oil trap (TPI) and settler (TPII). Streams are contaminated with suspended solids, chlorides, sulphates, oils and COD. The environmental limits on the concentrations of the five pollutants are 500, 400, 350, 1 and 800 ppm, respectively. The flow rates of streams and the concentrations of contaminants are given in Table 1 and the initial removal ratios - in Table 2. These initial ratios are applied at the first stage of designing method. Since environmental limits of chlorides, sulphates and COD are larger than concentrations of these contaminants we have considered only suspended solids and oils as contaminants.

Table 1. Wastewater stream data for the container glass factory case study

Stream number	Flow rate (t/h)	Contaminant concentration (ppm)				
		Suspended solids	Chlorides	Sulphates	Oils	COD
1	5.7	800	150	120	7	100
2	1.2	90	-	-	2	20
3	0.5	500	-	-	-	50

Table 2. Treatment process data for the container glass factory case study

Treatment processes	Removal ratios (%)	
	Suspended solids	Oils
TPI	30	77
TPII	55	25

Due to space limitation we will address here only the design model of the oil trap. General equation (1) represents dependence of removal ratios of solids and oil on parameters of process and apparatus as follows.

$$\begin{bmatrix} r_{SS}^{OT} \\ r_{OL}^{OT} \end{bmatrix} = \begin{bmatrix} f_{SS}\left(\underset{in}{Q}, \underset{in}{C_{SS}}, \xi\right) \\ f_{OL}\left(\underset{in}{Q}, \underset{in}{C_{OL}}, \xi\right) \end{bmatrix}, \tag{1}$$

where r_{SS}, r_{OL} – suspended solids and oils removal ratios, respectively, %; $\underset{in}{Q}$ – inlet treatment flow rate, t/h; $\underset{in}{C_{SS}}$, $\underset{in}{C_{OL}}$ – inlet concentration of suspended solids and oils, ppm. Symbol ξ denotes a set of constructional and operating parameters

$$\xi = \left[V,\ H,\ h_N,\ h_E,\ h,\ \rho_{SS},\ \rho_{OL},\ p_{SS},\ p_{OL},\ k_{OL}, T\right]$$

where V – total volume of oil trap, m^3; H – total height of oil trap, m; h_N, h_E, h – depth of neutral layer, height of edge and depth of settling accordingly, m; ρ_{SS}, ρ_{OL} – density of suspended solids and oils, t/m^3; p_{SS}, p_{OL} – humidity of sediment and floatable oils, %; k_{OL} – portion of emerged oils to total amount of trapped oils; T – wastewater temperature, °C. For oil trap equation (2) defines the decrease of flow rate due to discharge with floatables while removal ratio of oil is defined by (3).

$$\underset{loss}{Q_{OL}} = \frac{k_{OL}\cdot\left(\underset{in}{Q}\cdot\underset{in}{C_{OL}} - \underset{in}{Q}\cdot\underset{out}{C_{OL}} + \underset{loss}{Q_{SS}}\cdot\underset{out}{C_{OL}}\right)}{\rho_{OL}\cdot p_{OL}\cdot 10^{6} - k_{OL}\cdot\underset{out}{C_{OL}}\cdot 10^{4} - \rho_{OL}} \tag{2}$$

$$r_{OL}^{OT} = \frac{\underset{in}{Q}\cdot\underset{in}{C_{OL}} - a\cdot\left(\left(1-0.011\cdot\left(\frac{b}{d}\right)^{0.3}\cdot T^{0.486}\cdot d^{0.8}\right)^{0.9\cdot t}\right)\cdot\underset{in}{C_{OL}}}{\underset{in}{Q}\cdot\underset{in}{C_{OL}}}\cdot 100\%, \tag{3}$$

where

$$a = \frac{b^{3}\cdot\frac{\pi}{3}}{d} + \frac{k_{OL}\cdot\left(\underset{in}{Q}\cdot\underset{in}{C_{OL}} - \left(\left(1-0.011\cdot\left(\frac{b}{d}\right)^{0.3}\cdot T^{0.486}\cdot d^{0.8}\right)^{0.9\cdot t}\right)\cdot\underset{in}{C_{OL}}\cdot\left(\underset{in}{Q}+\frac{b^{3}\cdot\frac{\pi}{3}}{d}\right)\right)}{\rho_{OL}\cdot p_{OL}\cdot 10^{6} - k_{OL}\cdot\underset{out}{C_{OL}}\cdot 10^{4} - \rho_{OL}},$$

$$b = H - \left(h_N + h_E + h\right)$$

$$d = \frac{V}{\underset{in}{Q}}.$$

The optimal network calculated by the developed method is presented in Fig. 1. The value of the goal function for initial centralized network is 14.8 t/h and for optimal one is 12.53 t/h, that is 15% less than for the initial scheme. The solution shows that treatment flow rate through oil trap decreases by 35% and in settler by 15%. Stream redistribution also leads up to removal ratios changes. Suspended solids removal ratio in oil trap for optimal WWTN structure is 34%, and oils removal ratio in TPI is 80% instead initial values of 30% and 77%, respectively. Similarly removal ratio of suspended solids in settler has value of 60% in redistributed network against 55% initially.

It is of importance that the application of the rigorous mathematical models allowed obtaining new accurate values of removal ratios of suspended solids in oil trap and settler and new value of removal ratio for oils in oil trap. Also flow rate losses with sediment from settler and with oils and sediment from oil trap are obtained.

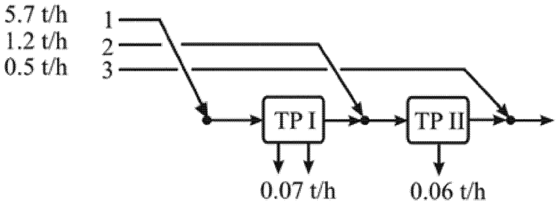

Fig. 1. Final design for glass container factory case study.

5. Summary and conclusions

The approach has been applied to synthesize and retrofit certain wastewater treatment systems of industrial plants. In this contribution we have addressed one case study. The investigations have shown that the wastewater treatment flow rate reduction up to 50% could be achieved for different treatment processes over existing wastewater treatment systems by effluent stream redistribution. The application of mathematical models of treatment processes allows taking into account changes of treatment process removal ratios and flow rates within design procedure. It accounts for losses and gains in particular treatment process and as result for changes in WWTN total flow rate within design procedure.

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