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Mathematical Programming with Water-Oxygen Pinch Analysis in Wastewater Treatment Plant

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Abstract

Water is utilized in various processes in every industries and its outcome is wastewater, which has to be refined qualitatively prior to be recharged to the environment. Water pinch analysis is known as an algorithm to design and rectify the system, which transfers mass within process equipment, and eventually lead to minimization of fresh water demand and optimization of the regenerated water. Furthermore, whilst analyzing Oxygen pinch, the oxygen demand will be considered in order to deal with the wastewater quality. In this paper, we seek to develop a mathematical model based on water pinch analysis in order to optimize wastewater-refining networks so that by considering the impact of multiple restricting pollutants in the network, the wastewater can be minimized and the quality of which can be watched simultaneously. The attempts have been made to solve and improve the wastewater-refining network using GAMS software. The result indicates the prospect of optimal structuring the network in order to reduce the operating costs by 12% in the wastewater treatment plant. In order to credit the proposed case, the density of COD parameter in the process of treatment has been studied. According to the calculation made based on Wang and Smith theories, this parameter has a density of 118.6 ppm. This will confirm the findings based on the proposed case and validate it as an innovative method to refine wastewater in any refinery plant with regard to the reduction in operation cost.

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Keywords: Water Pinch, Oxygen Pinch, Wastewater Treatment Plant, Refinery, GAMS

1. Introduction

In many processes such as petrochemical processes, refinery and chemical, water and energy are two important inputs in the production function, which causes a significant increase in the cost of industries' production. In recent years, new engineering techniques are developed in order to optimize water reechoing and decrease waste production volume, coupled with improved effluent quality, reduce energy consumption and operating costs in the process industry. Quality and quantity of wastewater are directly effective on the intensity of energy consumption for wastewater treatment and relevant operational costs. Pinch technology is based on thermodynamic laws and principles of heat transfer and mass, and is considered as a tool to design optimized process. [1] This technology will improve the design and consumption in water and wastewater treatment plants, with the aim of minimizing waste and operational costs in these processes. Since pinch analysis emphasizes on the quantity of wastewater so it is needed to combine it with another technique to improve the quality as well. [2-5] Therefore, in this study, the combination of oxygen pinch analysis as a modern method to form optimum oxygen in aerobic treatment processes with water pinch technology is proposed. Meanwhile, a comprehensive analysis is developed to manage the cost in wastewater treatment processes with mathematical methods.

In the late seventies AD, pinch analysis was presented as a systematic approach to design and synthesis of heat mass transfer networks in energy section and water consumers. The main reason is to reduce energy consumption. Later it was used to energy conversion efficiency. In 1994, Wang et al expressed the concept of water pinch with a case study. [6] Takama et al. used it in an oil refinery in Beijing, to reduce the existing costs and energy consumption in process. [7] In 2002, Hallale reduced the volume of wastewater through pinch technology and expressed it as a major way to solve the problem. [8] In 2000, Professor Zhilve extended the oxygen pinch analysis to improve the quality of effluent and reduce energy consumption and costs, in wastewater treatment systems. He proved that oxygen pinch analysis can manage costs and minimize the energy consumption in the process. He proposed the combination of these two with

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only one contaminant. [9] Later, there were further studies. In 2006 Song Li-li presented this new method with multiple contaminants. [10] In this study, a mathematical method is improved based on this analysis to optimize wastewater treatment plant and cost with multiple contaminants. The model is illustrated by a case study on a refinery effluent treatment, using GAMS software implementation and is estimated the potential to reduce operational costs.

2. Methodology

2.1. Methods and Material

The aim of this technology is to determine the cost rates and procedures specified in wastewater pollution in the process. Cost factors are related to wastewater treatment and pollution steps, based on effluent quality and quantity. The quantity directly related to the energy level of the required treatment. Water pinch analysis will improve the quantity of wastewater, while oxygen pinch analysis takes care of the quality part. The combination of these technologies provides an opportunity to have a better waste management.

It can be determined which parts need to be refined more and which stream should be bypassed. Water and oxygen pinch analysis is based on the chemical oxygen requirements. Water pinch is investigated on pollutant concentration in ppm², while oxygen is defined with COD³. So the relationship between the two pinch analyses has been determined as COD.

In this case, the first step is to consider the pollutants in two groups. The one that during the purification process, consume oxygen, with the appointment of the coefficient on the tables in scientific books, was converted to the COD and total renal. The others that prefer not to consume oxygen will be observed separately. The final effluent as the COD pollutant from aspects is imported as the main parameter in the model. Furthermore, the ability to convert it to other CODs is not considered as a separate parameter in the model. Finally, the model outputs applied to compare current values. In this paper, the operational cost was studied, and models are presented to make optimal wastewater treatment with a minimum amount of input and increase the quality of effluent.

Savelski and Bagajewicz presented general methods with mathematical programming and conceptual design to optimize water utilization system in process plants with single and multiple

² part per million

³ Chemical Oxygen Demand

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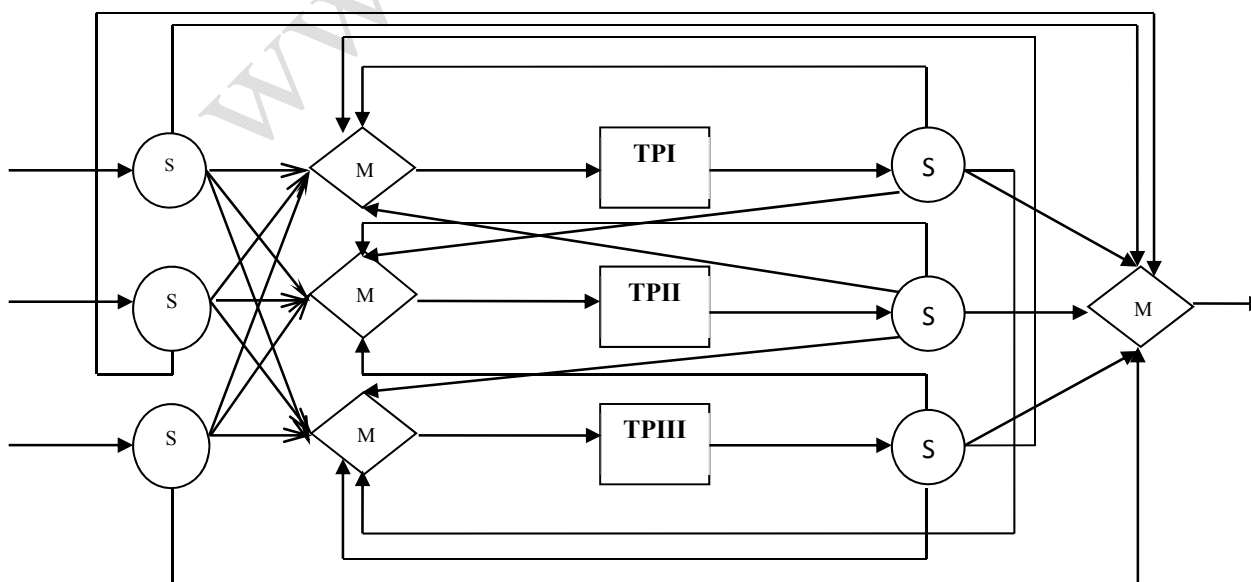


contaminants. In this method, first the minimum flow rate for wastewater has been determined by using graphical ways and then, the desired network is designed using a minimum flow rate and techniques of pinch. [11-12] This method has some limitations for complex systems; while mathematical programming method overcomes it. This has been used to design water and wastewater networks. It will provide the optimized mathematical models with mass balance, allowing analysis, synthesis and modification of existing networks.

2.2. Development and implementation of the model

The conceptual design approach leads to the minimum fresh water requirement, but when multiple contaminants are present, graphical methods are difficult and not accurate to follow, so the mathematical programming methods have been recommended. These methods are effective in optimizing large-scale systems [1, 2, 7, and 8].

The treatment plant is a system, in which wastewater can be treated more than once, including multiple streams and treatment processes. The flow rate to each process has been given, and the removal ratio is constant. To make it easier, first a superstructure is designed. Each stream flows into a splitting node, where it can follow to all the processes. There is a mixing node in front of each, where all streams coming from other operation units are mixed. Another splitting node is after each process to discharge it to the environment. In this case, the concentration of a contaminant must be less than the environmental limit. The superstructure model is shown in Fig.1.



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Fig.1 Superstructure model of wastewater treatment network in a refinery

The mathematical model with its objective function and subjects are shown as the followings:

Objective function:

$$COST = \sum_i \sum_j f_{i,j} \times Cost_i + \sum_i \sum_k X_{i,k} \times Cost_i \quad (1)$$

Subject to:

(1) Mass balance for each effluent stream j:

$$f_{j,in} = \sum_i f_{i,j} + f_{o,j} \quad (2)$$

(2) Mass balance across treatment process i as follows:

$$\sum_j f_{i,j} + \sum_k X_{i,k} = \sum_k X_{i,k} + W_i \quad (3)$$

(3) According to inlet concentration contaminants, the environmental limitation and the removal ratio in process i and j:

$$\sum_j f_{o,j} (C_{j,in}^l - C_e^l) + \sum_i W_i (C_{i,out}^l - C_e^l) \leq 0 \quad (4)$$

(4) In usual manner, rearrange to form a more linear set of constraints;

$$\sum_j f_{i,j} (\bar{C}_{j,in}^l - C_{j,in}^l) + \sum_k X_{i,k} [\bar{C}_{i,in}^l - (1 - r_k^l) \bar{C}_{k,in}^l] = 0 \quad (5)$$

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In order to optimize wastewater treatment network and to develop a non-linear model, these set of equation have been numerically solved by GAMS.

3. Case Study

The data has been collected from a water and wastewater network plant in a refinery and then validated to be employed in the model. In this specific refinery, the water needed to be employed in order to produce steam, electricity and used for other purposes, has been provided from seven wells close to the located refinery.

In the refinery, three units have been implemented to treat the wastewater:

- 1 - Sanitary plant that the disposal of it is used to irrigate of green space in the refinery area
- 2 - API separator that removes oil and grease
- 3- Biological treatment provides an aerobic condition with the injection of oxygen into wastewater treatment

The purpose of this study is to minimize the input of each of the units and to reduce the cost in wastewater treatment plant via increasing the effluent quality. These parameters are included as the discharge flow rate, concentrations of pollutants and other limiting factors of the equipment in the inlet and outlet of the wastewater treatment system in the refinery. The network consists of three effluent wastewater treatment processes, and six pollutants, which are shown in table (1). The removal ratio of each contaminants and operational costs in each process are presented in table (2).

Table 1. Contaminants in wastewater treatment plant

Stream Number	Flow rate $\frac{m^3}{hr}$	Temperature (°C)	Suspended Solid (ppm)	Free Oil (ppm)	COD (ppm)	BOD (ppm)	Total Hardness (ppm)	H ₂ S (ppm)
1	19	25	89	0	145	110	200	0
2	59	25	98	100	100	90	300	62.78
3	152	30.9	99	169.2	460	298	288	117.3

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Table 2. Removal rate of pollutants in each processes and operating cost

Treatment Process	Flow rate $\frac{m^3}{hr}$	Removal Rate (%)						Operation Cost(\$/m ³)
		Suspended Solid	Free Oil	COD	BOD	Total Hardness	H ₂ S	
Sanitary	19	66	0	65	65	00	00	0.6
A.P.I	59	60	70	65	66	36	65	0.2
D.A.F	152	70	72	70	70	42	65	1.2

At this stage, oxygen pinch method was applied. First pollutants were categorized into two groups. The pollutants that were converted to COD during the aeration phase and the ones that do not consume oxygen to be treated and are removed via physical processes. In this regard, those that use oxygen are basically related to aeration rate, dissolved oxygen injection, growth and longevity of microorganisms and used specific coefficients to convert to COD. The results of this conversion has been shown in table (3).

Table 3. COD concentrations in the effluent in a Refinery

Stream Number	Flow rate $\frac{m^3}{hr}$	Suspended Solid (ppm)	Total Hardness (ppm)	COD (ppm)	COD (BOD) (ppm)	COD (Free Oil) (ppm)	COD (H ₂ S) (ppm)	Total COD (ppm)
1	19	1	200	70	49	0	0	119
2	59	20	160	0	0	325.7	0	325.7
3	152	5.5	195	234.4	131.25	508.7	146.48	1020.83

According to the given parameters and data, the superstructure and mathematical model are set up to be the same as the following optimal wastewater treatment network shown in Fig 2.

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According to data presented on the Table (2), operational costs can be calculated as follows:

$$152(1/2) + 59(0/2) + 19(0/6) = 205/6 \text{ \$/h} \quad (6)$$

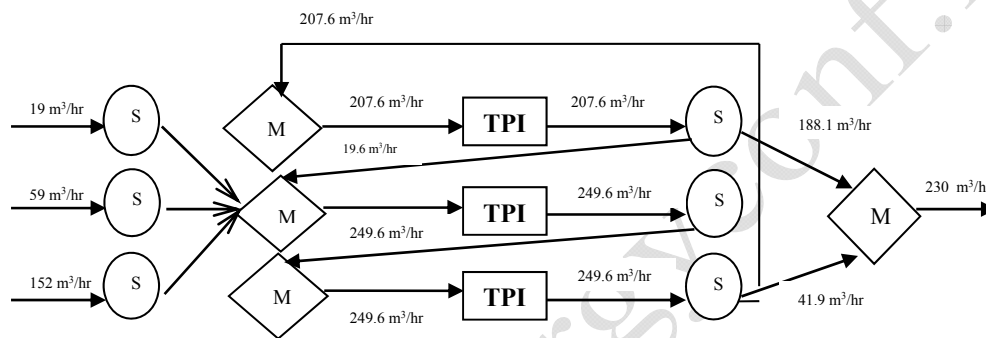


Fig. 3 View of optimized network design wastewater treatment plant in a refinery using a combination of oxygen and water pinch analysis

5. Conclusions

Water-oxygen pinch analysis combined with mathematical programming can set up all possibilities of the network and get the optimal result. Compared with the current operating cost in a refinery, the one is 174/51 \$/hr, which is reduced by 12%. According to the result of water-oxygen pinch analysis, the COD concentration is 118.6 ppm. Due to the Pinch law, all the streams needed to be treated and none of them should be bypassed. As it was obviously indicated in the Fig 2, first, all the streams are required to be treated by the A.P.I separator unit until the remaining oil and grease are completely removed. Then the flow without oil streamed to the biological processes and finally to sanitary section.

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However, in this method, stage of synthesis and programming are also simultaneous. Meanwhile, the fundamentals of this Procedure should be carried out with care. The initial step is to gather related data from the wastewater treatment plant of a refinery and then take care of design, modification and simplification of the final treatment plant. According to the wastewater treatment systems, which had already been designed, only operating cost has been considered in this study. If the wastewater treatment needs to be developed, some new equipment would be required as well. In other words, while operational costs are reducing, more excess capacity is established in the refinery for the future.

Notations

$f_{i,j}$	Wastewater flow rate from effluent stream j to treatment process i
$X_{i,k}$	Wastewater flow rate from treatment process k treated in treatment process i
$\sum_j f_{i,j}$	Total wastewater flow rate treated directly from the effluent streams
$\sum_k X_{i,k}$	Total wastewater flow rate treated in more than one treatment process
$f_{o,j}$	Wastewater flow rate from effluent stream j that bypassed all treatments
$f_{j,in}$	Total wastewater flow rate in j stream
$C_{j,in}^l$	Inlet concentration of contaminant l to treatment process j
$C_{i,out}^l$	Outlet concentration of contaminant l from treatment process i
$C_{k,out}^l$	Outlet concentration of contaminant l from treatment process k
$C_{j,out}^l$	Outlet concentration of contaminant l from treatment process j
C_e^l	Environmental concentration limit for contaminant l
W_i	Wastewater flow rate from treatment process i leaving the network

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