CHEMICAL ENGINEERING TRANSACTIONS

VOL. 89, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-87-7; **ISSN** 2283-9216

DOI: 10.3303/CET2189028

Concentration Fluctuation Penalty for Centralised Reused Water System

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Treated industrial wastewater from different industries can be used for non-potable applications while also reducing conventional water pressures. In recent studies, the penalty for the concentration fluctuation in the centralised reused water system has not been studied. This paper introduces the concentration fluctuation penalty model to identify the effects of penalty on the centralised system's profit using the mathematical modelling method. The General Algebraic Modeling System (GAMS) software is used to solve the nonlinear programming (NLP) model. The penalty is charged based on the treatment cost if the wastewater concentration from the supplier side suddenly exceeds the baseline concentration without prior notice as it would affect the total operating and treatment costs, thereby threatening the profit of the centralised system. Based on the results of the case study, as the wastewater concentration increases, the treatment cost also increases. The profit percentage changes showed that the centralised system could recover the costs by applying the penalty. Without penalty, the centralised system's profit faced losses of more than 15 % in some cases compared to the baseline profit. As a result, it is possible to conclude that penalty is necessary to ensure the participating plants take the responsibility for sudden fluctuations and that the centralised system remains profitable throughout the year.

1. Introduction

A centralised reused water system is a system where wastewaters from different plants are collected and treated in the centralised system before redistributing to the demand plants for reuse applications. The concentration or quality of the wastewater is a very important parameter in a centralised reused water system. Wastewater of poor quality may have a small possibility of being reused due to the numerous treatments required. Only wastewater that meets the quality criteria and has the potential to be recovered would be accepted for reuse. The quality of the wastewater supplied by the industrial plants shall comply with the quality criteria agreed by the participating parties. If the quality specifications exceed the agreed or baseline concentration, the treatment cost of the centralised system would increase.

Although there were a lot of past studies about the mathematical modelling of water integration between plants with the centralised system, the mathematical model regarding concentration fluctuation penalty has not been studied. The penalty is required to handle abrupt changes on the supplier side and this is something that should be addressed. Misrol et al. (2020) suggested a profit-maximising model that included both household and industrial wastewater. Sa'ad et al. (2021) proposed a mathematical model comprising multiple numbers of water reuse header collectors and distributors for wastewater segregation to minimise freshwater consumption. Misrol et al. (2021) introduced a model that utilises wastewater to generate reused water and biogas. These past studies did not address the penalty for the centralised reused water system.

In a biomass supply agreement, the compensation shall be paid by the supplier in the case the quality of biomass does not meet the quality criteria and in the case of a shortfall in the quantity supplied (International Finance Corporation, 2017). The power purchase agreement for one of the power supplies companies in India has proposed a penalty calculation in the event of the seller's delay in supplying power by the scheduled delivery

Paper Received: 19 June 2021; Revised: 14 October 2021; Accepted: 21 November 2021
Please cite this article as: Sa'ad S.F., Wan Alwi S.R., Lim J.S., Abdul Manan Z., 2021, Concentration Fluctuation Penalty for Centralised Reused Water System, Chemical Engineering Transactions, 89, 163-168 DOI:10.3303/CET2189028

date (Tata Power, 2015). The penalty is charged based on the capacity in the contract, the number of days and the penalty amount. The penalty is also charged if the availability is below 80 % of the capacity in the contract. Based on the example of the penalty in the agreements that have been proposed in the biomass and power supplies, the penalty could also be applied for the wastewater supplier of the centralised reused water system. In this paper, the concentration fluctuation penalty model is proposed to study the effects of the concentration fluctuations and the penalty charged on the centralised system's profit. The penalty is charged only when the concentration of the wastewater exceeds the baseline concentration.

2. Methodology

Figure 1 shows the centralised reused water network considering water headers.

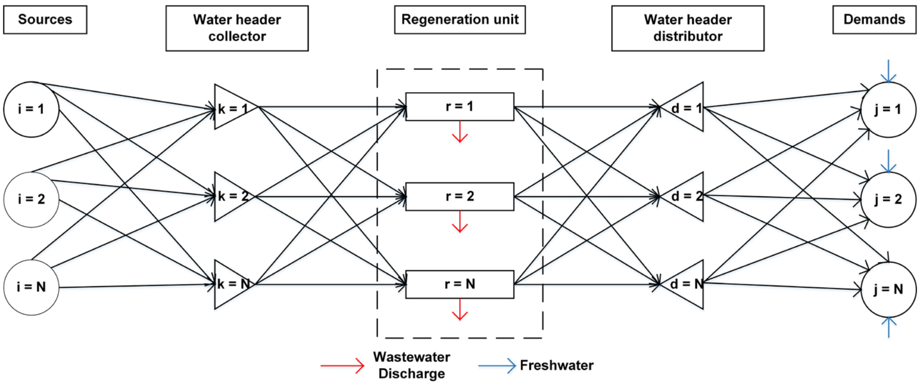

Figure 1: The centralised reused water network

2.1 Mathematical models

Water source is denoted by i, water demand is denoted by j, water header collector is denoted by k, centralised regeneration unit is denoted by r, water header distributor is denoted by d, and contaminant is denoted by m. The italic symbols indicate the variables and the non-italic symbols indicate the parameters. The objective function, as given in Eq(1), is to maximise centralised system's profit by selling reused water. T^{Rev} is the total revenue, T^{OC} is the total operating cost and $T^{penaltyi}$ is the total penalty paid by the sources i.

$$\text{Max } Profit = T^{Rev} - T^{OC} + T^{penaltyi} \quad (1)$$

Eq(2) to Eq(3) are the water source balances. $\mathrm{F^{i}}_{\mathrm{i}}$ is the source's flowrate, $F^{ik}{}_{i,k}$ is the source's flowrate to the water header collector, $\mathrm{C^{i}}_{\mathrm{i,m}}$ is the source's contaminant concentration, and $C^{ik}{}_{i,k,m}$ is the source's contaminant concentration to the water header collector.

$$F^{i}{}_{i} = \sum_k F^{ik}{}_{i,k} \ \forall_i \quad (2)$$

$$F^{i}{}_{i} \times C^{i}{}_{i,m} = \sum_k (F^{ik}{}_{i,k} \times C^{ik}{}_{i,k,m}) \ \forall_{i,m} \quad (3)$$

Eq(4) to Eq(5) are the water header collector balances. $F^{k}{}_{k}$ is the water header collector's flowrate and $C^{k}{}_{k,m}$ is the water header collector's contaminant concentration.

$$F^{k}{}_{k} = \sum_i F^{ik}{}_{i,k} \ \forall_k \quad (4)$$

$$F^{k}{}_{k} \times C^{k}{}_{k,m} = \sum_i (F^{ik}{}_{i,k} \times C^{ik}{}_{i,k,m}) \ \forall_{k,m} \quad (5)$$

Eq(6) to Eq(11) are the regeneration unit balances. $F^{kr}{}_{k,r}$ is the water header collector's flowrate to the regeneration unit, $C^{kr}{}_{k,r,m}$ is the water header collector's contaminant concentration to regeneration unit, $F^{r}{}_{r}$ is the regeneration unit's flowrate, $C^{r}{}_{r,m}$ is the regeneration unit's contaminant concentration, $C^{outr}{}_{r,m}$ is the regeneration unit's outlet contaminant concentration, $\mathrm{RR_{r,m}}$ is the regeneration unit's contaminant removal ratio, and $M^{r}{}_{r,m}$ is the regeneration unit's contaminant mass load removed.

$$\sum_r F^{kr}{}_{k,r} = F^{k}{}_{k} \ \forall_k \quad (6)$$

$$\sum_{r}(F^{kr}{}_{k,r} \text{ x } C^{kr}{}_{k,r,m}) = F^{k}{}_{k} \text{ x } C^{k}{}_{k,m} \ \forall_{k,m} \quad (7)$$

$$F^{r}{}_{r} = \sum_{k} F^{kr}{}_{k,r} \ \forall_{r} \quad (8)$$

$$F^{r}{}_{r} \text{ x } C^{r}{}_{r,m} = \sum_{k}(F^{kr}{}_{k,r} \text{ x } C^{kr}{}_{k,r,m}) \ \forall_{r,m} \quad (9)$$

$$C^{outr}{}_{r,m} = C^{r}{}_{r,m} \text{ x } (1\text{-}RR_{r,m}) \ \forall_{r,m} \quad (10)$$

$$M^{r}{}_{r,m} = [(C^{r}{}_{r,m} - C^{outr}{}_{r,m}) \text{ x } F^{r}{}_{r}]/1{,}000{,}000 \ \forall_{r,m} \quad (11)$$

Eq(12) to Eq(15) are the water header distributor balances. $F^{rd}{}_{r,d}$ is the regeneration unit's flowrate to the water header distributor, $C^{rd}{}_{r,d,m}$ is the regeneration unit's contaminant concentration to the water header distributor, $F^{d}{}_{d}$ is the water header distributor's flowrate, and $C^{d}{}_{d,m}$ is the water header distributor's contaminant concentration.

$$\sum_{d} F^{rd}{}_{r,d} = F^{r}{}_{r} \ \forall_{r} \quad (12)$$

$$\sum_{d}(F^{rd}{}_{r,d} \text{ x } C^{rd}{}_{r,d,m}) = F^{r}{}_{r} \text{ x } C^{outr}{}_{r,m} \ \forall_{r,m} \quad (13)$$

$$F^{d}{}_{d} = \sum_{r} F^{rd}{}_{r,d} \ \forall_{d} \quad (14)$$

$$F^{d}{}_{d} \text{ x } C^{d}{}_{d,m} = \sum_{r}(F^{rd}{}_{r,d} \text{ x } C^{rd}{}_{r,d,m}) \ \forall_{d,m} \quad (15)$$

Eq(16) to Eq(20) are the water demand balances. $F^{dj}{}_{d,j}$ is the water header distributor's flowrate to the demand plant, $F^{FW}{}_{j}$ is the freshwater flowrate, $F^{j}{}_{j}$ is the demand's required flowrate, $F^{djbaseline}{}_{d,j}$ is the water header distributor's baseline flowrate to the demand plant, C^{FW} is the freshwater contaminant concentration, and $C^{j}{}_{j,m}$ is the demand's required contaminant concentration.

$$\sum_{j} F^{dj}{}_{d,j} \leq F^{d}{}_{d} \ \forall_{d} \quad (16)$$

$$\sum_{j}(F^{dj}{}_{d,j} \text{ x } C^{d}{}_{d,m}) \leq F^{d}{}_{d} \text{ x } C^{d}{}_{d,m} \ \forall_{d,m} \quad (17)$$

$$F^{FW}{}_{j} + \sum_{d} F^{dj}{}_{d,j} = F^{j}{}_{j} \ \forall_{j} \quad (18)$$

$$(F^{FW}{}_{j} \text{ x } C^{FW}) + \sum_{d}(F^{dj}{}_{d,j} \text{ x } C^{d}{}_{d,m}) \leq F^{j}{}_{j} \text{ x } C^{j}{}_{j,m} \ \forall_{j,m} \quad (19)$$

$$F^{dj}{}_{d,j} \leq F^{djbaseline}{}_{d,j} \text{ x } P^{dj}{}_{d,j} \ \forall_{d,j} \quad (20)$$

Eq(21) to Eq(24) are the determination of pipes. Q is a huge positive integer. $P^{ik}{}_{i,k}$, $P^{kr}{}_{k,r}$, $P^{rd}{}_{r,d}$, $P^{dj}{}_{d,j}$ are the binary parameters.

$$F^{ik}{}_{i,k} \leq Q \text{ x } P^{ik}{}_{i,k} \ \forall_{i,k} \quad (21)$$

$$F^{kr}{}_{k,r} \leq Q \text{ x } P^{kr}{}_{k,r} \ \forall_{k,r} \quad (22)$$

$$F^{rd}{}_{r,d} \leq Q \text{ x } P^{rd}{}_{r,d} \ \forall_{r,d} \quad (23)$$

$$F^{dj}{}_{d,j} \leq Q \text{ x } P^{dj}{}_{d,j} \ \forall_{d,j} \quad (24)$$

Eq(25) is the total revenue equation. OH^{hr} is the fluctuation's operating hours and $SP^{rw}{}_{d}$ is the selling price of reused water.

$$T^{Rev} = OH^{hr} \text{ x } \sum_{d,j}[(F^{dj}{}_{d,j}/1{,}000) \text{ x } SP^{rw}{}_{d}] \quad (25)$$

Eq(26) to Eq(28) are the total operating cost equation. T^{OCpump} and T^{OCreg} are the total operating costs of pump and regeneration unit. T^{PCpump} is the total consumption of electricity for pumping, OC^{Elec} is the operational cost of electricity, and $OC^{reg}{}_{r,m}$ is the operational cost of treatment.

$$T^{OC} = T^{OCpump} + T^{OCreg} \quad (26)$$

$$T^{OCpump} = OH^{hr} \times T^{PCpump} \times OC^{Elec} \quad (27)$$

$$T^{OCreg} = OH^{hr} \times \sum_{r,m}(M^{r}{}_{r,m} \times OC^{reg}{}_{r,m}) \quad (28)$$

Eq(29) is the equation of the total penalty paid by the sources to the centralised system. $M^{penaltyi}$ is the mass to be penalized and $P^{penaltyi}{}_{i,m}$ is the penalty rate.

$$T^{penaltyi} = \sum_{i,m}(M^{penaltyi}{}_{i,m} \times P^{penaltyi}{}_{i,m}) \times OH^{hr} \quad (29)$$

Eq(30) is the equation of the amount of mass to be penalized. $C^{ibaseline}{}_{i,m}$ is the source's baseline concentration.

$$M^{penaltyi}{}_{i,m} = [(C^{i}{}_{i,m} - C^{ibaseline}{}_{i,m}) \times F^{i}{}_{i}]/1{,}000{,}000 \ \forall_{i,m} \quad (30)$$

3. Case study

Table 1 shows the baseline data of the centralised reused water system with different plants and two contaminants concentration, total suspended solids (TSS) and chemical oxygen demand (COD). The data were the modification of the data from Yu et al. (2013). In this work, the wastewaters were segregated into three qualities, which were low, medium and high quality. Three qualities of reused water were regenerated with low-quality wastewater produced low-quality reused water and vice versa. Table 2 shows the concentration fluctuation data from the source side with seven different cases. Cases 1 to 3 represent concentration fluctuation in one plant, Cases 4 to 6 for two different plants, and Case 7 for three different plants.

Table 1: The baseline data

Sources					Demands				
Plant	Number	Flowrate (m^3/h)	Concentration (ppm) TSS	COD	Plant	Number	Flowrate (m^3/h)	Concentration (ppm) TSS	COD
A	1	10.42	45	80	A	1	10.42	10	40
	2	14.58	70	120		2	41.67	20	50
	3	12.50	100	350		3	6.25	30	65
B	4	20.83	50	75	B	4	33.33	10	40
	5	37.50	65	110		5	83.33	20	50
	6	35.42	100	300		6	8.33	30	65
C	7	12.50	50	80	C	7	16.67	10	40
	8	17.50	60	110		8	54.17	20	50
	9	18.75	110	350		9	4.17	30	65

Table 2: The concentration fluctuation cases

Case	Plant	Number	Concentration of source (ppm) TSS	COD
1	A	1	60	100
2	B	6	130	400
3	C	8	80	140
4	A	1	60	100
	B	6	130	400
5	A	1	60	100
	C	8	80	140
6	B	6	130	400
	C	8	80	140
7	A	1	60	100
	B	6	130	400
	C	8	80	140

The penalty is charged based on the treatment cost of each quality of reused water produced. The operating hours of the fluctuation that occurred is assumed 24 h or one day. The selling price of the reused water is the subsidisation from the freshwater price, with 10 % for high-quality reused water, 15 % for medium-quality reused water, and 20 % for low-quality reused water. The average freshwater price is 0.75 USD/m^3 (SPAN, 2017) and the electricity price is 0.084 USD/kWh (TNB, 2014).

4. Results and discussion

GAMS software with the CONOPT solver is used to solve the NLP model (GAMS, 2016). Table 3 shows the economic results with and without penalty charge, and are being compared with the baseline results. The baseline results were based on the baseline data in Table 1. Figure 2 shows the profit percentage changes of the fluctuation cases from the baseline. The negative percentage changes show that the profits were lesser than the baseline profit and vice versa. For all cases, freshwater required was 78.34 m^3/h, the total revenue was 2,733 USD/d, and the total pumping cost was 63 USD/d. These three variables were unaffected by the concentration fluctuation because the centralised system produced the same concentration of reused water as the baseline case. The distribution reused water network of the other fluctuation cases was the same as the baseline optimal centralised reused water network as shown in Figure 3.
Based on the results in Table 3, the total operating and regenerating costs increased from the baseline because the centralised system required more treatment to produce the same concentration of reused water as the baseline case. The total penalty varies in each case because it depends on the mass to be penalized and also the treatment cost as the penalty rate. The total profits for the fluctuation cases with penalty charge were not much different from the baseline as the penalty could cover the extra costs required to treat the water. The profit percentage changes with penalty were most likely less than 1 % as shown in Figure 2. For the cases without the penalty charge, the profits were significantly decreased with some cases have percentage changes of more than 15 % and faced losses. According to the findings, the regeneration and operating costs increased in conjunction with the wastewater concentration from the source side, resulting in a profit reduction. The penalty is required to cover the extra costs and avoid major losses.

Table 3: The economic results with and without penalty

Case	Total operating cost (USD/d)	Total regenerating cost (USD/d)	Total penalty (USD/d)	Total profit (USD/d)	
				With penalty	Without penalty
Baseline	1,510	1,447	-	1,223	1,223
1	1,522	1,459	14	1,225	1,211
2	1,732	1,669	220	1,221	1,001
3	1,539	1,476	29	1,223	1,194
4	1,755	1,692	234	1,212	978
5	1,553	1,490	43	1,223	1,180
6	1,762	1,699	249	1,220	971
7	1,774	1,711	263	1,222	959

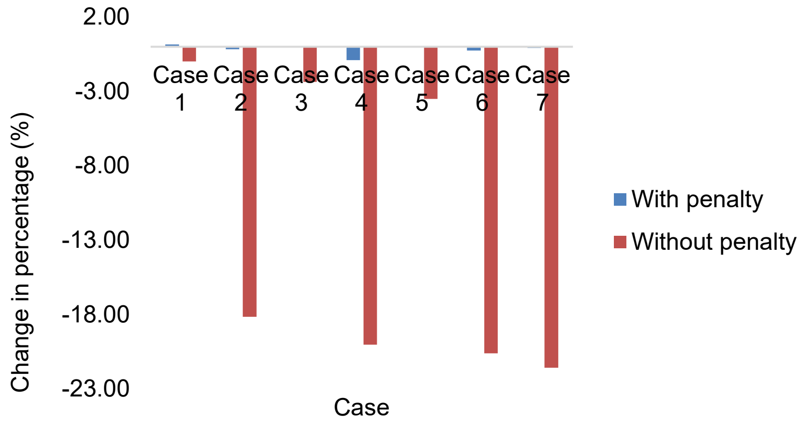

Figure 2: The profit percentage changes of the fluctuation cases from the baseline

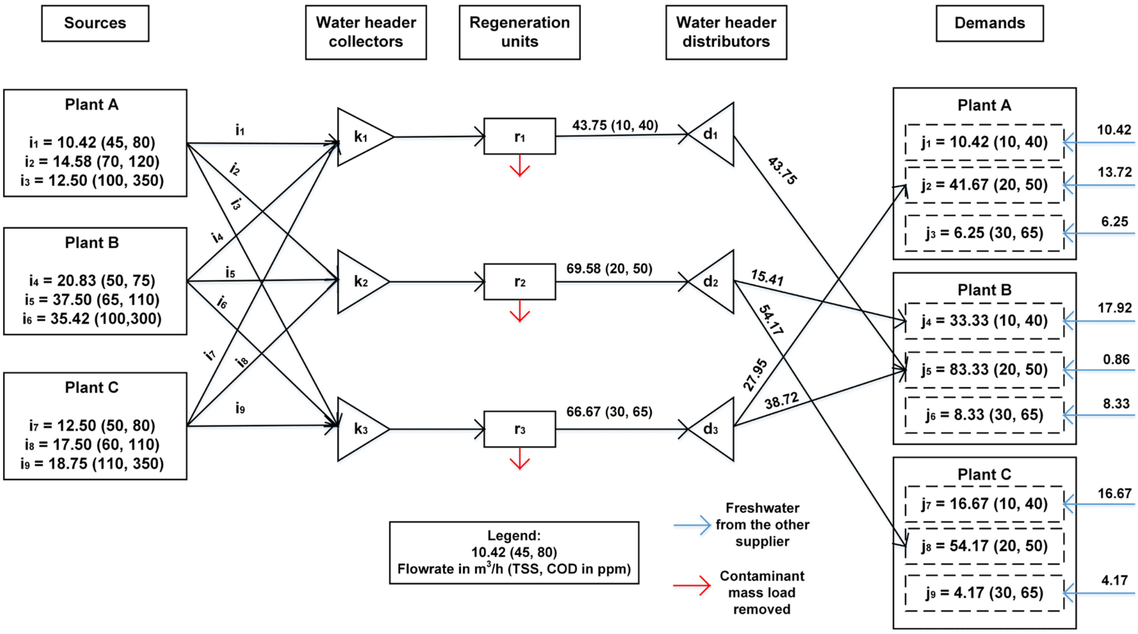

Figure 3: Optimal centralised reused water network of the baseline case

5. Conclusions

As the wastewater concentration increases, the treatment cost and total operating cost increase, resulting in a loss of profit for the centralised system. From the case study, the losses could be more than 15 % if the penalty is not charged, consequently, the centralised system's profit is jeopardised. By applying a penalty on the respective participating plant, the increase in the treatment cost could be recovered and at the same time, the profit could be maintained. In conclusion, to minimise substantial losses to the centralised system, a penalty should be applied if a sudden fluctuation occurs without prior notice.

Acknowledgments

The authors are grateful to Universiti Teknologi Malaysia (UTM) for financially supporting this research project via the Vote Number Q.J130000.2409.08G86, Q.J130000.3509.05G94, Q.J130000.3509.05G96 and Q.J130000.3551.05G97.

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