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Optimization of Water Network in a Viscose Fiber Plant

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In the production process of viscose staple fiber, a large amount of freshwater, steam and desalinated water will be consumed, and a large amount of acidic and alkaline wastewater will be generated, bringing great pressure on water resource and environmental protection. In this paper, the water using system of a viscose staple fiber plant in northwestern China is studied. The key constraints for water using in this system are pH, oxygen demand (COD) and suspended solid (SS). Since pH and COD are non-conserved quantities, their constraints are property-based. So, the optimization of the water network needs to be carried out from both conventional water system integration and property integration. In this paper, the Mathematical Programming method is used to solve the optimization problem. By analyzing the various constraints and taking the corresponding integration methods, the mathematical model is constructed to target the minimum freshwater flowrate, the minimum regenerated water flowrate and relevant parameters. The optimized network can reduce the freshwater consumption 93.1 m^3 /h and the wastewater discharge 131 m^3/h, achieving obvious water-saving and emission reduction effects.

1. Introduction

In the total industrial water consumption, water consumed in the textile industry accounts for a large proportion. Viscose fiber industry, an important part of the textile industry, consumes a large amount of freshwater and discharge a large amount of acidic and alkaline wastewater, bringing great pressure on water resource and environmental protection.

Water system integration can effectively reduce freshwater consumption and wastewater discharge. It has been successfully applied in many industrial fields, but there is no application in the viscose fiber industry.

There are two main methods for water system integration: graphical approach and mathematical programming. Since mathematical programming is suitable for multi-contaminant systems, it is used to optimize the water system of a viscose fiber plant in this paper.

In the process of viscose fiber production, the key constraints for water reuse are suspended solid(SS), chemical oxygen demand (COD) and pH. Among the three parameters, the SS is a conventional concentration constraint, while the latter two are non-conserved parameters, forcing the two to be considered by property integration.

Property integration is a common problem in the optimization of industrial water systems. Many mathematical models have been proposed to solve this problem. Jiménez-Gutiérrez et al. (2014) presented a model for the synthesis of water networks with a simultaneous integration of energy, mass and properties. Sotelo-Pichardo et al. (2014) reported a Mathematical Programming model of property-based water network targeting for the optimal cost. Li et al. (2018) carried out a general mathematical model to solve integration problems, involving property integration. Deng et al. (2018) proposed a superstructure of property-based water system integration consisting of water utility, water-using and water treatment sub-systems.

This paper focused on a viscose staple fiber plant in northwest China. The spinning and refining workshop is the main production process for viscose staple plants, consuming large amounts of freshwater and generating large amounts of wastewater. The water network of the spinning and refining workshop with seven units is optimized in this paper. The operational cost is adopted as the objective function. The commercial software GAMS is used to solve the problem.

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2. The current water network

2.1 Structure of water network

The current water network is shown in Figure.1. There are seven water using units in the network, namely fiber cutter, fiber feeder, scouring pool, first stage washing, second stage washing, third stage washing and fourth stage washing. The main types of water involved are primary water, soft water, steam and steam condensate. Steam is consumed in other unit of the plant and cannot be replaced. The generated steam condensate is partially delivered to the fourth bath unit. Thus the water network of Figure.1 does not contain steam but contains steam condensate. Because the water quality of the steam condensate is basically the same as the soft water quality, the steam condensate can be replaced by soft water and it is treated as soft water in Figure.1.
It consumes soft water 235 m³/h, including steam condensate. Meanwhile, it sends 235 m³/h wastewater to the regeneration units.

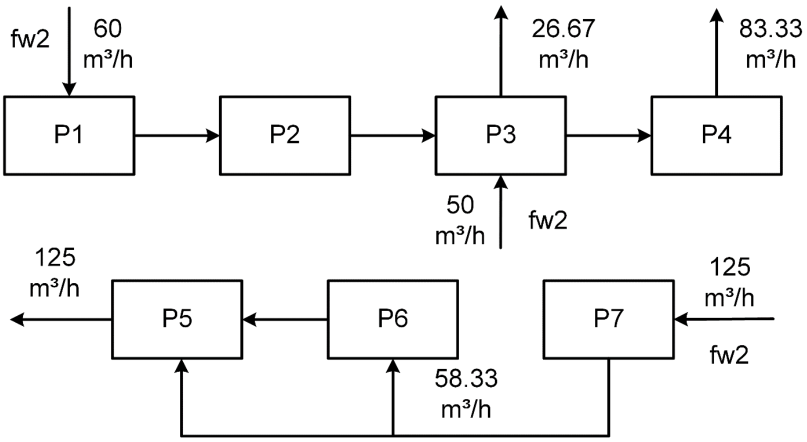

Figure 1: Current water system of the viscose staple fiber plant

2.2 Limiting data

There are two types of freshwater sources used in this viscose staple fiber plant, the primary water and the soft water. The primary water is obtained by simple treatment of groundwater, and the soft water is obtained by treating primary water through reverse osmosis (RO) and mixed beds. Data of the two water sources are shown in Table 1, including the concentration, the property and the cost. The limiting data of the seven units are shown in Table 2, including the limiting inlet data, the limiting outlet data and the mass load.

Table 1: Limiting data and cost of water sources

Water source	No	SS (mg/L)	pH	COD (mg/L)	Cost (USD/m³)
Primary water	fw1	30	7	30	0.15
Soft water	fw2	5	7	15	0.49

Table 2: Limiting data in each unit

Unit	No	Inlet data			Outlet data			Mass Load (SS)/(kg/h)
		SS/ (mg/L)	pH	COD/ (mg/L)	SS/ (mg/L)	pH	COD/ (mg/L)	
Fiber cutter	p1	5	6.8-8.5	15	200	6	300	11.7
Fiber feeder	p2	300	5-7.0	500	400	4.5	1,200	6
Scouring pool	p3	50	6.8-8.5	100	400	4	1,200	17.5
First bath	p4	400	3.0-7.0	1,200	600	2	1,800	16.67
Second bath	p5	300	6.8-9	1,500	400	12	1,600	12.5
Third bath	p6	200	6.8-8.5	800	300	9	1,000	5.83
Fourth bath	p7	5	6.8-8.5	15	50	7.5	100	5.63

3. Water network optimization

3.1 Superstructure

In the current water network, regenerated water is not used in this workshop. However, there is a wastewater treatment workshop in this plant, and wastewater can be treated into two kinds of regenerated water. Water quality data of the regenerated water are shown in Table 3. When considering the economic factors and water utilization factors, using regenerated water could make the water network more reasonable. It should be pointed out that the first-stage regenerated water is produced after further treatment on the second-stage regenerated water.

The superstructure of the water network with regeneration recycling is shown in Figure. 2. For each water-using unit, the inlet streams may include freshwater, outlet water from other water-using units and regenerated water from regeneration units, and the outlet water could be sent to other water-using units, to regeneration unit Rt2 and directly discharged.

For regeneration units, the inlet streams of Rt2 are outlet streams of each water-using unit, and the outlet stream may send to water-using units and Rt1 with water loss. The inlet stream of Rt1 is the regenerated water from Rt2, and the outlet stream may send to water-using units with water loss.

Table 3: Limiting data of regenerated water

Regenerated water	No	SS (mg/L)	pH	COD (mg/L)	Production rate (%)	Cost (USD/m³)
First-stage regenerated water	Rt1	5	7	15	55	0.67
Second-stage regenerated water	Rt2	70	7	100	80	0.24

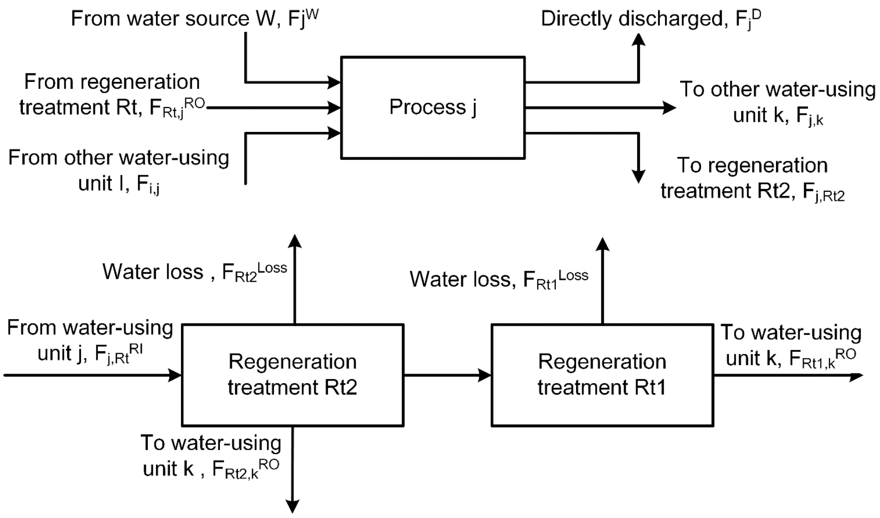

Figure 2: The superstructure of the water system

3.2 Mathematical model

3.2.1 Objective function

In this paper, the operational cost is taken as the objective function, which is the sum of the cost of all water sources and the cost of all discharge.

$$Min \sum_{W \in fw} \left(Cost_W \cdot \sum_{j \in P} F_j^W \right) + Cost_D \cdot \sum_{W} \sum_{j \in P} F_j^W \tag{1}$$

In the model, the water loss of regeneration units is treated as a discharge, and the discharge cost is 0.3 USD/m³. The constraints of the water network can be divided into two categories, namely, process constraints and property constraints. The former constrain the flowrate and mass of the water network, and the latter constrain the property of the water network.

The process constraints can be obtained based on the superstructure in Figure 2, shown as follows. The total flowrate balance of water-using unit j is:

$$\sum_{W\in fw} F_j^W + \sum_{\substack{i\in P\\ i\neq j}} F_{i,j} + \sum_{Rt\in T} F_{Rt,j}^{RO} = F_j^D + \sum_{\substack{k\in P\\ k\neq j}} F_{j,k} + F_{j,Rt\,2}^{RI} \tag{2}$$

The inlet mass balance of water-using unit j is

$$\sum_{W\in fw}\left(F_j^W\cdot C_s^W\right) + \sum_{\substack{i\in P\\ i\neq j}}\left(F_{i,j}\cdot C_{i,s}^{Out}\right) + \sum_{Rt\in T}\left(F_{Rt,j}^{RO}\cdot C_{Rt,s}^{Out}\right) = \left(\sum_{W\in fw} F_j^W + \sum_{\substack{i\in P\\ i\neq j}} F_{i,j} + \sum_{Rt\in T} F_{Rt,j}^{RO}\right)\cdot C_{j,s}^{In} \tag{3}$$

The total mass balance of water-using unit j is

$$\left(\sum_{W\in fw} F_j^W + \sum_{\substack{i\in P\\ i\neq j}} F_{i,j} + \sum_{Rt\in T} F_{Rt,j}^{RO}\right)\cdot C_{j,s}^{In} + M_{j,s} = \left(\sum_{W\in fw} F_j^W + \sum_{\substack{i\in P\\ i\neq j}} F_{i,j} + \sum_{Rt\in T} F_{Rt,j}^{RO}\right)\cdot C_{j,s}^{Out} \tag{4}$$

Limits for concentrations of water-using unit j are

$$C_{j,s}^{In} \le C_{j,s}^{In,Max} \tag{5}$$

$$C_{j,s}^{Out} \le C_{j,s}^{Out,Max} \tag{6}$$

The total flowrate balance of regeneration unit Rt is

$$\sum_{j\in P} F_{j,Rt}^{RI} + \sum_{Rm\in T} F_{Rm,Rt}^{RI} = \sum_{j\in P} F_{Rt,j}^{RO} + \sum_{Rn\in T} F_{Rt,Rn}^{RO} + F_{Rt}^{Loss} \tag{7}$$

The inlet mass balance of regeneration unit Rt is

$$\sum_{j\in P}\left(F_{j,Rt}^{RI}\cdot C_{j,s}^{Out}\right) + \sum_{Rm\in T}\left(F_{Rm,Rt}^{RI}\cdot C_{Rm,s}^{Out}\right) = \left(\sum_{j\in P} F_{j,Rt}^{RI} + \sum_{Rm\in T} F_{Rm,Rt}^{RI}\right)\cdot C_{Rt,s}^{In} \tag{8}$$

Constraints of properties are as follows.
The inlet property constraint of water-using unit j is

$$\sum_{W\in fw}\left(F_j^W\cdot\Psi_p\left(p_{W,p}\right)\right) + \sum_{\substack{i\in P\\ i\neq j}}\left(F_{i,j}\cdot\Psi_p\left(p_{i,p}^{Out}\right)\right) + \sum_{Rt\in T}\left(F_{Rt,j}^{RO}\cdot\Psi_p\left(p_{Rt,p}^{Out}\right)\right) = \left(\sum_{W\in fw} F_j^W + \sum_{\substack{i\in P\\ i\neq j}} F_{i,j} + \sum_{Rt\in T} F_{Rt,j}^{RO}\right)\cdot\Psi_{j,p}^{In} \tag{9}$$

Limit for property operator and property of water-using unit j are

$$p_{j,p}^{\min} \le p_{j,p} \le p_{j,p}^{\max} \tag{10}$$

$$\Psi_{j,p}^{\min} \le \Psi_{j,p} \le \Psi_{j,p}^{\max} \tag{11}$$

The inlet property constraint of regeneration unit Rt is

$$\sum_{j\in P}\left(F_{j,Rt}^{RI}\cdot\Psi_P\left(p_{j,p}^{Out}\right)\right) + \sum_{Rm}\left(F_{Rm,Rt}^{RI}\cdot\Psi_P\left(p_{Rm,p}^{Out}\right)\right) = \left(\sum_{j\in P} F_{j,Rt}^{RI} + \sum_{Rm} F_{Rm,Rt}^{RI}\right)\cdot\Psi_P\left(p_{Rt,p}^{In}\right) \tag{12}$$

The symbols used in these equations have the following meanings. F, C, p and Ψ mean the flowrate, concentration, property and property operator, respectively. The subscripts fw, i, j, k, P, Rt, Rm and Rn mean freshwater source fw, water-using unit i, water-using unit j, water-using unit k, set of water-using units, regeneration unit Rt, regeneration unit Rm and regeneration unit Rn, respectively. The superscripts W, In, Out, RI, RO, D and Loss mean set of freshwater sources, inlet of water-using unit, outlet of water-using unit, inlet of regeneration unit, outlet of regeneration unit, discharge and water loss, respectively. For the subscript of the symbol F separates two units by a comma, it means that water is transported from the previous unit to the latter unit. The subscript of the symbol C indicates the unit and the contaminant, separated by commas. The subscript of the symbol p indicates the unit and the property, separated by commas.

4. Optimization results

In this paper, the commercial software GAMS is used to program and solve this model by the solver BARON. The final result is shown in Tables 4 and 5. The optimal water network is shown in Figure 3.
Compared with the current network, the optimized network reduces the soft water consumption of unit P7 121 m^3/h and increases the primary water consumption of unit P2 40 m^3/h. Normally, producing 1m^3 soft water consumes 1.1 m^3 primary water. After conversion to primary water, the new network could reduce 93.1 m^3/h water.
The optimized water network can effectively reduce the freshwater consumption and the cost of the water system. When calculating the cost of water network, the freshwater production cost, the two stages regenerated water production cost and the wastewater discharge cost are considered. The operational cost of the optimized water network is 135.26 USD/h, reduced by 56.5 USD/h. In the optimized water network, it will consume primary water 40 m^3/h, soft water 64 m^3/h, first-stage regenerated water 20 m^3/h, and second-stage regenerated water 121 m^3/h. There is 104 m^3/h water discharged and 245 m^3/h wastewater is to be regenerated. The utilization rate of regenerated water of the optimized water network reaches 57.55 %. Compared with the current water network, the optimized network reduces 131 m^3/h water discharge.

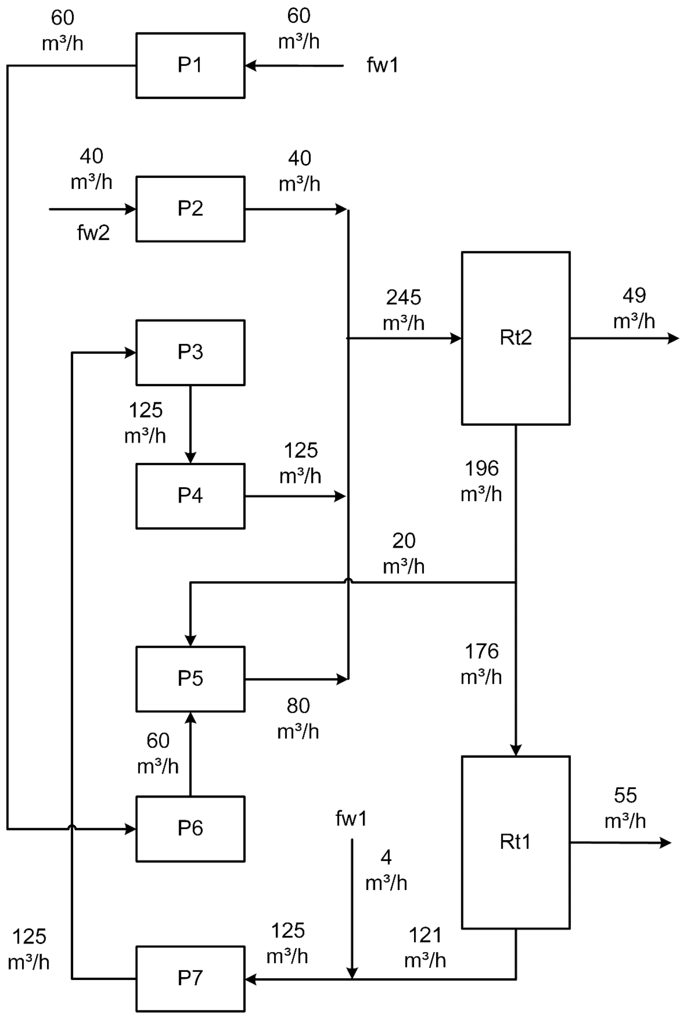

Figure 3: The optimal water network

Table 4: Contaminant data of the optimal water network

Indicator	Inlet							Outlet						
	p1	p2	p3	p4	p5	p6	p7	p1	p2	p3	p4	p5	p6	p7
SS (mg/L)	5	30	50	190	240.42	200	5	200	180	190	323.33	396.67	297.22	50
COD (mg/L)	15	30	100	540	395.83	300	15	300	1080	540	940	552.08	494.44	100
pH	7	7	7.5	4	8.9	6	7	6	4.5	4	2	12	9	7.5

Table 5: Flowrate data of the optimal water network

	p1	p2	p3	p4	p5	p6	p7
freshwater	fw1=60	fw2=40					fw1=4
from water-using unit			F7,3=125	F3,4=125	F6,5=60	F1,6=60	
from regeneration unit					FRt2,5=20		FRt1,7=121
discharge							
to water-using unit	F1,6=60		F3,4=125			F6,5=60	F7,3=125
to regeneration unit		F2,Rt2=40		F4,Rt2=125	F5,Rt2=80		

5. Conclusions

In this paper, the water system of the spinning and refining process in a viscose staple fiber plant was optimized by mathematical programming method with operational cost as the objective function. Since the limiting key parameters in this system are SS, COD and pH, the mathematical model was built based on the property integration, and the optimal water network with two stages regeneration recycling was determined in this paper. The freshwater saving rate reached 34.55%, the wastewater discharge reduced 55.74 %, and the operational cost reduced 29.47 %.

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