CHEMICAL ENGINEERING TRANSACTIONS

VOL. 72, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jeng Shiun Lim, Azizul Azri Mustaffa, Nur Nabila Abdul Hamid, Jiří Jaromír Klemeš

ISBN 978-88-95608-69-3; **ISSN** 2283-9216

DOI: 10.3303/CET1972050

Design of Interplant Water Network of Multiple Contaminants with an Interplant Water Main

Xuelei Wang, Xiaoyan Fan, Zhi-Yong Liu*

School of Chemical Engineering and Technology, Hebei University of Technology, Tianjin 300130, China
liuzhiyong@hebut.edu.cn

Compared to integration of water networks of a few plants separately, the integration of interplant water network can save more freshwater. This paper proposed an iterative method for design of interplant water network of multiple contaminants with an interplant water main by using the Concentration Potential Concepts. The key for design procedure of an interplant water network is to classify all processes into two groups based on reusing the water of the interplant water main or not. Then the design can be simplified into a design of a conventional single plant water integration with a central water main. An example is shown that the design procedure is simple and effective.

1. Introduction

Water is an important resource in industrial production. How to reduce the consumption of freshwater and the discharge of wastewater has become one of the hot research issues nowadays (Samanaseh et al. 2017). Water system integration is one of the most effective methods for reducing freshwater consumption and wastewater emission. Compared to the water networks of a few plants designed separately, the interplant water network can further reduce freshwater consumption and wastewater discharge. The research methods for the interplant water networks can be summarized as pinch-based analysis and mathematical programming methods.

Olesen and Polley (1996) proposed a pinch point analysis method based on the fixed load model of interplant water network. Bandyopadhyay et al. (2010) presented a generalized decomposition technique to solve segregated targeting problems through pinch analysis. Recently, Ahmad Fadzil A.F. et al. (2017) presented a new Pinch Analysis methodology to reduce both freshwater consumption and wastewater discharge in the integration of plants with centralised water reuse headers. The pinch-type methods are generally only applicable to single contaminant water networks, while the mathematical programming methods are more effective. Chew and Foo (2009) extended the automatic targeting technology of single plant water network to interplant water network. Lim and Park (2010) proposed a nonlinear programming model to reduce freshwater consumption. Aviso (2014) proposed a robust optimization approach which could effectively operate under various possible circumstances. Alnouri et al. (2014) introduced pipeline merging approaches for a given arrangement of plants amongst water allocation, transmission, and distribution within an industrial zone. Jia et al. (2015) proposed an interplant integration considering water supply constraint and water price. Liu et al. (2017) developed an optimization mathematical model for multi-period concern and achieved the optimal network configurations and water management plans.

Water main can simplify the structure of water network and improve the controllability and flexibility of the system (Ma et al., 2007). In addition, interplant water main in an interplant water network can reduce pipeline costs, because geographical distances between different plants are normally larger than the distances within individual plants (Chen et al., 2010). In order to simplify the pipeline connection, Chen et al. (2010) set up a central and decentralized water main for connecting the water unit. Lee et al. (2014) applied water main to interplant network that mixed continuous and batch modes to minimize the freshwater consumption.

This paper designs an interplant water network of multiple contaminants with an interplant water main based on the Concentration Potential method proposed by Liu et al. (2009). The interplant water main collects and re-allocates water to the individual plants. The application of this method is illustrated by an example.

Paper Received: 18 April 2018; Revised: 18 September 2018; Accepted: 15 November 2018

Please cite this article as: Wang X., Fan X., Liu Z.-Y., 2019, Design of interplant water network of multiple contaminants with an interplant water main, Chemical Engineering Transactions, 72, 295-300 DOI:10.3303/CET1972050

2. Design procedure

The method proposed for interplant water networks includes four steps: (1) Calculate the CPD value of each process, and arrange all processes in ascending order. Divide all processes into two groups, reusing the water of interplant water main or not, and the processes that not require the interplant water main can be performed, simultaneously. (2) After performing the processes not reusing the water of interplant water main, the total amount of other processes can be used to estimate the initial amount of the interplant water main; (3) The group reusing the water of interplant water main can be performed; (4) Adjust the initial amount of the interplant water main to make the difference between the initial amount and the usage amount of the interplant water main less than the minimal value ε (in this article, ε is taken as 0.1t/h), and the final design is obtained. The design procedure is shown in Figure 1.

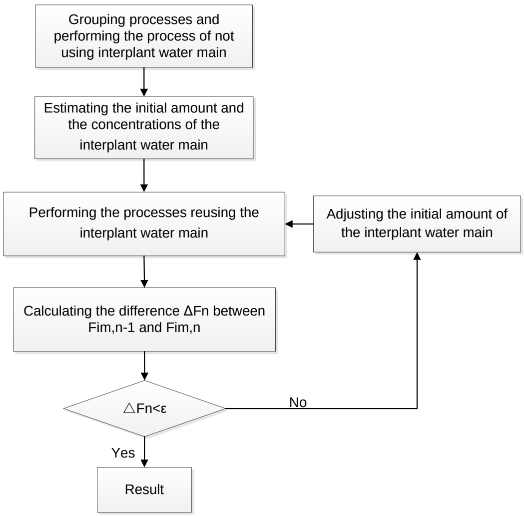

Figure 1: Design procedure

2.1 Grouping processes and performing the processes not reusing the interplant water main

The Concentration Potential method is used to determine whether the processes reuse the water of interplant water main. Detailed method as follow:

(1) The CPDs of all processes can be calculated according to the limiting concentrations (Liu et al., 2009), as shown in Eq(1). Based on the value of CPDs, all processes can be arranged in ascending order. $R_{i,j}$ is virtual allocation rate, as shown in Eq(2), which represents the maximum allocation ratio of the source S_i reused to the demand D_j.

$$CPD(D_j) = \sum_{i=1}^{NS} \min_{k=1,2...NC} \left\lfloor \frac{C_{D_j,k}^{\lim}}{C_{i,k}^{\lim,out}} \right. \quad (1)$$

$$R_{i,j} = \min_{k=1,2...NC} \left. \frac{C_{D_j,k}^{\lim}}{C_{S_i,k}} \right\rfloor \quad (2)$$

where $C_{D_j,k}^{lim}$ is the limiting concentration of contaminant k in demand Dj; $C_{D_i,k}^{lim,out}$ is the limiting outlet concentration of contaminant k in process i; NS and NC is the number of the source streams and the contaminants; $C_{S_i,k}$ is the concentration of contaminant k in source Si.

(2) Process with minimum CPD value is performed first. When a demand stream is satisfied by source streams, the source stream with largest $R_{i,j}$ value will be considered. If the demand stream and the source stream with largest $R_{i,j}$ value are in the same plant, the process of the demand stream is classified into the processes not reusing the water of the interplant water main, and the demand stream can be satisfied by the source stream with largest $R_{i,j}$ value. Otherwise the process of the demand stream is classified into the processes reusing the water of the interplant water main. In this way, all processes can be divided into two groups: the processes not reusing the water of interplant water main, and the ones reusing the water of interplant water main. If a source stream is used up, it will not be considered in the next design.

The allocation amount can be calculated as follow:
When a source stream is sufficient, there are two situations.
When $R_{i,j}<1$, the demand stream is satisfied by freshwater and in-plant source stream (or interplant water main). The reuse amount $F_{i,j}$ ($F_{m,j}$) of source stream (or interplant water main) and the amount $F_{f,j}$ of freshwater can be calculated by Eq(3) and (4).

$$F_{i,j} = F_{D_j}^{\max} \quad R_{i\ j} \tag{3}$$

$$F_{f,j} = F_{D_j}^{\max} \quad F_{i\ j} \tag{4}$$

where $F_{D_j}^{\max}$ is the largest amount of the demand stream D_j.

When $R_{i,j} \geq 1$, freshwater is not required. The reuse amount $F_{i,j}$ ($F_{m,j}$) of source stream can be obtained from Eq(5).

$$F_{i,j} = \max_{k=1,2...NC}[\frac{M_{j,k}}{C_{j,k}^{\lim,out} - \quad _{S_i\ k}}] \tag{5}$$

where $M_{j,k}$ is the mass load of contaminant k in process j;
When the source stream is insufficient, the source stream is completely reused. The remaining concentration of demand stream can be calculated based on the remainder of maximum flowrate and mass loads. The remainder maximum flowrate can be calculated by subtracting the reuse amount of the source from the maximum flowrate of the demand. Similarly, the remainder mass loads can be obtained according to mass balance. Then another source with the largest $R_{i,j}$ value in the same plant should be reused. (Liu et al., 2009)
(3) The outlet stream of the performed process can be taken as a source stream to satisfy the downstream demands. Return to step (2), until all processes not reusing the water of interplant water main are performed.

2.2 Estimating the initial amount and the concentrations of the interplant water main

(1) The values of concentration potential of sources (CPSs), as shown in Eq(6), are used to determine the order of the sources allocated to the interplant water main. The sources can be listed in ascending order based on their CPS values.

$$CPS(S_i) = \sum_{j=1}^{ND} \frac{1}{R_{i,j}} \tag{6}$$

where ND is the number of demand streams.
(2) The initial amount of the interplant water main can be estimated by Eq(7).

$$_{im,0} = \alpha F_{total} \tag{7}$$

where α is taken as 40 % in this paper; F_{total} is the total amount of the processes reusing the water of interplant water main.
The sources with lower CPS values will constitute the interplant water main. The initial concentrations of interplant water main can be calculated by mass balance.

2.3 Performing the processes reusing the interplant water main

(1) The allocation amount can be calculated by Eqs(3-5). The usage amount of the interplant water main $F_{im,n}$ can be obtained from Eq(8)

$$F_{im\ n} = \sum_j \quad _{m,j} \tag{8}$$

where n is the iteration number.
(2) The difference ΔF_n between the initial amount and usage amount of the interplant water main can be obtained from Eq(9).

$$F_n = F_{im,n-1} - F_{im,n} \tag{9}$$

where $F_{im,n-1}$ is the initial amount of the interplant water main; $F_{im,n}$ is the usage amount of the interplant water main.

2.4 Adjusting the initial amount of the interplant water main

If the difference exceeds the allowable value ε, the usage amount of the interplant water main is used as the initial amount of interplant water main for the next iteration. The sources with lower CPS values will reconstitute the interplant water main. Return to the step of 2.3 until the difference is within the allowable range.

3. Case study

The examples of Wang et al. (2003); Feng et al. (2008); Wang and Smith (1994) consist of plants 1-3, with the data shown in Table 1.

Table 1: Limiting process data for plants 1-3

Plant	Process	$C^{max,in}$ (ppm)			$C^{max,out}$ (ppm)			M (kg/h)			F^{max}
		A	B	C	A	B	C	A	B	C	(t/h)
1	1	0	0	0	100	90	50	3	2.7	1.5	30
	2	0	0	0	50	70	70	0.8	1.12	1.12	16
	3	40	60	20	150	80	70	8.25	1.5	3.75	75
	4	30	40	70	160	100	90	2.73	1.26	0.42	21
	5	110	135	60	210	200	120	2.9	1.885	1.74	29
	6	0	0	0	80	70	80	5.2	4.55	5.2	65
	7	100	75	20	300	290	170	12.2	13.115	9.15	61
	8	90	50	34	210	170	100	6.84	6.84	3.762	57
2	9	0	0	0	110	120	100	3.85	4.2	3.5	35
	10	200	170	150	350	400	210	6	9.2	2.4	40
	11	90	130	100	150	180	210	2.4	2	4.4	40
	12	110	80	150	210	150	220	3	2.1	2.1	30
	13	260	200	180	350	320	310	2.7	3.6	3.9	30
	14	340	350	400	800	1,100	1,000	29.44	48	38.4	64
	15	950	850	900	1,500	2,100	1,800	27.5	62.5	45	50
3	16	150	700	800	900	4,500	3,000	22.5	114	66	30
	17	20	300	45	120	12,500	180	3.4	414.8	4.59	34
	18	120	20	200	220	45	9,500	5.6	1.4	520.8	56

3.1 Step 1 Grouping processes and performing the processes not reusing the interplant water main

The values of CPDs of all processes are listed in Table 2. Since the CPDs of processes 1, 2, 6 and 9 is 0, it means that only freshwater can be used. The amounts of freshwater are 30 t/h, 16 t/h, 65 t/h, and 35 t/h.

Table 2: Order of CPD values

Process	1,2,6,9	17	18	3	7	4	8	5	12	11	16	10	13	14	15
CPD	0	1.97	2.11	2.49	2.52	2.88	4.01	7.25	7.98	8.22	14.76	14.90	18.05	30.33	78.58

According to the order of CPD values, P_{17} should be performed then. But the source that can provide the maximum value of $R_{i,17}$ is S_2, not in plant 3. Therefore, P_{17} cannot be performed by S_2, which classified into the group reusing the water of interplant water main. The same situation appears for P_{18}. Next, for P_3, S_1 can provide the largest value of $R_{i,3}$, besides S_1 and P_3 are in the same plant. Therefore, P_3 belongs to the group not reusing the water of interplant water main, and the reuse amount of S_1 is 30t/h from Eq(3), and the consumption of freshwater is 45 t/h from Eq(4). P_7 and P_4 are similar with P_3.For P_8, S_4 can provide the largest value of $R_{i,8}$, meanwhile, S_4 and P_8 are in the same plant. Therefore, P_8 belongs to the group not reusing the water of interplant water main. The reuse amount of S_4 is 28.5 t/h from Eq(3), however, the amount of S_4 is just 21 t/h. S_4 will be used up. Then the source stream S_3 with second largest $R_{i,8}$ in the plant 1 should be considered. The 9.69 t/h of S_3 is reused, and the consumption of freshwater is 26.31 t/h. P_5 is similar with P_8.
The other processes are same as P_{17}. The group that not reusing the water of interplant water main includes processes 1-9, and the reusing amount of the sources are shown in Table 3. The CPS values of the current available sources are listed in Table 4. The remainder processes 10-18 belong to the group reusing water of interplant water main and will be satisfied by the interplant water main.

Table 3: The reusing amount of the sources

Performing Oder	Allocation	Amount (t/h)	Allocation	Amount (t/h)	Freshwater (t/h)
D_3	(S_1, D_3)	30	-	-	45
D_7	(S_3, D_7)	17.43	-	-	43.57
D_4	(S_2, D_4)	12	-	-	9
D_8	(S_4, D_8)	21	(S_3, D_8)	9.69	26.31
D_5	(S_2, D_5)	4	(S_3, D_5)	19.93	5.07

Table 4: CPS order of available source streams

Source	S_6	S_9	S_3	S_8	S_5	S_7
CPS	0.041	0.061	0.069	0.096	0.097	0.12

3.2 Step 2 Estimating the initial amount and the concentrations of the interplant water main

The initial amount of the interplant water main is 149.6 t/h from Eq(7). According to Table 4, S_6 (65 t/h), S_9 (35 t/h), S_3 (27.95 t/h) and part of S_8 (21.65 t/h) form the interplant water main. The initial interplant water main concentration is (118.03, 93.03, 85.70) ppm.

3.3 Step 3 Performing the processes reusing the interplant water main

According to the virtual allocation rate, P_{10} need not freshwater, and the consumption of interplant water main is 29.97 t/h from Eq(5). P_{11} need freshwater. The allocation amount of the interplant water main is 30.50 t/h from Eq(3), and the consumption of freshwater is 9.50 t/h from Eq(4). The unperformed processes will be performed as P_{10} and P_{11}. The usage amount of the interplant water main $F_{im,1}$ is 229.04 t/h from Eq(8). The difference ΔF_1 is -79.44 t/h from Eq(9).

3.4 Step 4 Adjusting the initial amount of the interplant water main

Because of $\Delta F_1 > \varepsilon$, the amount of 229.04 t/h will be taken as the initial amount of the interplant water main. S_6 (65 t/h), S_9 (35 t/h), S_3 (27.95 t/h), S_8 (57 t/h), S_5 (29 t/h) and part of S_7 (15.09 t/h) form the interplant water main, and the second iterative will be carried out as discussed above. After fifth iteration, ΔF_5 is $-0.01 < \varepsilon$ t/h and the final design can be obtained, as shown in Figure 2. The total freshwater consumption is 374.38 t/h. The in-plant connections are 30, and the cross-plant connections are 15.

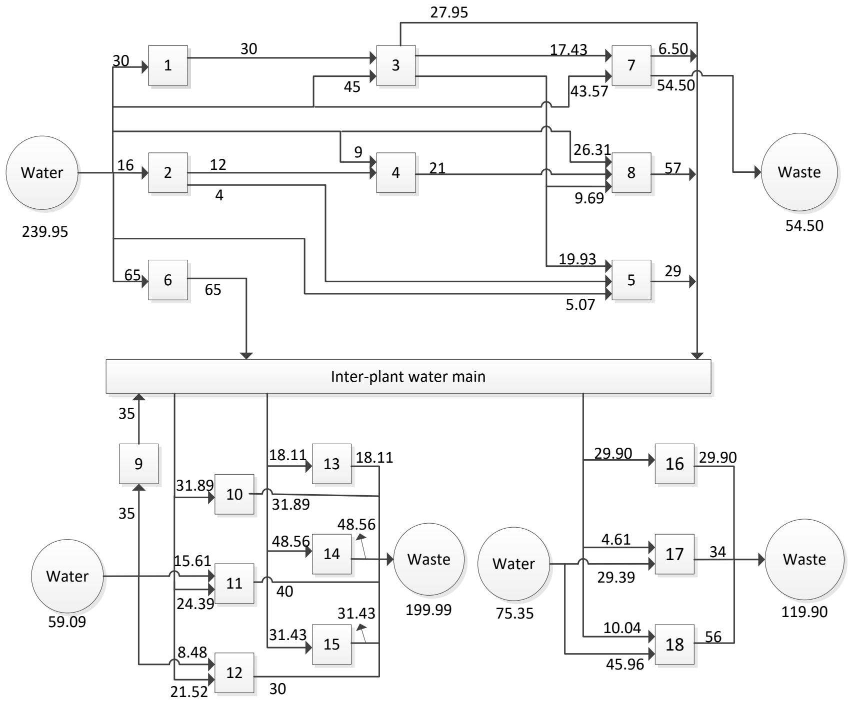

Figure 2: Design result (t/h)

If the three plants are designed separately based on the Concentration Potential method, the freshwater consumptions are 77.02 t/h, 239.95 t/h, and 113.34 t/h for plants 1-3, with the total amount of 430.31 t/h. It can be seen that freshwater consumption can be reduced by 13.00 % with the interplant water main structure.

4. Conclusions

This paper extends the application of Concentration Potential methods to the design of interplant water networks. According to the design method, a complicated interplant water network can be obtained by hand calculation. This design uses an interplant water main to connect all cross-plant water streams, which not only increases the flexibility of the system but also makes the interplant water network more economical and practical. The results show that interplant water integration can reduce the consumption of freshwater, compared to integration of water networks of a few plants separately.

References

Ahmad Fadzil A.F., Wan Alwi S.R., Abdul Manan Z., Klemeš J.J., 2017, Total Site Centralised Water Integration for Efficient Industrial Site Water Minimisation, Chemical Engineering Transactions, 61, 325–330.

Alnouri S.Y., Linke P., El-Halwagi M., 2014, Optimal interplant water networks for industrial zones: addressing interconnectivity options through pipeline merging, AIChE J., 60(8), 2853–2874.

Aviso K.B., 2014, Design of robust water exchange networks for eco-industrial symbiosis, Process Safety Environmental Protecttion, 92(2), 160–70.

Bandyopadhyay S., Sahu G.C., Foo D.C.Y., Tan R.R., 2010, Segregated targeting for multiple resource networks using decomposition algorithm, AIChE Journal, 56(5), 1235–1248.

Chew I.M.L., Foo D.C.Y., 2009, Automated targeting for interplant water integration, Chemical Engineering Journal, 153(1-3), 23–36.

Chen C.L., Hung S.W., Lee J.Y., 2010, Design of interplant water network with central and decentralized water mains, Computers and Chemical Engineering, 34, 1522–31.

Feng X., Shen R.J., Yu X.J., 2008, Optimization of regeneration recycling water networks with internal water mains, Journal of Chemistry Industry & Engineering, 59, 2046–2051.

Jia X., Li Z., Wang F., Chen C.L., Foo D.C.Y., 2015, Interplant Water Integration with Considerations of Water Supply Constraint and Differential Water Price, Chemical Engineering Transactions, 45, 139–144.

Lee J.Y., Chen C.L., Lin C.Y., Foo D.C.Y., 2014, A two-stage approach for the synthesis of interplant water networks involving continuous and batch units, Chemical Engineering Research and Design, 92, 941–953.

Lim S.R., Park J.M., 2010, Inter-factory and intrafactory water network system to remodel a conventional industrial park to a green eco-industrial park, Industrial and Engineering Chemistry Research, 49(3), 1351–1358.

Liu L.L., Wang J., Song H.D., Du J., Yang F.L., 2017, Multi-period water network management for industrial parks considering predictable variations, Computers and Chemical Engineering 104 (2017), 172–184.

Liu Z.Y., Yang Y., Wan L.Z., Wang X., Hou K.H., 2009, A heuristic design procedure for water-using networks with multiple contaminants, AIChE Journal 55, 374–382.

Ma H., Feng X., Cao K., 2007, A rule-based design methodology for water networks with internal water mains, Transactions of the Institute of Chemical Engineers, 85(4), 431–444.

Samanaseh V., Noor Z.Zainon., Hassan C.H.C., Sabeen A.H., 2017, Water-Energy-Nexus in Water Supply: A Case Study on Greenhouse Gases Emissions Trends of a Water Utility Company in Johor, Malaysia, Chemical Engineering Transactions, 56, 1711–1716

Olesen S.G., Polley G.T., 1996, Dealing with plant geography and piping constraints in water network design, Transactions of the Institute of Chemical Engineers, 74(B4), 273–276.

Wang B., Feng X., Zhang Z., 2003, A design methodology for multiple-contaminant water networks with single internal water main, Computers and Chemical Engineering, 27(7), 903–911.

Wang Y.P., Smith, R., 1994. Wastewater minimization, Chemical Engineering Science, 49, 981–1006.