CHEMICAL ENGINEERING TRANSACTIONS
VOL. 45, 2015
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216 DOI: 10.3303/CET1545091

Retrofitting of Water-Using Networks with Multiple Contaminants by Adding Regeneration Unit

Xiao-Yan Fan, Zhi-Yong Liu*

Hebei University of Technology, Tianjin, China
liuzhiyong@hebut.edu.cn

To reduce fresh water consumption and/or meet stricter environmental regulations, the existing water network needs to be retrofitted. This paper presents a design procedure to retrofit existing water network by adding regeneration units. In the retrofitting, the following issues are considered: (1) how to select suitable source streams to regenerate; (2) how to determine the flow rate of regenerated stream. The retrofitting procedure is simple and the final design could be obtained by manual calculation. The results of the example illustrate that the method proposed can provide very good retrofit design for water-using networks. The retrofit results are economic and environmental friendly.

1. Introduction

Recently, the severe shortage of fresh water is threatening human beings (Malin and Aaron, 2014). At the same time, water resource is polluting by harmful bacteria and other industrial pollutants (Galbraith, 2015). To reduce consumption of fresh water, an effective way is to retrofit the existing water-using networks. Generally, there are two main methods to retrofit the water networks, one is Pinch Analysis method, and another is mathematical programming approach.

Pinch Analysis approach is an insight-based method that the fresh water consumption target can be determined before retrofitting. Khor et al. (2012) retrofitted a petroleum refinery water network with Pinch Analysis. The desired frameworks were developed by water reuse, regeneration and recycle opportunities. Shenoy and Shenoy (2014) targeted and designed bio-ethanol networks by Unified Targeting Algorithm, which is a kind of Pinch Approach. The retrofitting cases showed that nearly 94 % savings could be generated. Mamdouh (2015) constructed a new graphical method to analyze heat recovery systems in a water network. The existing water networks were analyzed by the Pinch approach and 40 % of cooling water could be saved.

Another practical method to retrofit the water networks is mathematical programming method. A superstructure is established first, and then the mathematical programming approaches are used to solve the mathematical models developed based on the superstructure to obtain the retrofitting design. Tokos et al. (2012) retrofitted a large-scale water system by integrating water-using operations and wastewater treatment units. The mixed-integer nonlinear programming model was used for water reuse and regeneration reuse. Reddy et al. (2013) reduced operating and capital costs for closed-loop water systems. The retrofitting design was obtained by mixed-integer linear programming models. Poplewski (2014) optimized flexible water networks by theorem of corner points. The design with minimal consumption of fresh water in all possible production situations could be obtained.

In this paper, we present a new retrofit technique for water-using networks with multiple contaminants by adding new regeneration units. In the existing network, the suitable streams will be selected to regenerate, and then the regenerated stream will be reused in the system. The final design can be obtained by several times of iterative calculation.

Please cite this article as: Fan X.-Y., Liu Z.-Y., 2015, Retrofitting of water-using networks with multiple contaminants by adding regeneration unit, Chemical Engineering Transactions, 45, 541-546 DOI:10.3303/CET1545091

2. Basic design methodology

In 2009, Liu et al (2009a) proposed the methodology concepts of Concentration Potential to determine the concentration order of the streams with multiple contaminants. The value of Concentration Potential of a Demand (CPD) reflects the possibility of the demand stream reusing the source streams. Correspondingly, the value of Concentration Potential of a Source (CPS) reflects the possibility of the source stream to be reused by the demand streams. To design the water-using networks with multiple contaminants, the precedence order of the processes is determined by CPDs values (Liu et al., 2009a). The definitions of CPD(D_j) and CPS(S_i) are as follows:

$$CPD(D_j) = \sum_{i=1}^{NS} \min_{k=1,2,\cdots,NC} \left[\frac{C_{Dj,k}^{\lim}}{C_{Si,k}^{\lim}} \right] \tag{1}$$

$$CPS(S_i) = \frac{1}{\sum_{j=1}^{ND} \min_{k=1,2,\cdots,NC} \left[\frac{C_{Dj,k}^{\lim}}{C_{Si,k}^{\lim}} \right]} \tag{2}$$

where $C_{Dj,k}^{\lim}$ is the limited concentration of contaminant *k* in demand stream D_j, $C_{Si,k}^{\lim}$ is the limited concentration of contaminant *k* in source stream S_i, NS is the number of the source streams, ND is the number of the demand streams, and NC is the number of the contaminants.

3. Retrofitting method

The retrofit design will be carried out based on the existing water network by adding a regeneration unit in the existing network. In the existing network, the un-reused streams will be selected for regeneration, and then the regenerated stream will be reused in the network as a source stream. However, the flow rate and concentrations of the regenerated stream are unknown before the final design obtained (Pan et al., 2012). So, an initial regenerated stream should be estimated and the stream will be added in the existing network to form the network involving regeneration (Liu et al., 2009b). The final retrofitting design will be obtained by iteration calculation. The retrofit procedure is shown in Figure 1.

3.1 Selecting suitable streams for regeneration

Generally speaking, the lower the concentrations of the stream to be regenerated, the lower the regeneration cost. Therefore, the un-reused streams in the existing network with lower concentrations should be selected to regenerate. For a multiple contaminant system, the streams to be regenerated will be selected by ascending order of their CPS values, because the CPS values can reflect the possibility of the source stream to be reused as discussed above.

3.2 Iterative calculation

To start the calculation, the initial regenerated flow rate and concentrations should be estimated first. After the first iteration, the flow rate and concentrations of the regenerated stream can be determined with the results of the last iteration. When the relative differences of both regenerated flow rate and concentrations in two adjacent iterations are lower than 0.1 %, the iteration can be finished.

The initial values of regenerated flow rate and concentrations can be obtained as follows:

a) The initial flow rate of the regenerated stream: the sum of the flow rate of all the un-reused streams, which are discharged directly in the existing water network, will be the initial flow rate of the regenerated stream;

b) The initial concentrations of the stream before regeneration can be obtained from the mixing concentrations of discharged streams in the existing water network;

c) The initial regenerated concentrations: the concentrations can be calculated with Eq(3):

$$C_{out,k} = C_{in,k} \times (1-RR_k) \tag{3}$$

where $C_{out,k}$ is the concentration of contaminant *k* in the regenerated stream, $C_{in,k}$ is the concentration of contaminant *k* in the stream to be regenerated, and RR_k is the removal ratio of the regeneration unit for contaminant *k*.

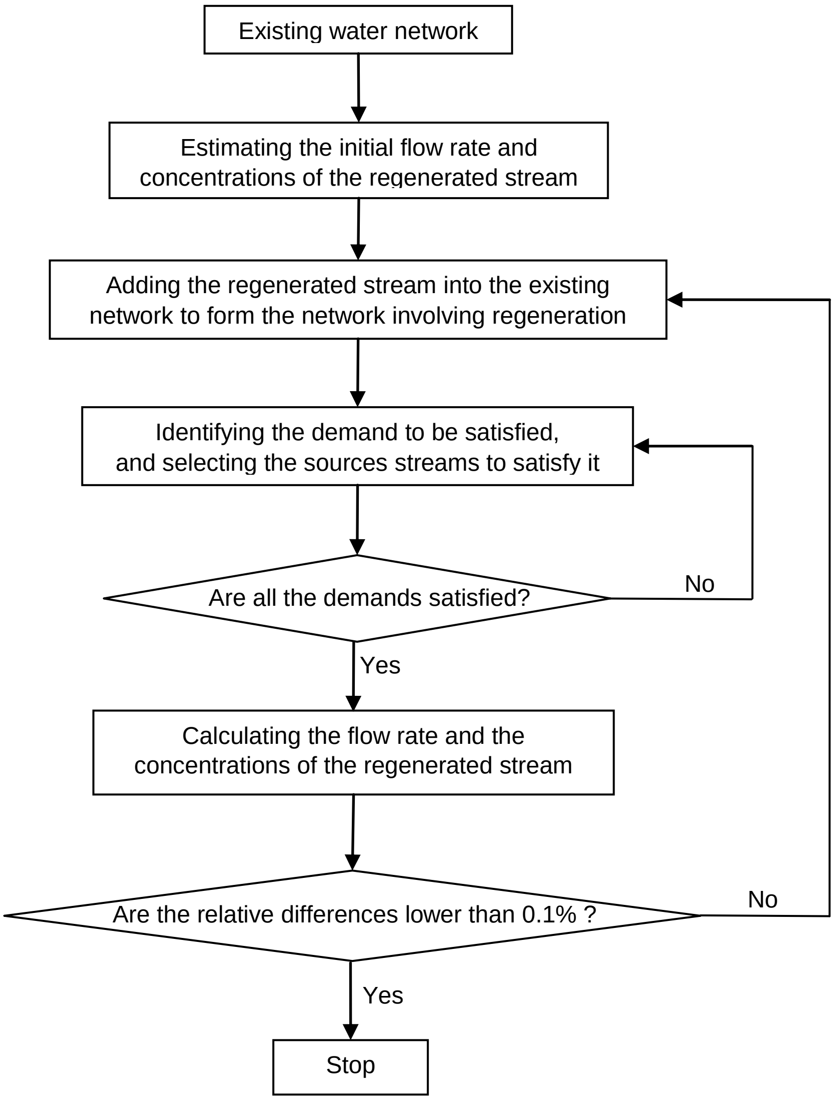

Figure 1: The retrofit procedure proposed

4. Case study

This example is taken from Sotelo-Pichardo (2011), with two contaminants in the system, which are phenol and acetone. The existing network is shown in Figure 2. Table 1 shows the data of the source streams, where C_{phenol} is the mass fraction of phenol, $C_{acetone}$ is the mass fraction of acetone. F^{lim} is the limiting flow rate of the source streams. The cost of fresh water is listed in the last column of Table 1. Table 2 shows the concentration constraints of the demand streams.

Table 1: The data of source streams

	C_{phenol} (kg/kg total)	$C_{acetone}$ (kg/kg total)	F^{lim} (kg/h)	Cost ($/kg)
S_1	0.016	0.000	3,666	--
S_2	0.024	0.010	1,769	--
S_3	0.220	0.028	1,488	--
Fre_1	0.000	0.000	∞	1.3×10^{-3}
Fre_2	0.012	0.005	∞	0.88×10^{-3}

Table 2: The constraints of demand streams

	C_{phenol} (kg/kg total)	$C_{acetone}$ (kg/kg total)	F^{lim} (kg/h)
D_1	0.015	0.015	2,722
D_2	0.100	0.010	1,129
D_3	0.015	0.020	1,996

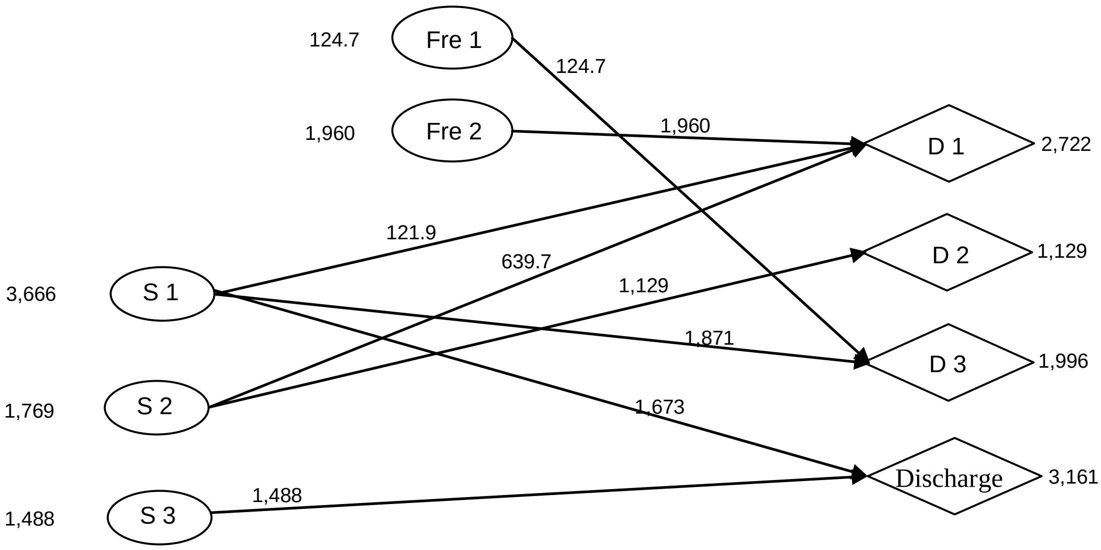

Figure 2: The existing network for the example. The numbers are the flow rates of the streams (kg/h).

Phenol is considered as a toxic component. In the existing network, the discharged mass fraction is 0.112 kg/kg for phenol, and 0.013 kg/kg for acetone. The new environmental regulation requires that both the mass fraction of phenol and acetone should be lower than 0.005 kg/kg. To meet the new discharged standard, the regeneration units should be installed to retrofit the existing network. There are three available regeneration units. The parameters of the regeneration units are listed in Table 3.

Table 3: Parameters for regeneration unit

Regeneration	Reg 1	Reg 2	Reg 3
RR (phenol)	0.94	0.00	0.80
(acetone)	0.00	1.00	0.82
Installation fixed cost (N=1) 0≤flow rate≤3,187	10,470	8,022	21,456
Installation fixed cost (N=2) 3,188≤flow rate≤6,374	14,655	11,229	25,876
Installation fixed cost (N=3) 6,375≤flow rate≤9,561	17,046	13,062	28,976
Installation variable cost (N=1)	9.03	6.92	15.97
Installation variable cost (N=2)	6.69	5.13	13.76
Installation variable cost (N=3)	6.02	4.61	11.82
Unitary operational cost, $/Kg	0.7×10^{-3}	0.4×10^{-3}	0.9×10^{-3}

The retrofitting procedure can be carried out as follows:

To determine the initial values of the regenerated stream, the total flow rate of the un-reused source streams, S_1 and S_3, 3,161 kg/h, is taken as the initial flow rate of regenerated stream. The initial concentrations of the stream before regeneration are (0.112, 0.013) kg/kg, which is the mixing concentration of S_1 and S_3. The initial regenerated concentrations are related to RR values of the

regeneration units. There are three regeneration units available. However, it is found that only the concentrations of the regenerated stream of Reg1 are low enough for reusing. Therefore, regeneration unit 1 should be added to the existing network. The initial regenerated concentrations are (0.00672, 0.0132) kg/kg.
To determine the performing order and reusing order, the CPD and CPS values should be calculated. D_1, D_3, D_2 should be satisfied in turn as the ascending order of their CPD values. S_1, S_2, S_3 should be reused in turn as the ascending order of their CPS values. The regenerated stream S_{reg1} with concentration of (0.00672, 0.0132) kg/kg should be added to the system as a source stream. When the regenerated stream is reused for a demand stream, the consumption of fresh water can be reduced.
To satisfy D_1, S_1 and S_{reg1} can be reused. From mass balance, it can be seen that the reused amount of S_1 and S_{reg1} are 2,428 kg/h and 293.2 kg/h.
To satisfy D_3, S_1, S_2 and S_{reg1} should be reused. The flow rates are 1,238 kg/h of S_1, 291.3 kg/h of S_2 and 46.25 kg/h of S_{reg1}.
To satisfy D_2, S_2 should be reused only, and the consumption of S_2 is 1,129 kg/h.
The remainder of the source streams S_2 and S_3 should be discharged. To satisfy the discharged standard, the source stream should be treated further. The regeneration unit 1 and 3 are selected, because the outlet stream of them can meet the environmental regulations. According to the regulations mentioned above, 174.6 kg/h of S_2 and 1,487 kg/h of S_3 should be mixed and regenerated by unit 1 and 3,173 kg/h of S_2 should be discharged directly.
In sum, the required amount of regenerated stream is 1,662 kg/h, which could be taken as the regenerated stream amount for the next iteration. For the second iteration, the un-reused stream should be selected by ascending order of their CPS values to form the regenerated streams, which are 174.6 kg/h of S_2 and 1,487 kg/h of S_3. Add the regenerated stream to the system, and satisfy the demand streams. Repeat the calculation similarly as mentioned above until the relative differences of the two adjacent is lower than 0.1%. The retrofit design could be obtained, as shown in Figure 3.

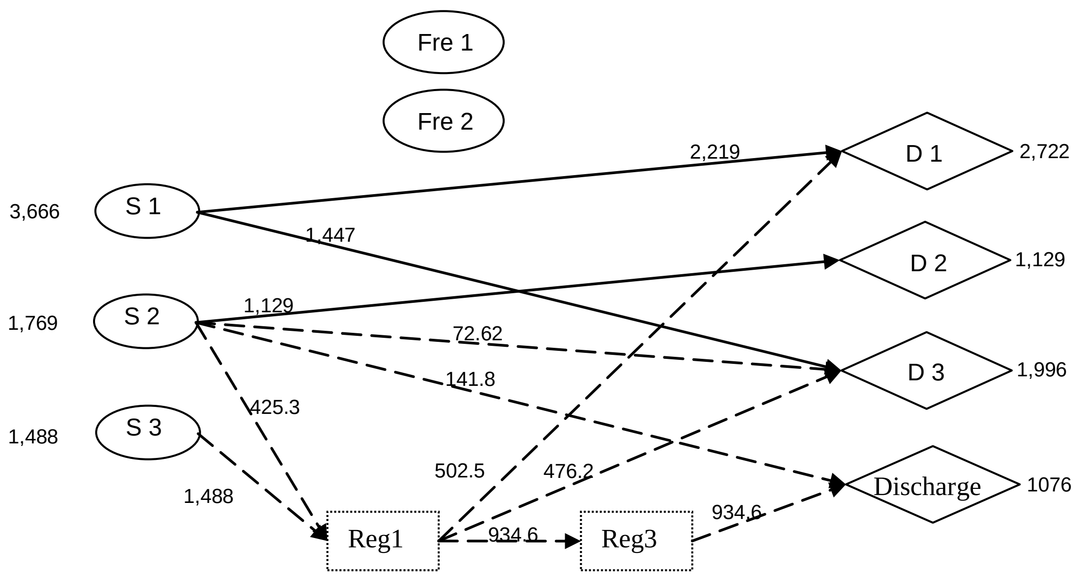

Figure 3: The retrofit design for the example. The numbers are the flow rates of the streams (kg/h).

The comparison for the retrofitting results is listed in Table 4. The items are calculated by the formula listed in the literature (Sotelo-Pichardo, 2011). The system operates 8,600 h/year. The pumping cost is 1.3×10^{-3} \$/kg. From Table 4, it can be seen that the mass fraction of phenol and acetone could be decreased to 0.005 kg/kg and 0.005 kg/kg, which meet the standard for discharge. Fresh water is not needed anymore in the retrofit design. After retrofitting, the amount of discharge will be reduced by 65.94 %, which is the same as the results in the literature (Sotelo-Pichardo, 2011). The total annual cost will be reduced by 12.0 % compared to the existing network, and that is 10.8 % in the literature. The retrofitting method proposed in this paper is better than that of the literature.

Table 4: Comparison for the retrofitting design

	Existing network	Retrofitting in literature	Retrofitting in this paper
Concentration of phenol for discharge	0.112	0.005	0.005
Concentration of acetone for discharge	0.013	0.000	0.005
Waste , kg/h	3,161	1,076	1,076
Fresh sources cost, $/y	15,094	0	0
Capital cost for treatment units, $/y	—	22,183	21,163
Operational cost for treatment units, $/y	—	18,186	17,443
Pumping costs, $/y	93,683	101,711	101,620
Additional treatment cost required to satisfy the new environmental regulations, $/y	50,561		
Total annual cost, $/y	159,339	142,081	140,227

5. Discussion and Conclusions

To meet stricter environmental regulations and/or reduce fresh water consumption, the existing water network might be retrofitted. In this article, a new procedure is proposed for retrofitting design of water network by adding a regeneration unit into the existing network. The discharged streams in the existing network with ascending order of their CPS values should be selected for regeneration. Adding the regenerated stream into the existing network, the network involving regeneration is formed. The final retrofitting design could be obtained by several iterations. In the design procedure, the concentration potential concepts (Liu et al. 2009a) are used to determine the precedence order of the processes and the selection of the source streams to be regenerated. The final design can be obtained easily. The example illustrates that the retrofitting method proposed in this work is effective.

References

Galbraith N, 2015, Harmful bacteria found in Frederick, Md. freshwater lakes, streams, <www.your4state.com/37430/kPUZNAAs8Uub5ccmkzu3rA> accessed 16.07.2015.

Khor C.S., Shah N., Mahadzir S., 2012, Optimisation of petroleum refinery water network systems retrofit incorporating reuse, regeneration and recycle strategies, Canadian Journal of Chemical Engineering, 90(1), 137-143

Liu Z.Y., Yang Y., Wan L.Z., Wang X., Hou K.H., 2009a, A heuristic design procedure for water-using networks with multiple contaminants, AIChE Journal, 55(2), 374-382.

Liu Z. Y., Li Y. M., Liu Z. H., 2009b, A simple method for design of water-using networks with multiple contaminants involving regeneration reuse, AIChE Journal, 55(6), 1628-1633.

Malin P., Aaron J.P., 2014, The design of the water supply in the metropolitan area of Jakarta, Chemical Engineering Transactions, 42, 25-30.

Mamdouh A.G., 2015, A new graphical method for pinch analysis and energy integration, Chemical Engineering Transactions, 43, 1291-1296.

Pan C.H., Shi J., Liu Z.Y., 2012, An iterative method for design of water-using networks with regeneration recycling, AIChE Journal, 58(2), 456-465.

Poplewski G., 2014, Design Method of Optimal and Flexible Water Networks with Regeneration Processes, Chemical Engineering Transactions, 39, 73-78.

Reddy C.C.S., Rangaiah G.P., Long L.W., Naidut S.V., 2013, Holistic approach for retrofit design of cooling water networks, Industrial & Engineering Chemistry Research, 52(36), 13059-13078.

Shenoy A.U., Shenoy U.V., 2014, Designing optimal bio-ethanol networks with purification for integrated biorefineries, Energy Conversion and Management, 88, 1271-1282,

Sotelo-Pichardo C., Ponce-Ortega J.M., El-Halwagi M.M., 2011, Optimal retrofit of water conservation networks, Journal of Cleaner Production, 19(14), 1560-1581.

Tokos H., Pintaric Z.N., Yang Y.R., Kravanja Z., 2012, Multilevel strategies for the retrofit of large-scale industrial water system: A brewery case study, AIChE Journal, 58(3), 884-898.