Maximising Water Recovery through Water Pinch Technology – The Use of Water Cascade Table

[1]Foo Chwan Yee, [2]Zainuddin Abdul Manan, [2]Rosli Mohd Yunus and [1]Ramlan Abdul Aziz
[1]Chemical Engineering Pilot Plant (CEPP)
[2]Chemical Engineering Department (UTM)
Universiti Teknologi Malaysia
81310 Skudai, Johor, Malaysia

ABSTRACT

The environmental impact of industrial wastewater and higher cost of raw water are serious challenges facing the chemical process industries nowadays. From the focus on the end-of-pipe treatment in the 1970s, chemical manufacturers have increasingly emphasised on the waste minimisation policies where pollutants are mitigated at the source. Less pollutant translates into less raw water cost as well as reduced wastewater treatment cost. One of the key techniques addressing the systematic design of water recovery network is the well-known *water pinch* technique. This paper will demonstrate a newly developed tool called the *Water Cascade Table* (WCT) to establish the minimum utility (water) requirement for a maximum water recovery (MWR) network. This tool has been adapted from water surplus diagram which has overcome the previous assumed mass transfer model for the water-using operations. Yet, the WCT which is tabulated in nature, has overcome the tedious graphical drawing exercise and inaccuracy problem associated with water surplus diagram. A downstream petrochemical case study of acrylonitrile (AN) production plant will be used to illustrate this newly developed tool. Prior to network design, the WCT locates the minimum water consumption as well as the wastewater generation for a MWR network for this process.

Keywords
Water minimisation, maximum water recovery, water cascade table, minimum utility target.

INTRODUCTION

Industrial water reuse and recycling are common activities in the process plant nowadays. The main driving force behind these activities is that, apart from the stringent environmental regulation, the fresh water cost and wastewater treatment cost have both risen significantly over the years. Process plants are now taking more serious measurement towards the minimisation of fresh water consumption. Such measures result in a reduced effluent generation and reduced treatment cost. Hence, the issue of systematic design of water recovery network have gain much interests in the research community, especially in the past 5 – 10 years (1-20).

Two main approaches are generally used to address the issue of systematic design of a water recovery network, i.e. the graphical approach (or more commonly known as the water pinch technique) and mathematical programming approach. The former technique normally divides the design problem into a two-step procedure, i.e. targeting and design. The main advantage of this approach is that the minimum utility (water) consumption is targeted ahead of any network design. The later technique serves as a great tool in addressing a more complex system, such as that with many water-using processes or multiple contaminant problems.

The synthesis of a water recovery network can be stated as:

Given a set of water-using processes, it is desired to determine a network of interconnections of water streams among the water-using processes so that the overall fresh water consumption is minimised while the processes receive water of adequate quality (18).

The first attempt to solve the water recovery network problem in a systematic way is reported by Takama *et al.*(1) for a petroleum refinery case study. Utilising a mathematical programming approach, these authors firstly set up a superstructure of all water-using operations. This superstructure is then optimised to remove the irrelevant and uneconomical options.

Wang and Smith (2) later initiated the water pinch technique based on the more generalised problem of mass exchange network synthesis (MENS) (21, 22). In this two-step procedure, the limiting composite profile is introduced to locate the minimum fresh water and wastewater flowrates prior to any network design. The opportunities for regeneration-reuse and regeneration-recycling were also explored. The basic concept underlying this approach is that the water-using processes are modelled as mass transfer operations.

The mass transfer model-based approach in handling the water recovery network might not be always adequate. Some operations in the process industry, such as boiler blow down, cooling tower make-up and reactor effluent are typical examples where water quantity are more important than the water quality. The mass transfer-based approach has fails to model these operations. Dhole *et al.* (5) later corrected the targeting approach by introducing a new water source and demand composite curves. They also showed that proper mixing and bypassing could further reduce the fresh water consumption. This approach has gained the attention of the researchers who came later (7, 9).

More recently, Hallale (18) pointed out that the water source and demand composite curves may not give a clear picture of the analysis. The targets obtained may not be a true solution, as they greatly depend on the mixing patterns (which is suppose to be a part of the network design) of the process streams. In turn, a water surplus diagram is presented (18) for the targeting of minimum fresh water consumption and wastewater generation in a water recovery network. This is by far the most appropriate targeting technique in locating the utility in a water recovery network. It overcomes the limitations of the mass transfer-based approach (2) and yet, this new representation does automatically build in all mixing possibilities to determine the true pinch point and reuse target.

However, the use of water surplus diagram involves tedious graphical drawing in locating the minimum water target of the network (13, 19). Apart from the inaccuracy problem associated with the normal graphical approach, the major limitation of the water surplus diagram is that, the diagram is generated based on an assumed fresh water value. Often, this water surplus diagram has to be drawn for a few times, before the correct fresh water flowrate is finally located. Tan *et al.*(19) lately introduced a tabular-based numerical approach called the *water cascade table* (WCT) to overcome the limitations associated with the graphical water surplus diagram.

In this paper, we will firstly analyse a few types of water-using operations found in a process plant. This includes the mass transfer-based as well as the non-mass transfer-based water-using operations. A downstream petrochemical case study of Acrylonitrile (AN) production plant will later be used to demonstrate the newly developed WCT in locating the utility targets. It will also be shown that the mass transfer model (2) is not appropriate to be used here, as the water flowrate is also an important parameter to be considered in this case. Prior to network design, the WCT locates the minimum water consumption of the overall process.

THE WATER-USING OPERATIONS

Before we demonstrate how the minimum water target can be located by the WCT, we will firstly analyse the two main types of water-using operations in a process plant, i.e. the mass transfer-based operation and the non-mass transfer-based operation. This will enable us to understand how the water-using processes are operated.

In the mass transfer-based type of operation, water is fed to the process continuously. At the same time, the same amount of water is continuously withdrawn, carrying a certain amount of contaminant from the process. Hence, the operation acts as water demand and water source simultaneously. A typical example of this type of operation is the normal washing process, where water (fresh or recycle water) is used to clean the process vessel or plant site. During cleaning, water is needed (as a demand) and at the same time, wastewater is generated (as a source) from the process (Figure 1).

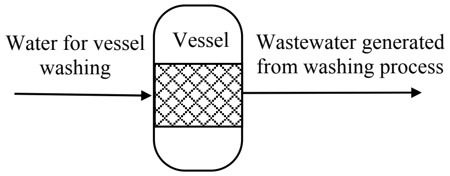

Figure 1: Washing process serves as water demand and water source simultaneously

The second type of the water operation is the non-mass transfer-based model. This includes the operation where only water demand or water source occurs in the process. Two typical examples for this case are the cooling water make-up (water demand only) and boiler blowdown (water source only), shown in Figure 2. Clearly, these operations cannot be modelled by the mass transfer model, as it requires the inlet and outlet streams to have a uniform flowrate.

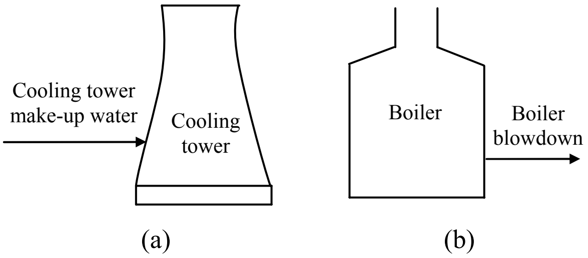

Figure 2: Two common types of water-using operations that could not be modelled as mass transfer operation: (a) cooling tower make up ; (b) boiler blowdown

In these non-mass transfer-based types of water-using operations, the water flowrate is more important than the amount of contaminant being picked up from the process. Hallale (18) showed another good example where the mass transfer model failed to model a reactor system with several streams entering and leaving the equipment at different concentrations (Figure 3).

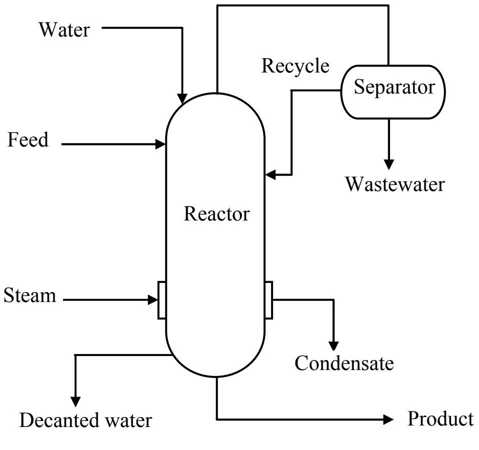

Figure 3: A reactor system that cannot be modelled purely as mass transfer operation

EXAMPLE PROBLEM

Figure 4 shows the process flowsheet of the Acrylonitrile (AN) production case study from El-Halwagi (22) along with the pertinent material balance data. The AN is produced via the vapour-phase ammoxidation of propylene.

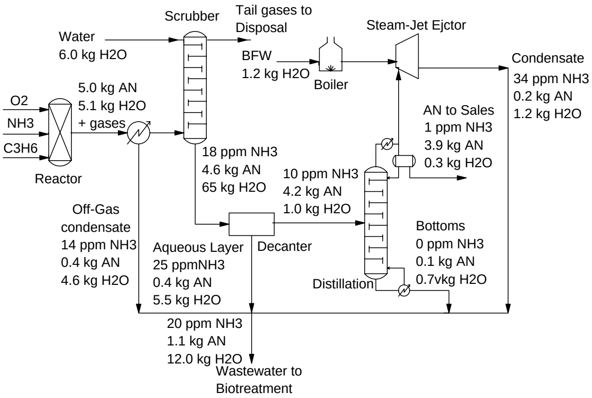

Figure 4: Flowsheet of AN production

Two water demands of this process consist of the boiler feed water (BFW) and the water feed stream to the scrubber. Besides, there are four water sources which consist of the off-gas condensate, aqueous layer from the decanter, bottom product of the distillation column and the condensate from the steam-jet ejector. The main contaminant in this process is taken as ammonia (NH_3). The wastewater from the water sources are sent to a biotreatment facility, which is operated at full capacity thereby causing a bottleneck in the plant.

One of the proposed methods is to debottleneck the overall process is via water reuse and recycling. However, any proposed solution will have to comply with the few technical constraints for the following equipment:

i. Scrubber
    - $5.8 \leq$ flowrate of wash feed (kg/s) ≤ 6.2
    - $0.0 \leq NH_3$ content of wash feed ≤ 10.0

ii. Boiler feed water
    - NH_3 content = 0.0 ppm
    - AN content = 0.0 ppm

iii. Decanter
    - $10.6 \leq$ feed flowrate (kg/s) ≤ 11.1

iv. Distillation column
    - $5.2 \leq$ feed flowrate (kg/s) ≤ 5.7
    - $0.0 \leq NH_3$ content of feed (ppm) ≤ 30.0
    - $80.0 \leq$ AN content of feed (wt%) ≤ 100.0

The first step in establishing the targeting approach is to identify the limiting water data for the process. This has to be incorporated with the above listed process constraints. Among the four listed constraints, only the first two (i.e. scrubber and boiler feed water) which involve the selected process stream for water reuse analysis are taken into account. The first constraint requires that the volume and the NH_3 content of the wash feed to the scrubber should bound between a given range. Hence, in order to maximise the reuse of water, we should maximise the NH_3 content while maintaining the water volume of this water source to its minimum. This is in accordance with maximising the water reuse approach proposed by Wang and Smith (2). Besides, the second constraint implies that only pure water (0 ppm of NH_3) could be use for the boiler feed water (BFW). The limiting data for these water demands along with those of the water sources are summarised in Table 1.

Table 1. Limiting water data for AN production

Water demands, D_j		Flowrate	Concentration
j	Stream	F_j (kg/s)	C_j (ppm)
1	Boiler feed water (BFW)	1.2	0
2	Scrubber	5.8	10

Water sources, S_i		Flowrate	Concentration
i	Stream	F_i (kg/s)	C_i (ppm)
1	Distillation bottoms	0.8	0
2	Off-gas condensate	5	14
3	Aqueous layer	5.9	25
4	Ejector condensate	1.4	34

As shown in Table 1, none of these operations can be modelled as a mass transfer process. Viewing the limitations of the mass transfer approach, El-Halwagi (22) proposed another targeting model in determining the water target for this system. However, this model is over-simplified and does not take into account the driving force for possible water reuse. Figure 5 shows the proposed targeting model, where only water volume balance is considered. Clearly, without considering the thermodynamic constraint (the mass transfer driving force for possible water reuse in this case) of the system, one would easily miss out the true minimum target of the system. This is also apparent in all other network system synthesis, e.g. heat exchange network synthesis (HENS) (23) or mass exchange network synthesis (MENS) (22).

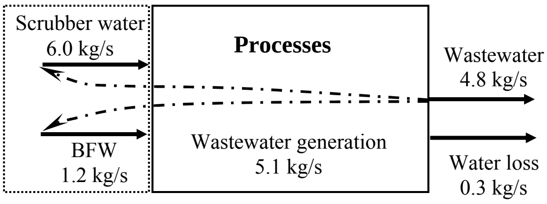

Figure 5: Targeting model by El-Halwagi (22)

El-Halwagi (22) also proposed a systematic way to design the water reuse network for this process, utilising the source-sink mapping diagram. However, without a good targeting tool to establish the minimum target ahead of design, there will always be questions such as “Is this the minimum water required for the process?”, “Could there be further improvement?” or even “How shall we improve?”. Hence, it is always essential to locate a target before any design work is carried out. We shall demonstrate this concept through the use of WCT in the next section.

THE WATER CASCADE TABLE

Tan *et al.* (19) proposed the use of Water Cascade Table (WCT) as a supplement to water surplus diagram introduced by Hallale (18). WCT is tabular and numerical in nature, similar to the problem table analysis in HENS problem (23) or composition interval table in MENS problem (22). It can eliminate the tedious trial-an-error graphical solution of the water surplus diagram during the determination of the minimum utility targets. However the previous version of the targeting procedure incurs the following limitations:

1. For cases with overall water demands flowrate equal to that of the wastewater flowrate, no guideline is given for the guess of the initial fresh water flowrate.
2. For cases with overall water demands flowrate larger or equal to that of the wastewater flowrate, and when there are more than one water demand or water source, no guideline is given for the guess of the initial fresh water flowrate.
3. When there is no negative value in the column of cumulative water surplus in the WCT, this does not mean always means that we have reach the minimum utility solution. This pitfall is obvious in the AN production case study.

Hence, we propose a revised version of the WCT targeting procedure in this paper, as shown in Figure 6. Readers are referred to the previous publication (19) for the detailed explanation of the targeting procedure. Though some initial guesses are needed to locate the initial estimated fresh water flowrate, this procedure does embedded the sequence in getting the right target finally.

Using the revised procedure, the WCT for the AN production case study is constructed (Table 2). The process pinch concentration is located at 14 ppm, representing the most constraint part of the water network. A total of 2.06 kg/s of fresh water is needed in the process, while the wastewater generated from the process is targeted at 8.16 kg/s. These targets are verified through the network design conducted earlier (22). Only at this stage, when we have a utility target set ahead of design, we can justify that the initial proposed design by the source-sink mapping diagram (22) does achieve the objective of maximum water recovery of the plant.

Table 2. WCT for AN production plant

Conc, C(ppm)	Purity, P	$\Sigma F_{D,j}$	$\Sigma F_{S,i}$	$\Sigma F_{D,j}$ + $\Sigma F_{S,i}$	Cum. water flowrate, kg/s	Water surplus, kg/s	Cum. water surplus, kg/s
					2.06		
0	1.000000	-1.2	0.8	-0.4			
					1.66	0.0000166	
10	0.999990	-5.8		-5.8			0.0000166
					-4.14	-0.0000166	
14	0.999986		5.0	5			0
					0.86	0.0000095	
25	0.999975		5.9	5.9			0.0000095
					6.76	0.0000608	
34	0.999966		1.4	1.4			0.0000703
					8.16	8.1600000	
							8.1600703

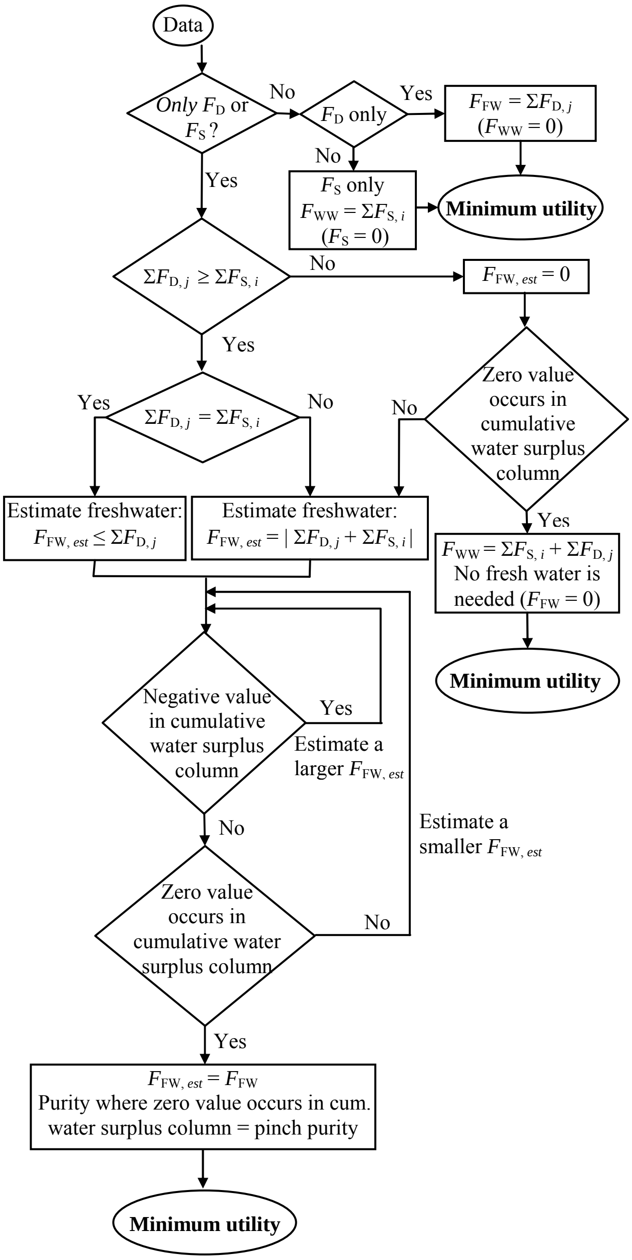

Figure 6: Revised procedure of WCT targeting approach

CONCLUSIONS

A revised procedure is presented in this paper for utility targeting approach via Water Cascade Table (WCT). This is demonstrated through the case study of the Acrylonitrile (AN) production plant. It is also shown that certain operations in the process plant are not appropriate to be modelled merely as mass transfer operations. This is the limitation of the targeting approach in the conventional water network analysis. This pitfall has been overcome by the newly introduced WCT targeting procedure. The procedure in this work is fully automated and can be easily translated into any computer language for software development. A process engineer might also easily employ this procedure into a spreadsheet for ease of calculations.

ACKNOWLEDGEMENT

The financial support of Ministry of Science, Technology and Environment, Malaysia through Intensified Research Priority Area (IRPA) research grant and National Science Fellowship (NSF) scholarship is gratefully acknowledged.

NOTATION

C = contaminant concentration, ppm
$F_{\mathrm{D},\,j}$ = flowrate of water demand, *j*, kg/s
F_{FW} = flowrate of fresh water needed, kg/s
F_{FW} = estimated fresh water flowrate, kg/s
$F_{\mathrm{S},\,i}$ = flowrate of water source, *i*, kg/s

REFERENCES

1. Takama, N., Kuriyama, T., Shiroko, K. and Umeda, T. (1980) “Optimal water allocation in a petroleum refinery”, Computers Chem. Eng., **4**, 251–258.

2. Wang, Y. P. and Smith, R. (1994). “Wastewater minimisation”. Chem. Eng. Sci., **49**, 981–1006.

3. Wang, Y. P. and Smith, R. (1995). “Time pinch analysis”. Trans. IChemE, Part A, **73**, 905–914.

4. Kuo, J. W. C. and Smith, R. (1998). “Designing for the interactions between water-use and effluent treatment”. Trans. IChemE, Part A, **76**, 287–301.

5. Dhole, V. R., Ramchandani, N., Tainsh, R. A. and Wasilewski, M. (1996). “Make your process water pay for itself”. Chemical Engineering **103**, 100–103.

6. Olesen, S. G. and Polley, G. T. (1997). “A simple methodology for the design of water networks handling single contaminants”. Trans. IChemE, Part A, **75**, 420–426.

7. Sorin, M. and Bédard, S. (1999). “The global pinch point in water reuse networks”. Trans. IChemE, Part B, **77**, 305–308.

8. Castro, P., Matos, H., Fernandes, M. C. and Nunes, C. P. (1999). “Improvement for mass exchange network design”. Chem. Eng. Sci, **54**, 1649–1665.

9. Polley, G. T. and Polley, H. L. (2000). “Design better water networks”. Chem. Eng. Prog., **96** (2): 47–52.

10. Savelski, M. J. and Bagejewicz, M. J. (2000). “On the optimality conditions of water utilization systems in process plants with single contaminants”. Chem. Eng. Sci., **55**, 5035–5048.

11. Savelski, M. J. and Bagejewicz, M. J. (2001). Algorithmic procedure to design water utilization systems featuring a single contaminant in process plants, Chem. Eng. Sci., **56**, 1897–1911.

12. Bagajewicz, M., 2000, “A review of recent design procedures for water networks in refineries and process plants”, Computers Chem. Eng., **24**, 2093–2113.

13. Dunn, R. F. and Wenzel, H. (2001). “Process integration design methods for water conservation and wastewater reduction in industry, Part 1: Design for single contaminant”. Clean Prod. Processes, **3**, 307–318.

14. Dunn, R. F. and Wenzel, H. (2001). “Process integration design methods for water conservation and wastewater reduction in industry, Part 2: Design for multiple contaminants”. Clean Prod. Processes, **3**, 319–329.

15. Dunn, R. F. and Bush, G. E. (2001). “Using process integration technology for CLEANER production”. J. Cleaner Prod., **9**, 1–23.

16. Parthasarathy, G. and Krishnagopalan, G. (2001). “Systematic reallocation of aqueous resources using mass integration in a typical pulp mill”. Adv. Env. Res., **5**, 61–79.

17. Xiao, F. and Seider, W. D. (2001). “New structure and design methodology for water networks”. Ind. Eng. Chem. Res., **40**, 6140–6146.

18. Hallale, N. (2002). “A new graphical targeting method for water minimisation”. Adv. Env. Res., **6** (3), 377–390.

19. Tan, Y. L., Manan, Z. A. and Foo, C. Y. (2002). “Water minimisation by pinch technology – water cascade table for minimum water and wastewater targeting”. *9th Asian Pacific Confederation of Chemical Engineering (APCChE 2002) Congress.*

20. Foo, C. Y., Manan, Z. A., Yunus, R. M. Aziz, R. A. and Tan, Y. L. (2002). “Water minimisation for batch process systems – A pinch technology approach”. *2nd World Engineering Congress*.

21. El-Halwagi, M. M. and Manousiouthakis, V. (1989). “Synthesis of mass exchange networks”, AIChE Journal, **35**(8), 1233–1244.

22. El-Halwagi, M. M. (1997). “*Pollution prevention through process integration: systematic design tools*”. Academic Press, San Diego, USA.

23. Linnhoff, B., Townsend, D. W., Boland, D., Hewitt, G. F., Thomas, B. E. A., Guy, A. R. and Marshall, R. H. (1982). “*A user guide on process integration for the efficient use of energy*”. IChemE, Rugby, UK.