A simple methodology for targeting of Water minimization

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Abstract

This paper presents the load problem table (LPT) a numerical technique to establish the minimum water, wastewater targets
and the pinch locations for continuous water using processes.
The LPT has been adapted from the numerical technique problem table analysis (PTA) in heat integration and composition interval table (CIT) in mass integration . The LPT which is tabulated in nature, has overcome the tedious graphical drawing exercise and inaccuracy problem associated with graphical technique. The broad applicability and ease of implementation of LPT are shown and verified through the solution of several previous case studies published in earlier literature includes mass transfer based as well as the non mass transfer based water using operation and problems with multiple pinch points. In addition, the LPT procedure is characterized by its simplicity and can be implemented by hand calculations.

Keywords: wastewater minimisation, vertical cascading, wastewater reuse, utility targeting

Introduction

Water is a key element for the normal functioning of the chemical and petrochemical industry. Steam stripping, liquid-liquid extraction and washing operations are among the many processes present in refineries and chemical plants where water is intensively utilized. In refineries, steam is used in atmospheric and vacuum crude fractionation, as well as in coking, hydrocracking, visbreaking, sweetening, hydrotreating, alkylation, ether synthesis, etc. In addition, water is used in desalters to remove primarily the salted water droplets that the crude contains. Water is also intensively used in hydrometallurgy where many suspended solids as well as a large variety of ionic metals can be found. The food and agricultural industries (sugar factories, dairy industries, breweries) make use of water for a variety of washing operations and steam in evaporators. Other industries with intense use of water are the textile industry, the pharmaceutical and electronic component industry. As a result, wastewater streams containing several contaminates create an environmental pollution problems.

Water using operations in a process plant can generally be classified into the mass transfer-based and the non mass transfer-based operations. A mass transfer-based water using operation is characterized by the preferential transfer of species from a rich stream to water, which is being utilized as a mass separating agent, (Takama et al.,1980; Wang and Smith 1994; Olesen and Polley1997; Castro et al.,1999; Feng and Seider 2001). Note that the input and output flow rates of a mass transfer processes are assumed to be constant.

The non mass transfer based water using operation covers functions of water other than a mass separation agent. The non mass transfer based operation also coves cases where is being utilized as heating or cooling media. For such operations, usually, only water demands or water sources exist (Dhole et al.,1996; Sorin and Bedard,1999; Hallale, 2002; El-Halwagi et. al.,2003). Note that, for the non mass transfer based water using operations, the water flow rate is more important than the amount of contaminants accumulated.

The current drive towards environmental sustainability and the rising costs of fresh water and effluent treatment have encouraged the process industry to find new ways to reduce fresh water consumption and waste water generation. Concurrently, the development of systematic techniques for water reduction, reuse and recycling within a process plant has seen extensive progress.

There are two groups of methods for the systematic design of a water recovery networks, one group of methods is based on the concept of pinch analysis and the other one on the application of mathematical optimization techniques. The methods based on the principle of pinch analysis are graphical. They allow the targeting and design of water networks with minimum fresh water consumption and maximum reuse of water, given the water quality constrains within the process.

The first attempt to minimize water usage by maximizing water reuse was reported by Wang and Smith (1994),they presented a graphical approach that was adapted from heat integration using pinch technology. By plotting the limiting composite curves versus the limiting composition interval , one can locate the minimum fresh water and wastewater flow rates prior to any network design. The opportunities for regeneration-reuse and regeneration recycling were also explored. They also presented a network design procedure, which allowed the target to be met. The basic concept underlying this approach is that the water using processes are modeled as mass transfer operations.

The methodology on a mass transfer model is a large drawback. Certain operations such as washing, extraction, scrubbing, etc., can be adequately modeled in this way. However, many process units, such as reactors, boilers, cooling towers, etc., cannot be described as mass transfer operation. In this type of operation, water quantity are more important than the water quality.

Dhole et al (1996) correctly pointed out that some unit operations such as reactors, cooling towers, and boilers may not be adequate to be modeled as mass transfer operations. They in turn proposed the use of water source and demand composite curves to locate the minimum fresh water consumption and waste water generation. They also suggested process change like making and by passing to further reduce the fresh water consumption. They note that the pinch divided the problem into two regions; that above the pinch and that below it. In order to achieve the targets, fresh water should not be used below the pinch and also, sources above the pinch should not be discharged as waste water.

However, Polley and Polley (2000) later pointed out that, unless the correct stream mixing system was identified, the apparent targets generated by Dhole's technique could be substantially higher than the true minimum fresh water and waste water targets.

Sorin and Bedard (1999) correctly observed that the approach of Dhole et al. (1996) actually defines many local pinch points. These authors developed an approach termed the Evolutionary Table. This is a numerical method that is used to determine the fresh water and waste water targets without resorting to graphical solutions. However, if there happens to be more than one global pinch, this approach may not locate them correctly. This can give incorrect guide lines regarding process modifications and regeneration.

Hallale (2002) presented an alternative graphical method called the water surplus diagram to target the minimum fresh water and wastewater. This approach was adapted from the hydrogen pinch analysis the method has introduced by Alves (1999) ; a similar representation to the water source and demand composite curve proposed by Dhole et al.(1996), there by overcoming the limitations in the mass transfer-based approach Wang and Smith (1994). The new representation by Hallale (2002) could handle all mixing possibilities and yet resulted in the true pinch point and reuse target. However, the water surplus diagram has the same drawbacks like the composite curves. It is tedious and time consuming to draw as it involves trial and error to find the pinch point and water targets. Besides, it has limitations in terms of generating highly accurate targets due to its graphical nature. El-Halwagi and Spriggs (1996) addressed the problem of water usage and discharge through a source – sink representation. They developed a source- sink mapping diagram along with lever arm rules that identify optimal allocation of sources to sinks.

El-Halwagi et. al. (2003) developed a graphical technique (material recycle pinch analysis). First, the problem is formulated mathematically to provide a systematic basis for its solution. Then, dynamic programming techniques are employed to derive the mathematical conditions and characteristics of an optimal solution strategy. These conditions and characteristics are transformed into a graphical form that can be readily used to identify targets for minimum usage of fresher source , maximum integration of process recycles , and minimum discharge of waste.

This paper will demonstrate a developed tool called the Load Problem Table (LPT) . The LPT has been adapted from the Problem Table Analysis (PTA) in heat integration(Linnhoff et. al.1982) and Composition Interval Table (CIT) in mass integration(El-Halwagi and Manousiouthakis 1989). The main objective of the LPT is to establish the minimum water target, i.e. the overall fresh water requirement and wastewater generation for a process after looking at the possibility of using the available water sources within a process to meet its water demands . To achieve this objective, one has to establish the net water flowrate as well as the water surplus and deficit at different water purity levels within the process under study. The interval water balance table has been introduced for this purpose. Through LPT , the LPT technique offers two key advantages over the graphical technique in realizing the minimum water targets , apart from its power to eliminate tedious iterative steps of graphical technique to quickly yield the exact utility targets and the pinch locations. The first key advantage is that the LPT clearly displays both the minimum fresh water and wastewater flowrate targets.

Note that, in the case of graphical technique, only the minimum fresh water target is known (obtained from the trial and error procedure).

However, the value of the minimum wastewater flowrate is not available from the graphical technique. The second key advantage of using LPT is that it enables a designer to clearly identify the pinch causing stream and exact water allocation for the regions above and below pinch to achieve the minimum water targets during network design. Such important insights on pinch causing stream and water allocation are evident the LPT but not available from the graphical technique.

Several test problems published in earlier literature includes the mass transfer based as well as the non mass transfer based water using operation and problem with multiple pinch points are solved to illustrate the ease and applicability of the developed targeting technique .

Problem statement

Consider a process that consists of a set of process sinks and a set of process sources described as follows:

The set of process sinks { j=1,2,….,Nsinks } each sink , j , has a flowrate G_j , and a composition of a single targeted species, x_j .

The set of process sources { i=1,2,…, Nsources } each sources , i, has a flowrate Wi , and a composition of a single targeted species , y_i .

Also available for service is a fresh (external) resource that can be purchased to supplement the use of process sources in sinks.

Given the above described process, the objective is to develop a method that determine the target for minimum usage of the fresh resource, maximizing the usage of process sources and minimizing water discharge.

The load problem table technique

The objective of the LPT is to establish the minimum water target, i.e. the overall fresh water requirement , wastewater generation and location of pinch point . The LPT can be determined through the following procedure:

1- The first column in setting up the LPT is to list out all the cumulative load are arranged in ascending order to obtain the number of intervals. These intervals are numbered through index K which starts with K=0 at the zero load level and go up at each interval.

2- Next, in column 2 , the load within interval K is calculated as the difference between load level at interval K and K-1 , as follow:

$$\Delta M_K = M_K - M_{K-1} \qquad (1)$$

Where M_K is the load at each level K.

3-In the third column, each source (and each sink) is represented as an arrow whose tail corresponds to its starting load and head corresponds to it ending load.

4- In the fourth column, calculate the flowrates of the source and sink within interval k, followed by calculating the net flowrate between the source and the sink as follows

for source :

$$\Delta W_k = \frac{\Delta M_k}{Y_k} \qquad (2)$$

for sink :

$$\Delta G_k = \frac{\Delta M_k}{X_k} \qquad (3)$$

The net flowrate between source and sink

$$\Delta m_k = \Delta W_k - \Delta G_k \qquad (4)$$

5- In the fifth column, cascade analysis by using vertical cascading approach , the net flow rate between the source and sink within each interval is cascaded vertically down from one interval to another.

The cascade analysis ,(infeasible column), is starting with no fresh water .the most negative residual value indicates the minimum amount of fresh water must be supplied to the process.

This value is added to the first interval,(feasible column), and calculate the revised residuals. The residual flow leaving the last interval is the target for minimum wastewater discharge . the interval with the first zero residual is the pinch point.

***Example1*: *mass transfer based water using operations*,**

This example is taken from Wang and Smith(1994), it comprises of four mass transfer based water using operations. The data for the problem are given in table 1. there are four water using operations. The inlet of each operation is a demand and the outlet is a source.

Table1: process information for example 1.

Water demand D_j	Flow rate (ton/h)	Concentration (ppm)	Load (kg/h)	Cumulative load (kg/h)
1	20	0	0	0
2	100	50	5	5
3	40	50	2	7
4	10	400	4	11
Water source S_i	Flow rate (ton/h)	Concentration (ppm)	Load (kg/h)	Cumulative load (kg/h)
1	20	100	2	2
2	100	100	10	12
3	40	800	32	44
4	10	800	8	52

The LPT is illustrated in table 2. As can be seen from the column of cascade analysis, the most negative residual is -90 ton/hr. therefore, the target for minimum fresh water is 90 ton/hr. when this value is added to first interval, we can carry out the revised cascade calculations leading to a target of minimum wastewater discharge (residual leaving last interval) of 90 ton/hr. the zero residual designates the pinch location. Hence, the pinch point is located at the horizontal lines separating intervals 4 and 5, which corresponds to100 ppm on the source side. These results agree exactly with those found by Wang and Smith (1994) using their graphical method.

Table2: The LPT for example 1.

Interval	Load (kg/h)	Interval load (kg/h)	Processes		Cascade analysis			
			sources	sinks	infeasible		feasible	
	0.0					0		**90**
1	0.0	0		D_1	-20	-20	-20	70
2	2	2	S_1	D_2	-20	-40	-20	50
3	5	3			-30	-70	-30	20
4	7	2	S_2	D_3	-20	-90	-20	**0**
5	11	4		D_4	30	-60	30	30
6	12	1			10	-50	10	40
7	44	32	S_3		40	-10	40	80
8	52	8	S_4		10	0	10	**90**

Example 2: Combination of mass transfer and non mass transfer based water.

This example is taken from Polley and Polley (2000), The problem involves four sources and four sinks, and relevant information about them is provided into table 3.

Table 3 : process information for example 2.

Water demand D_j	Flow rate (ton/h)	Concentration (ppm)	Load (kg/h)	Cumulative load (kg/h)
1	50	20	1	1
2	100	50	5	6
3	80	100	8	14
4	70	200	14	28
Water source S_i	Flow rate (ton/h)	Concentration (ppm)	Load (kg/h)	Cumulative load (kg/h)
1	50	50	2.5	2.5
2	100	100	10.0	12.5
3	70	150	10.5	23.0
4	60	250	15.0	38.0

This example comprises of a combination of mass transfer and non mass transfer based water.

Table 4 shows the minimum fresh flow rate of 70 ton/h, wastewater flow rate of 50 ton/h. Additionally, the pinch concentration is shown to correspond to source 3 (150 ppm), the minimum fresh water and waste water targets found above are identical to Polley and Polley (2000) using their method. Polley and Polley did not locate a pinch point; however, Hallale (2002), using a water surplus diagram, determined the pinch location to be 150 ppm, which is in agreement with the value obtained here.

Table 4: The LPT for example 2.

Interval	Load (kg/h)	Interval load (kg/h)	Processes		Cascade analysis			
			sources	sinks	infeasible		feasible	
	0.0					0		**70**
1	1.0	1.0		D_1	-30	-30	-30	40
2	2.5	1.5	S_1	D_2	0	-30	0	40
3	6.0	3.5			-35	-65	-35	5
4	12.5	6.5	S_2	D_3	0	-70	0	5
5	14.0	1.5			-5	-55	-5	**0**
6	23.0	9.0	S_3	D_4	15	-50	15	15
7	28.0	5.0			-5	-60	-5	10
8	38.0	10.0	S_4		40	-20	40	**50**

Example 3: multiple pinch points problem

The correct identification of the true pinch point is crucial in water network analysis especially with problems involving multiple pinch points and near pinches. Hallale (2002) shows that the wrong pinch point will result in missed opportunities during network debottlenecking . we will now use an example involving multiple pinch points from Sorin and Bedard (1999) to illustrate the effectiveness of the method in identifying the pinch points.

The data for the problem are given in table 5 . There are six water using operations, the inlet of each operation is a demand and the outlet is a source and so there will be six demands and five sources, with the exception of process 3 , which consumes its entire flow rate and therefore has no outlet.

Table 5: Process information for example 3

Water demand D_j	Flow rate (ton/h)	Concentration (ppm)	Load (kg/h)	Cumulative load (kg/h)
1	120	0	0	0
2	80	50	4	4.0
3	80	50	4	8.0
4	140	140	19.6	27.6
5	80	170	13.6	41.2
6	195	240	46.8	88.0
Water source S_i	Flow rate (ton/h)	Concentration (ppm)	Load (kg/h)	Cumulative load (kg/h)
1	120	100	12	12
2	80	140	11.2	23.2
3	-	-	-	-
4	140	180	25.2	48.4
5	80	230	18.4	66.8
6	195	250	48.75	115.55

The first step , cumulative load for the whole process is arranged in ascending order to obtain the number of intervals followed by calculating the flow rate net of the sinks and sources through each interval The cascade analysis is then starting with no fresh water. The most negative residual value indicates the minimum amount of fresh water must be supplied to the process in order to accomplish the required task as shown in table. As can be seen from table , the minimum fresh water discharge is 120 ton/h. these values agree exactly with those found by Sorin and Bedard (1999) using their algebraic evolutionary table method and El. Halwagi et al. (2003) using their graphical techniques, as well as Hallale (2002) through an iterative water surplus diagram. Table 6   also shows that two pinch points exit in this problem , corresponding to composition of 100 and 180 ppm through the evolutionary table method, Sorin and Badard (1999) located a limiting source concentration of 180 ppm that they deemed the global pinch source the existence of multiple pinch point at 100 and 180 ppm in this problem was discovered by Hallale (2002) using the water surplus diagram and identical to those found by El-Halwagi et al (2003) using their method.

In problems involving multiple pinches , more than two thermodynamics regions exist with respect to the pinch location . for this example, three distinct thermodynamic regions exist due to the occurrence of a limiting pinch and a secondary pinch . these include the region above the limiting pinch, the region between two pinches and the region below the secondary pinch . using the LPT , one can easily identify the pinch causing source streams and the exact water allocation for the water sources in each of the thermodynamic region.

Thus, the LPT provides very useful guide lines in designing the network.

Table 6: The LPT for example 3.

Interval	Load (kg/h)	Interval load (kg/h)	Processes: sources	Processes: sinks	Cascade analysis: infeasible	Cascade analysis: feasible
	0.0				0.0	**200**
1	0	0		D$_1$	-120 → -120	-120 → 80
2	4	4		D$_2$	-40 → -160	-40 → 40
3	8	4	S$_1$	D$_3$	-40 → -200	-40 → **0.0**
4	12	4			11.40 → -188.6	11.40 → 11.4
5	23.2	11.2	S$_2$	D$_4$	0 → -188.6	0 → 11.4
6	27.6	4.4			-7 → -195.6	-7 → 4.4
7	41.2	13.6	S$_4$	D$_5$	-4.4 → -200	-4.4 → 0.0
8	48.4	7.2		D$_6$	10 → -190	10 → 10
9	66.8	18.4	S$_5$		3.3 → -186.7	3.3 → 13.3
10	88.0	21.2			-3.5 → -190.2	-3.5 → 9.8
11	115.55	27.55	S$_6$		110.2 → -80	110.2 → **120**

Conclusions

A systematic approach has been proposed for targeting fresh water and wastewater minimisation. The proposed approach when applied to problems previously reported in the literature yield optimum solutions which are consistent with the reported values and it overcomes the drawbacks of using graphical technique.

All the key features and the systematic of the LPT make it easy for the technique to be automated and translated into any computer language.

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