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Optimisation of Regeneration Unit to Achieve Zero Discharge in a Paper Mill

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Abstract

The advent of water pinch analysis as a tool for the design of optimal water recovery network has been one of the most significant advances in the area of water conservation over the last decade. Water pinch analysis is a systematic technique for implementing strategies to maximise water reuse and recycling through integration of water-using activities or processes. In this paper, possibility of achieving complete elimination of wastewater, i.e. zero discharge is assessed through the use of water regeneration units. Water regeneration has been widely accepted as an effective mean to further reduce water targets in water pinch analysis. Water regeneration involves the partial or total upgrading of water purity using any purification techniques. The regenerated water can either be reused in other water-using processes or recycled to the same process to further reduce water consumption and wastewater generation. A case study on a water-intensive paper mill process is used to illustrate how the water network can be optimised to achieve zero discharge. The targeting technique of water cascade analysis is used to locate the various network targets prior to the development of detailed network design. A solution with the minimum capital and annual operating costs was obtained.

Keywords: Water minimisation, pinch analysis, regeneration, zero discharge, water cascade analysis.

Introduction

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 freshwater consumption and wastewater generation. Concurrently, the development of systematic techniques for water reduction, reuse and recycling within a process plant has seen extensive progress. The advent of water pinch analysis (WPA) as a tool for the design of optimal water recovery network has been one of the most significant advances in the area of water conservation over the last decade [1-16]. Water pinch analysis is a systematic technique for implementing strategies to maximise water reuse and recycling through integration of water-using activities or processes. Maximising water reuse and recycling can minimise freshwater consumption and wastewater generation. Typical WPA solution comprises of two steps, i.e., setting minimum fresh water requirement and wastewater generation (i.e. the baseline water targets) followed by network design to achieve the baseline targets. In setting baseline water targets, the recent developed *water cascade analysis* (WCA) technique [15] has been proven to a promising tool in locating minimum water and wastewater targets in a maximum water recovery (MWR) network. "Water cascade" refers to the reuse of a spent water source to satisfy a lower quality water demand.

In this paper, a water-intensive paper mill case study is used to illustrate how WCA can be effectively used to optimise water regeneration units to achieve zero discharge in a MWR network.

Paper Mill Case Study

Figure 1 shows a preliminary water network for a paper mill process that was not designed based on the systematic technique of WPA. Old newspapers and magazines as feedstocks for the paper mill are blended with dilution water and chemicals to form pulp slurry called stock. The stock is sent to the forming section of the paper machine to form paper sheet. In the forming and pressing sections, fresh water (demand) is fed to remove debris while wastewater (sources) are removed from the stock during paper sheet formation. Part of these water sources are sent water storage tank to be reused in other processes.

To remove printing ink from the main stock, the de-inking pulper (DIP) and its associated processes (denoted as "DIP-Others") receive a mixture of fresh water and spent water from the water storage tank. The effluent water from the DIP main process is mixed with freshwater to dilute the stock being pumped to the deculator in the approach flow system (AF) while the effluent from "DIP-Others" is sent to water storage tank. The chemical preparation unit (CP) also consumes fresh water to dilute de-inking chemicals for use during ink removal process in the DIP unit. Part of wastewater from the forming section and the DIP unit are sent for effluent treatment before being finally discharged to the environment.

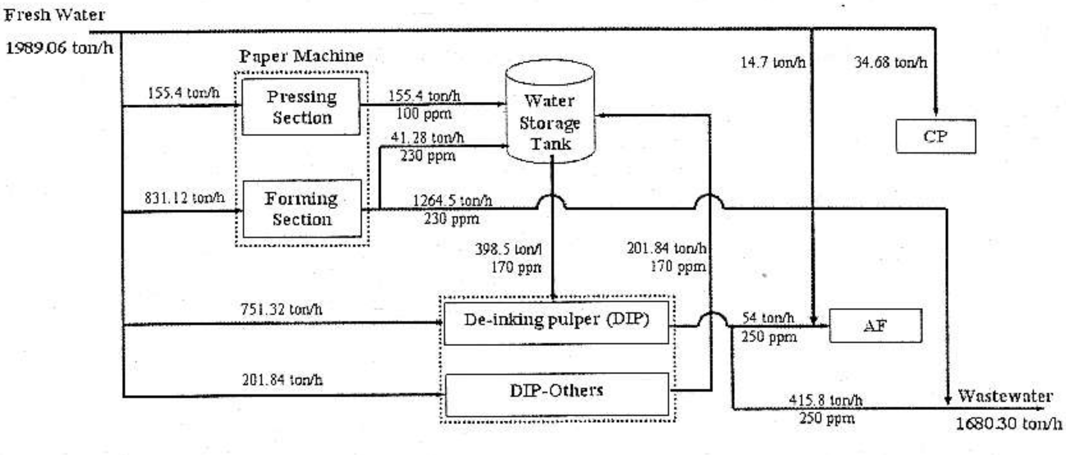

Figure 1 - A Preliminary Water Network for the Paper Mill Case Study

For the paper mill water network in Figure 1, the total fresh water consumption is 1989.06 ton/h and the total wastewater generation is 1680.3 ton/h. At a first glance, this paper mill seems to have been designed with an extensive water recovery scheme. However, it will be shown later that there are ample rooms for further recovery since the water and wastewater flowrates are still far from the baseline water targets. Table 1 shows the limiting data for the paper mill case study, i.e. the maximum permissible inlet (C_j) and outlet (C_i) concentrations for the water demands and the water sources respectively. The most significant water quality factor, i.e. total suspended solid (TSS) was chosen for the analysis.

Table 1 - Limiting Water Data for Paper Mill Case Study

Water demands, SK_j		F_j	C_j
j	Stream	(kg/s)	(ppm)
1	Pressing section	155.40	20
2	Forming section	831.12	80
3	DIP-Others	201.84	100
4	De-inking pulper (DIP)	1149.84	200
5	Approach flow (AF)	34.68	20
6	Chemical preparation (CP)	68.70	200
Water sources, SR_i		F_i	C_i
i	Stream	(kg/s)	(ppm)
1	Pressing section	155.40	100
2	Forming section	1305.78	230
3	DIP-Others	201.84	170
4	De-inking pulper (DIP)	469.80	250

Following the WCA approach [15], the minimum fresh water (F_F) and wastewater discharge (F_D) flowrates for the case study, before any water regeneration takes place are identified as 828.12 ton/h and 539.36 ton/h respectively (Table 2). The pinch point is identified at the concentration level of 230 ppm. Forming section (SR_2) was identified as the pinch causing stream in this case.

Table 2 – Targeting for Paper Mill Case Study

k	C_k (ppm)	$\Sigma_i F_i - \Sigma_j F_j$ (kg/s)	F_C (kg/s)	Δm (kg/s)	Cum. Δm (kg/s)
			F_F=**848.12**		
1	0	0			
			848.12	16.96	
2	20	-190.08			16.96
			658.04	39.48	
3	80	-831.12			56.44
			-173.08	-3.46	
4	100	-46.44			52.98
			-219.52	-15.37	
5	170	201.84			37.62
			-17.68	-0.53	
6	200	-1218.54			37.09
			-1236.22	-37.09	
7	230	1305.78			**0.00**
			69.56	1.39	(PINCH)
8	250	469.80			1.39
			F_D=**539.36**	539226.03	
9	1000000				539227.42

Optimisation of Regeneration Unit to Achieve Zero Discharge

A regeneration unit is normally rated in terms of either fixed outlet concentration (C_{out}) or fixed contaminant removal percentage (R). The former rates a regenerator based on a fixed outlet water concentration (e.g., 20 ppm). On the other hand, the latter is a rating based on a fixed amount of contaminant load removal and may result in changing outlet concentration. For instance, a wastewater flow at 100 ppm fed to a unit rated at 90% contaminant removal will produce an outlet flow at 10 ppm.

The paper mill water network consists of two independent thermodynamic regions which exist above and below the pinch concentration. A regeneration unit can either be placed entirely above the pinch or across it since both options will reduce the fresh water and wastewater flowrates. Common regeneration units for the removal of suspended solids in paper mill industry include the saveall disc filter (SDF) and dissolved air flotation (DAF) unit. For this example, the use of a DAF unit is considered. The DAF has a contaminant removal percentage (R) of 90% and an operating cost of \$0.50/kg of contaminant load removed. A DAF regenerates wastewater to a higher purity by introducing fine gas (usually air) bubbles to attach and lift particles to the water surface for removal.

Any of the four water sources of the paper mill can be purified before reuse within the water network, since the DAF unit is capable of regenerating these sources to the region above the pinch (note from Figure 5 that the pinch occurs at 230 ppm). For optimal regeneration, three key factors must be considered:

i. Selection of the optimal sequence to purify the available water sources
ii. Deciding the right amount to purify each of the available water sources
iii. Formulating the most cost-effective regeneration scheme

The mass load removed from a water source i ($\Delta m_{S,i}$) in a regenerator is given as follows:

$$\Delta m_{S,i} = F_{R,i} \times \Delta C_R \quad (1)$$

where $F_{R,i}$ is the flowrate and $\Delta C_R = C_{in} - C_{out}$ is the inlet and outlet concentration difference of water source i sent for purification. Since the operating cost is a linear function of Δm removed, clearly, less total mass load removed from the water sources will lead to lower operating cost of a regeneration unit.

Note also that, since the source flowrate ($F_{R,i}$) is inversely proportional to ΔC_R, a smaller $F_{R,i}$ would be required to regenerate a dirtier water source (larger ΔC_R) as compared to that for a cleaner water source (smaller ΔC_R) for a fixed amount of Δm removed. For instance, for R = 90%, a source at 250 ppm needed to be purified to 25 ppm (ΔC_R = 225 ppm) while a source at 100 ppm, to 10 ppm (ΔC_R = 90 ppm). Hence, in order to achieve zero discharge with the minimum capital and operating cost, the following heuristic is proposed:

Purify water sources one by one in descending order of concentration level

The heuristic means that in order to minimise the capital and operating costs, one should first purify the water source at the highest concentration level (or the "dirtiest") and continue with sources at the next highest concentration level until all water sources have been purified and wastewater eliminated to achieve zero discharge. Doing so will always lead to a smaller $F_{R,i}$ and hence, a smaller total regeneration flowrate (F_{reg}) and ultimately a smaller and cheaper equipment.

For the paper mill process, we began by purifying source SR_4 from 250 ppm to 25 ppm (Δm_{S4} = 105.71 kg/h, Figure 2a). This reduced the fresh water and wastewater flowrates to 429.39 ton/h and 120.63 ton/h respectively, but this alone did not lead to zero discharge. We next proceeded with source S_2 at 230 ppm. Purifying S_2 from 230 ppm to 23 ppm (Δm_{S2} = 27.75 kg/h) finally led to zero liquid discharge.

The WCA procedure revealed that only 134.05 ton/h of SR_2 ($F_{R,2}$) needed to be regenerated to achieve zero discharge. Knowing the exact regeneration flowrate is crucial in avoiding excessive over-design, and hence, unnecessary capital expenditure. A fresh water target of 308.76 ton/h generated using WCA matched the one computed from the difference between the sum of water sources and the sum of water demands (Table 3). The annual operating cost associated with the addition of DAF is approximately \$533,800, calculated based on the total regeneration flowrate (F_{reg}) of 603.85 ton/h and total Δm removal of 133.45 kg/h.

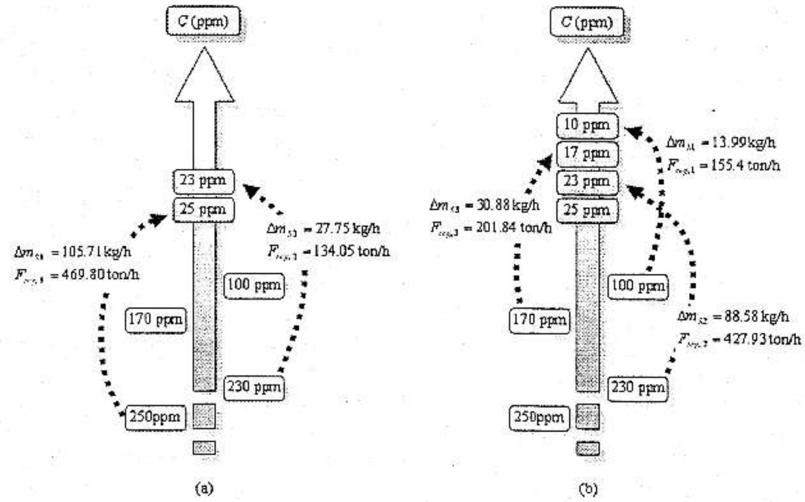

Figure 2 - Placement of a Regeneration Unit in the Context of an Overall Network

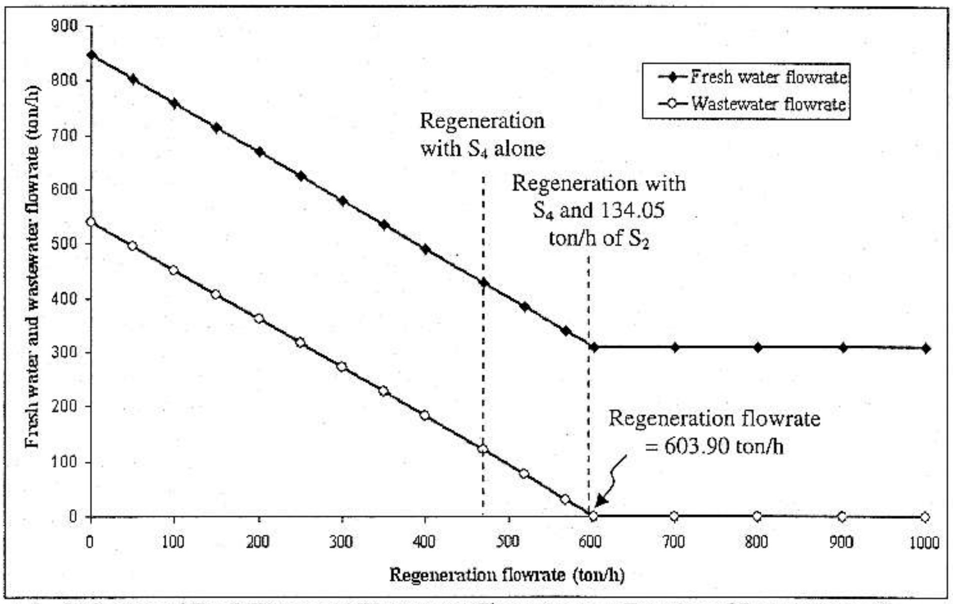

Figure 3 - Reduction of Fresh Water and Wastewater Flowrates as a Function of Regeneration Flowrate

Table 3 - Targeting for Paper Mill Case Study

k	C_k (ppm)	$\Sigma_i F_i - \Sigma_j F_j$ (kg/s)	F_C (kg/s)	Δm (kg/s)	Cum. Δm (kg/s)
			F_F=308.76		
1	0	0			
			308.76	6175.20	
2	20	-190.08			6175.20
			118.68	356.04	
3	23	134.05			6531.24
			252.73	505.46	
4	25	469.8			7036.70
			722.53	39739.15	
5	80	-831.12			46775.85
			-108.59	-2171.80	
6	100	-46.44			44604.05
			-155.03	-10852.10	
7	170	201.84			33751.95
			46.81	1404.30	
8	200	-1218.54			35156.25
			-1171.73	-35151.90	
9	230	1171.73			4.35
			F_D=0.00	-4.35	
10	1000000				**0.00** (PINCH)

Note that if one had started by purifying the "cleanest" water source, i.e., SR_1, followed by SR_3 and SR_2 (Figure 2b), one would have achieved the same annual operating cost of \$533,800 (for the same amount of Δm removed). However, in this case, a larger F_{reg} value of 785.17 ton/h, and hence a larger DAF unit would be needed to achieve zero discharge. Hence a much higher capital cost is expected for the purchase of a new regeneration unit.

Figure 3 shows a plot of the regeneration flowrate versus fresh water and wastewater flowrates for the DAF unit, following the heuristic of purifying water sources in descending order. Note that fresh water fed to the process remains constant at the regeneration flowrate of 603.90 ton/h. This is the turning point for the paper mill process to achieve zero liquid discharge.

One of the many possible water networks to achieve zero discharge is shown in Figure 4. Apart from the total elimination of wastewater, the final network which includes regeneration managed to achieve 84.5% reduction in fresh water. This is an additional 27.1% reduction as compared to reuse/recycle alone (Table 2).

Conclusion

A new method to optimise regeneration units into a maximum water recovery (MWR) network to achieve zero liquid discharge has been developed. Water cascade analysis (WCA) technique provides a quick and accurate means in identifying a solution with the minimum capital and annual operating costs.

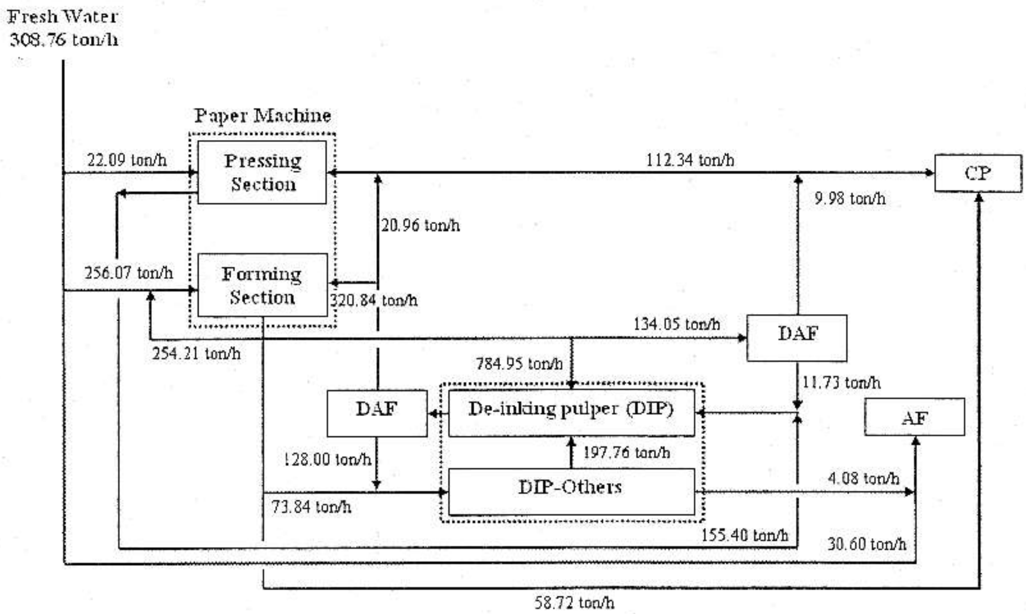

Figure 4 - Zero Wastewater Discharge Network for the Paper Mill Case Study

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